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FINAL

ASSESSMENT OF 'LESSONS LEARNED' FROM THE OPERATIONS OF EXISTING FRESHWATER DIVERSIONS IN SOUTH LOUISIANA

Prepared for

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COASTAL PROTECTION AND RESTORATION AUTHORITY OF LOUISIANA **May 27, 2011**

Wax Lake Delta - Cover photograph from LSU Coastal Louisiana Ecosystem Assessment 2010 Landsat 5 Thematic Mapper Satellite Image, 17 Nov. 05. Image provided by John Barras, U.S. Geological Survey

EXECUTIVE SUMMARY

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The primary purpose of river diversions is to supply freshwater, nutrients, and sediments to restore and maintain coastal wetlands that have been lost over the last 70 years. Ecosytem restoration plans, especially those developed after Hurricane Katrina, recommend more river diversions.

Existing river diversions have been designed for different purposes. Types of diversions include large-scale freshwater diversions, crevasses, siphons, and flood control spillways. The large-scale diversions (Caernarvon, Davis Pond, and Bayou Lamoque) were designed and constructed to divert freshwater and associated nutrients, not necessarily large amounts of sediments. The recently constructed West Bay, Delta Wide, and Channel Armor Gap crevasse projects were designed to divert freshwater, sediments, and nutrients. The Wax Lake Delta was created by the creation of Wax Lake Outlet as a flood control structure. Delta National Wildlife Refuge was created by the creation of Cubit's Gap. Several small siphon diversions are also currently in operation or have been operated in the past (including White's Ditch, Violet, La Reussite, West Point a la Hache, and Naomi) to divert freshwater and nutrients. The Bonnet Carré and Morganza spillways are opened occasionally to divert excess water from the Mississippi River for flood control purposes. The Old River Control Structures are operated continuously to maintain the distribution of flow between the Mississippi River and Atchafalaya Rivers.

Ecosystem changes, such as river diversions, will have both benefits and drawbacks. The challenge is to understand and quantify these effects so that effective management decisions can be made; and to enhance the benefits and mitigate the drawbacks. The effects of large river diversions on estuarine and marine organisms are a concern, as well as the effects of high nutrient loads coupled with low sediment input on marsh vegetation.

The objectives of this report are to examine the available data, literature, and reports on existing river diversions in south Louisiana to develop a "Lessons Learned" document. Specifically, this document summarizes the effects of diversions on coastal elements including: soils, vegetation, wildlife, and fisheries. Although abundant information on Mississippi River diversions is available, only information pertaining to effects of existing freshwater diversion projects on these particular coastal elements was analyzed for this report.

The initial step in the development of this report was to collect and organize the existing literature on river diversions in coastal Louisiana. The literature was a mix of traditional, peer-reviewed literature (white literature), as well as agency reports, conferences, and meeting proceedings (grey literature). As a result, a literature database was developed to provide a central location for these documents. To data, approximately 1,272 documents have been recorded in this database.

The diversions that appeared to build the most land were those that diverted significant amount of sediment and included the Atchafalaya Delta, Cubit's Gap, and the Delta Wide Crevasses Project. The Atchafalaya and Wax Lake deltas have rapidly evolved through the processes of seaward channel extension and bifurcation as well as lobe fusion and upstream growth by coarse sediments (primarily fine sand). It was estimated that approximately 153 km^2 above the -0.6 m contour was created from 1981 to 1995. Maintenance dredging has caused differences in the Atchafalaya and Wax Lake deltas. Since dredging ceased on the Wax Lake Outlet in 1980, the delta has been building naturally. Dredged material placement along the channel banks in the Atchafalaya Delta has formed a proficient channel which carries sediment to the Gulf of Mexico and hampers the delta-building process for the surrounding areas when compared to the Wax Lake Delta. Systematic monitoring has shown that a direct correlation exists between growth of the delta with flood duration and volume.

The total land gain for the Delta Wide Crevasses (State Project Number MR-09) project is 499 acres at approximately 23 acres/year per crevasse. Elevation gain is impacted by the crevasse angle of orientation and width. Wider crevasses and crevasses oriented at 60 degree angles from their parent channels gained elevation and created subaerial land at rates faster than narrower crevasses oriented 90 degrees from parent channels. Deeper areas take longer to fill because they require more sediment and subaerial expression of the crevasse splay may be delayed. Abnormally high river stages cause more shoaling than normal in the main channel which results in additional dredging. This additional shoal material, combined with high river flows, increases the volume of sediments introduced into the crevasses areas. Cubit's Gap, an artificial crevasse created in1862, essentially created 48,000 acres of land that became Delta National Wildlife Refuge in 1935. Land is still being lost in the outfall of the West Pointe a la Hache siphon.

The Bonnet Carré Spillway deposits sediment (mostly silt and sand) during each opening. In a major flood, the river can deposit more than 12 million cubic yards of sediment on Spillway lands. During the 1973 opening, an area of silty sand (an average of 19 cm thick) was deposited near the mouth of the Spillway.

Vegetation habitat in the Breton Sound Basin changed from 1978 to 2000 due to the operations of the Caernarvon Freshwater Diversion. Freshwater marsh was not observed in 1978; however, 628 acres were documented in 2000. Since 1978, brackish and saline marsh decreased, and intermediate marsh increased by 10,582 acres.

For Delta Wide Crevasses, lower plant diversity is observed in the late stages of succession as the more stable competitive species begin to dominate. Primary succession can be observed by combining the elevation and vegetation data; new plant growth follows land creation. In 1999, a non-diverse group of pioneer plants were observed. Post-construction of the crevasses (2002), a more diverse community of competitive species became dominant.

Plant succession is dynamic at the Atchafalaya Delta and can be divided into three categories. Some species have increased over time and converged on certain elevational zones. Other species are relatively stable over time with elevational shifts attributable to local erosion or accretion. Some species are present over a wide range initially, eventually disappearing at low elevations.

Freshwater releases through the Caernarvon Diversion and Davis Pond have increased the amount of submerged aquatic vegetation coverage. Increased phytoplankton growth has been noted after Bonnet Carré Spillway openings. Phytoplankton composition changes after the 2008 Spillway opening were similar to those of the 1997 opening. Blue-green algae dominated the phytoplankton community in 2008, but were less severe than in 1997, when a large blue-green algae bloom resulted in lake-wide recreation health advisories.

Ammonium concentrations were highest at sites near Caernarvon during months of high flow; however, concentrations at the far site were less variable. Porewater concentrations of ammonium increased with depth and ammonium concentrations were greater at the upstream and transition sites compared to the downstream site. Concentrations of phosphate (PO_4) during late spring and early summer were typically higher towards Caernarvon and at the marine end of the estuary. Total phosphorus was also higher during high discharge periods. Distinct zones of high phosphate concentrations were evident during high discharge periods in the winter.

Freshwater from Caernarvon may help to maintain low sulfide concentrations. Increased frequency and volume of riverine discharge could potentially decrease sulfide levels. Sulfide concentration was significantly correlated to belowground biomass. Sulfide concentrations during the growing season appeared to be correlated to lower biomass at the sites least affected by the diversion. Introductions of river water may be successful at decreasing chloride concentrations and increasing habitat space for organic rich, freshwater marshes.

Average aboveground biomass production was greater at sites near Caernarvon than sites in the lower basin. In marshes affected by Caernarvon, biomass typically occurs in the upper 30 cm of the soil column, and the greatest amount of belowground biomass production generally occurs at the 0–20 cm depth range. Belowground biomass productions in the upper and lower basins were essentially the same with a slightly greater amount at the upper station nearest freshwater input.

Wildlife populations generally show increasing trends, especially for alligator, muskrat and waterfowl. The best examples of diversions creating wildlife habitat are the Atchafalaya Delta, Wax Lake Outlet, and the Delta National Wildlife Refuge. The data suggest that alligator populations and nests increase with freshwater diversions and an increase in the aerial extent of freshwater and intermediate marsh habitats. Information from Caernarvon and the 1927 flood event did indicate a likely relationship between diversions and increased populations of muskrat.

For fisheries, the literature indicates that most species showed a slight increase in abundance associated with a diversion. Catches of many nekton species were higher in the post-operation Caernarvon area, however only some differences were statistically significant. Nekton density and biomass was significantly higher at flooded marsh sites near Caernarvon than in the reference marsh sites. The Caernarvon area had increased coverage of submerged aquatic vegetation and the nekton communities were dominated by marsh resident species. Increases in density and biomass for the outfall area, when compared to the control area, were attributed primarily to differences in water depth, duration of flooding, and increased submerged aquatic vegetation coverage caused by the diversion pulses.

At Caernarvon, fishery species that indicated increases, in some sampling gears, after the operation began include: spotted seatrout, red drum, black drum, Atlantic croaker, sand seatrout, bay anchovy, striped mullet, grass shrimp, blue crab, and oyster. Brown shrimp catches were significantly less in the seine samples during the post-operation period at Caernarvon indicating the lower catches may be due to the diversion. Trawl catches were lower in the post-operation period, but this difference was not statistically significant. Likely, these changes are because the diversion operates mainly during the period of time when the brown shrimp post larvae and juveniles are recruiting the coastal marshes. It is logical that brown shrimp may show lower numbers in that they are recruiting from the offshore spawning grounds during the periods of peak discharge in the spring. White shrimp did not change during the post-operation period at Caernarvon.

Populations of silver carp, bighead carp, grass carp, and common carp are established in the outfall of Davis Pond. Silver carp, bighead carp, common carp, black carp, and zebra mussel populations are also established in the Atchafalaya River and drainage area downstream of the Old River Control Structure. In mid-April 2009, large numbers of juvenile silver carp were collected from the pools of the Bonnet Carré Spillway. Pallid sturgeon has been collected in the outfall of Bonnet Carré and David Pond.

For the Bonnet Carré Spillway, there were generally higher catches of fishes and aquatic organisms during the opening in 2008 when compared to years when the spillway was not opened. Trawl catches of bay anchovy, blue crab, and brown shrimp in Lake Pontchartrain and bay anchovy, Atlantic croaker, northern white shrimp, and sand seatrout in Lake Borgne were higher in 2008 than in the other years tested. Trawl catches of Gulf menhaden in Lake Pontchartrain; and blue crab, Gulf menhaden, hardhead catfish, and northern brown shrimp in Lake Borgne were not significantly different. The only species with significantly lower catches in 2008 after the Spillway opening were Atlantic croaker and sand seatrout in Lake Pontchartrain and spot in Lake Borgne. Gill net catches of Gulf menhaden and hardhead catfish, and seine catches of bay anchovy, Gulf menhaden, and inland silversides were not significantly different among the years tested.

Following the 1997 opening of the Bonnet Carré Spillway, toxic cyanobacterial blooms occurred on Lake Pontchartrain. The blooms caused decreases of dissolved oxygen in the lake, and fish kills occurred in some places in June and July. Blue green algal blooms appeared during the summers of 1994, 1995, and 1997 and fish kills occurred during the 1995 and 1997 blooms.

For both fisheries and wildlife, it is recommended that adequate data be collected in the pre- and post-operation phases of diversions to evaluate the actual affects of the diversions and that an adequate control area is included when possible. This may require data collection at appropriate stations and may require a long-term program to actually determine trends and relationships. Other information should be collected and analyzed to filter out other parameters that can affect populations, such as harvests, regional and global population trends (such as migratory waterfowl), weather patterns as they can affect data collection, and any other factor that can affect populations. Sufficient data should be collected in a manner to enable a Before, After, Control, and Impacts (BACI) analysis to be conducted. Although populations may appear higher post-operation, they may not be significantly higher. Although counts may be significantly higher or lower post-operation, the differences observed may not be due to the operation of the diversion. Likely there are various sources of data that have been collected by various agencies that could be analyzed to evaluate the wildlife value of existing diversions, such as population counts by the Louisiana Department of Wildlife and Fisheries or the U.S. Fish and Wildlife Service.

Recommendations for diversions in the literature include planning strategies, design, operation, and monitoring. For example, all phases of planning and project management should be coordinated and must share information, not only to maximize the benefits on a project-by-project basis, but also to carry the information learned from past projects into the development of future projects. Project goals should be quantified as much as possible to aid evaluation of project effectiveness. Instead of attempting to restore a large, highly impacted area, perhaps work within a regressed saltmarsh landscape that is sustainable, even if it is a much smaller in area. Other strategies should be employed in conjunction with diverted Mississippi River water, such as restoring suspended sediment loading in the Mississippi, installing numerous smaller-scale sediment diversions, and local hydrological restoration. To preserve all of Breton Sound's land surface area, it was estimated that the equivalent to sixteen diversions similar to the Caernarvon Diversion project, each diverting 4.5×10^5 metric tons sediment/year, would be needed to contribute 10 mm long-term accretion annually, allowing the marsh surface elevation to keep pace with modern rates of relative sea level rise.

From the literature, it was recommended that gated structures provide for greater flexibility in operations. The most important lesson we should learn in the selection and design of future outfall management projects is to properly consider the structural integrity of existing topographic features (i.e., spoil banks, cheniers, etc.) that project structures will depend on to function. In the event that they can be compromised through subsidence, increased water velocity, or erosion during the 20-year life of the project, then proper consideration should be given to the maintenance efforts and costs, and these costs should be included in the selection criteria. Engineering strategies should place as much focus on receiving area configuration and trapping efficiency as sediment delivery in order to maximize sediment retention. Landscape modifications such as spoil banks and weirs reduce the benefits of river water introduction by limiting wetland-water interaction and should be removed or breeched as part of outfall management in conjunction with river diversion implementation for effective wetland restoration.

Sediment diversions would be more successful it they were designed after natural crevasses and other successful crevasses such as Delta Wide Crevasses and Cubit's Gap. The riverine side of the diversion would need to be oriented upriver or river-oblique to intercept significant sand moving in a downriver vector. Crevasses should be designed to retain significant energy flowing through the river end of the sluice or tunnel to avoid settling of significant suspended mud during the low discharge period of the year.

Politics have a very important role in operations of diversion projects. Concern about lawsuits involving diversion projects contributed substantially to the failure to implement a maintenance plan. Operating diversions has been a challenge as many different resource user groups are affected by diversion structures. This has resulted in conservative use of the structures, which limits the ability to evaluate the potential benefits. The current pulsed diversion management plans could be optimized by timing the pulsing events to coincide with rising limbs of the Mississippi River flood events in late winter and early spring, or by increasing the discharge allowed through the diversion, particularly during frontal events, would optimize sediment availability with adequate transport mechanisms to marshes. Some of the water control structures are currently being operated without a contract. A consistent plan for operation and maintenance is needed for diversion projects.

It was recommended that measurement of sediments be included in funding for future projects. The quantity and quality of sediment being transported into the project area can be combined with land gain data and used to model and increase predictive capabilities of crevasse splay development. Measuring and modeling sediment elevation can be a good short-term indicator that a diversion project is successful. Although the endpoint for determining project success is land gain measured from aerial photography, the elevation data can identify project success earlier than photography and also show additional benefits (i.e., subaqueous infilling).

The variability in marsh elevation and local hydrology are significant factors effecting productivity which should be accounted for in future studies. Ideally, efforts to mitigate coastal wetland loss should include measures that assure that adequate mineral sediment is supplied to salt marsh.

Currently structural, hydrological, and even human constraints determine the placement of controlled river diversions along the Mississippi River. Soil type and the organic matter that gives the marsh soil its structure and resilience to perturbations should be considered. The variability in marsh elevation and local hydrology should be accounted for in future freshwater diversion evaluations as they are significant factors affecting productivity.

Operating the diversion consistently in response to saltwater intrusion events may help to maintain marsh species composition along the estuarine gradient while increasing species survival and rates of production. Whatever benefits result from increases in the inorganic sediment supply should be weighed against the impact of adding nutrients that may weaken the soils.

Greater flushing of parts of the estuary would be beneficial by reducing the potential for algal blooms. Diverting river water during higher river stages, and when southerly winds are present, may increase flushing and reduce excessive phytoplankton abundance. Implications for phytoplankton management include avoiding higher diversion discharges under high light and high temperature regimes, carrying out diversions in the winter and spring, and changing hydrology to reduce residence time.

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‘LESSONS LEARNED’ FROM THE OPERATIONS OF EXISTING FRESHWATER DIVERSIONS IN SOUTH LOUISIANA

‘LESSONS LEARNED’ FROM THE OPERATIONS OF EXISTING FRESHWATER DIVERSIONS IN SOUTH LOUISIANA

1.0 INTRODUCTION

The diversion of waters from the Mississippi River into wetlands and estuaries is one of the restoration techniques discussed in the Louisiana Coastal Area (LCA) report, the State Master Plan, and the U.S. Army Corps of Engineers (USACE) Louisiana Coastal Protection and Restoration (LACPR) reports. Land loss in coastal Louisiana is attributed to many factors, including loss of freshwater, nutrient, and sediment input from the river due to the construction of levees, dams, and ship channels. Coastal subsidence, mineral extraction, and sea level rise are other factors attributed to coastal land loss.

The primary purpose of river diversions is to supply freshwater, nutrients, and sediments to aid in the restoration and maintenance of coastal wetlands. Historically, sediments deposited during overbank flooding of the Mississippi River gradually built up and maintained Louisiana’s coastal wetlands. Freshwater and sediment input has been largely eliminated by river modifications such as flood protection levees and upstream dams. The diversion of freshwater, sediments, and nutrients from the Mississippi River into various wetlands and estuaries is an effort to decrease salinity stress on freshwater flora and fauna, to provide a sink for excess nutrients that contribute to the *dead zone* off the Louisiana coast in the Gulf of Mexico, and to nourish the marshes by providing an influx of sediments to re-build the wetlands that have been lost over the last 50 years. Restoration plans, especially those developed after Hurricanes Katrina and Rita, suggest that more river diversions are needed. Today, there are approximately 15 existing diversions and approximately 11 proposed restoration diversions (Figure 1-1).

Existing diversion projects have been designed for different purposes. Three main types of diversions have been used: concrete structures, crevasses, and siphons. The large-scale diversions (Caernarvon, Davis Pond, and Bayou Lamoque; Figures 1-2 to 1-4) were designed and constructed to divert freshwater and associated nutrients, not large amounts of sediments. The recently constructed West Bay, Delta Wide Crevasses, and Channel Armor Gap artificial crevasse projects were designed to divert freshwater, sediments, and nutrients. Cubits Gap was created in 1862 and resulted in the creation of what is now Delta National Wildlife Refuge. Wax Lake Outlet functions as a diversion although it was designed for flood control (Figures 1-5 to 1-9). There has been much discussion over the benefits of these projects and West Bay’s effects on shoaling in the river and the Breaux Act Task Force voted to close West Bay. Several small siphon diversions are also currently in operation or have been operated in the past (including White’s Ditch, Violet, La Reussite, West Point a la Hache, and Naomi) to divert water and sediment (Figures 1-10 to 1-12).

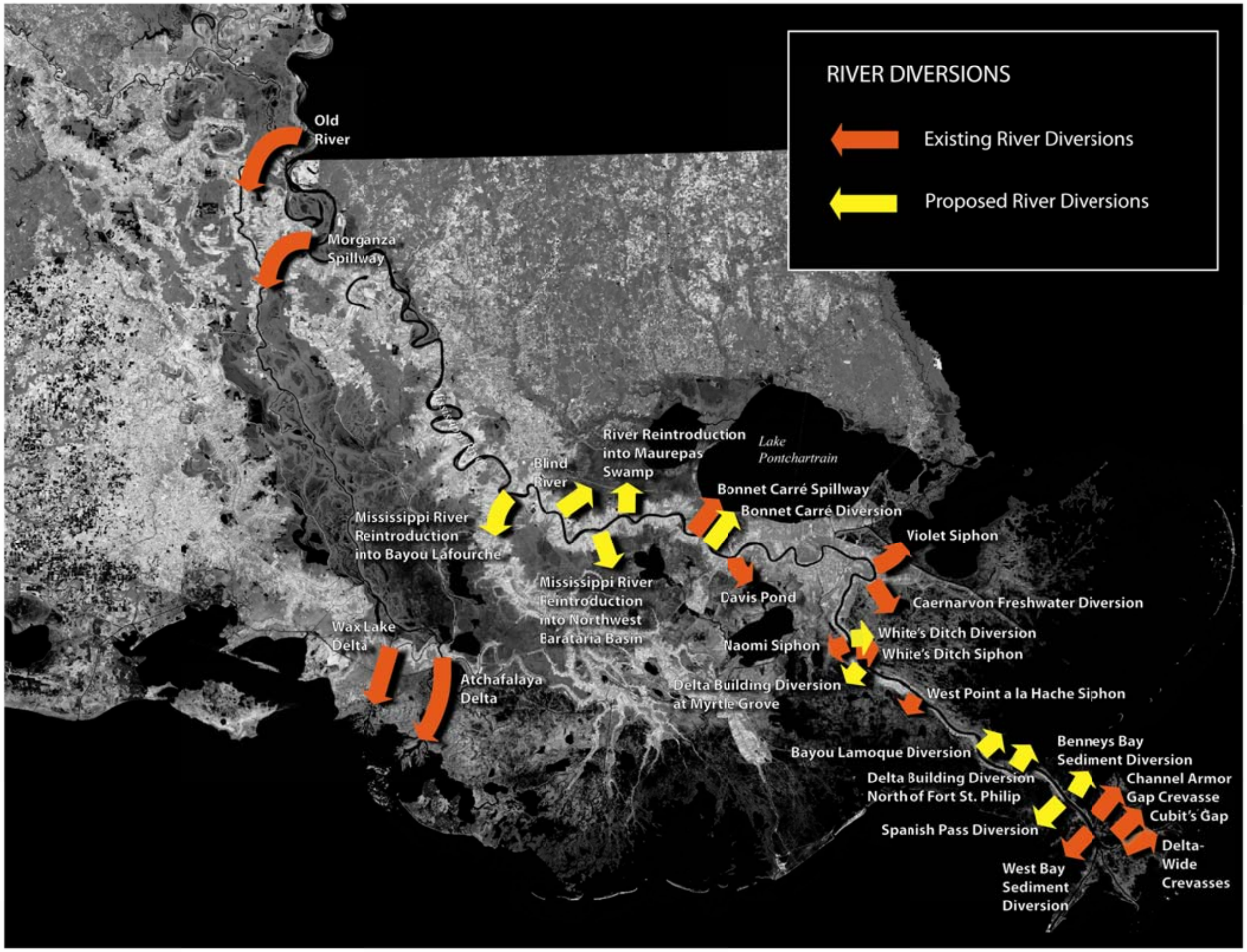

Figure 1-1. Locations of existing and proposed river diversions in south Louisiana (Modified from White *et al.* undated)

Figure 1-2. Photo of Caernarvon (capable of diverting up to 10,650 cfs) (from CPRA 2010)

Figure 1-3. Photo of Davis Pond (capable of diverting up to 8,800 cfs) (from LDNR 2003)

Figure 1-4. Photo of Bayou Lamoque Diversion (capacity 12,000 cfs). Currently in disrepair, unauthorized operation except for oil spill. (from Louisiana Coastal Wetlands Conservation and Restoration Task Force 2007)

Figure 1-5. Photo of West Bay Diversion (20,000 cfs capacity) The Breaux Act Task Force voted to close West Bay. [from Louisiana Coastal Wetlands Conservation and Restoration Task Force 2004 (rev.)]

Figure 1-6. Photo of Cubit's Gap (opening on left)
[From Center for Environmental Communications, Loyola University 2010]

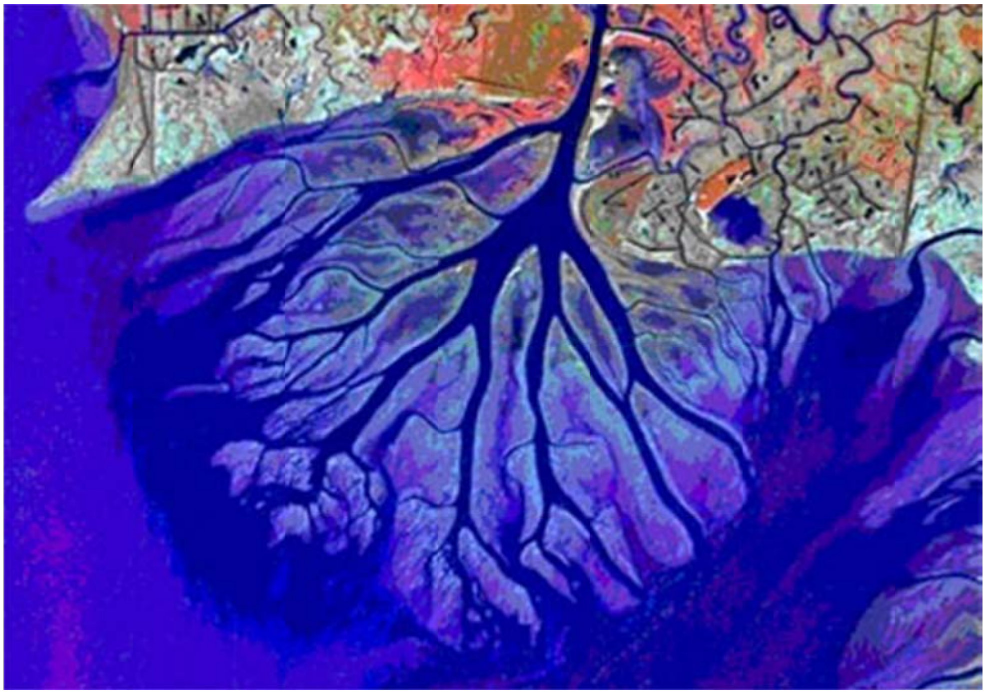

Figure 1-7. Wax Lake Delta aerial photo
(from LSU Coastal Louisiana Ecosystem Assessment 2010 Landsat 5
Thematic Mapper Satellite Image, 17 Nov. 05. Image provided
by John Barras, U.S. Geological Survey.)

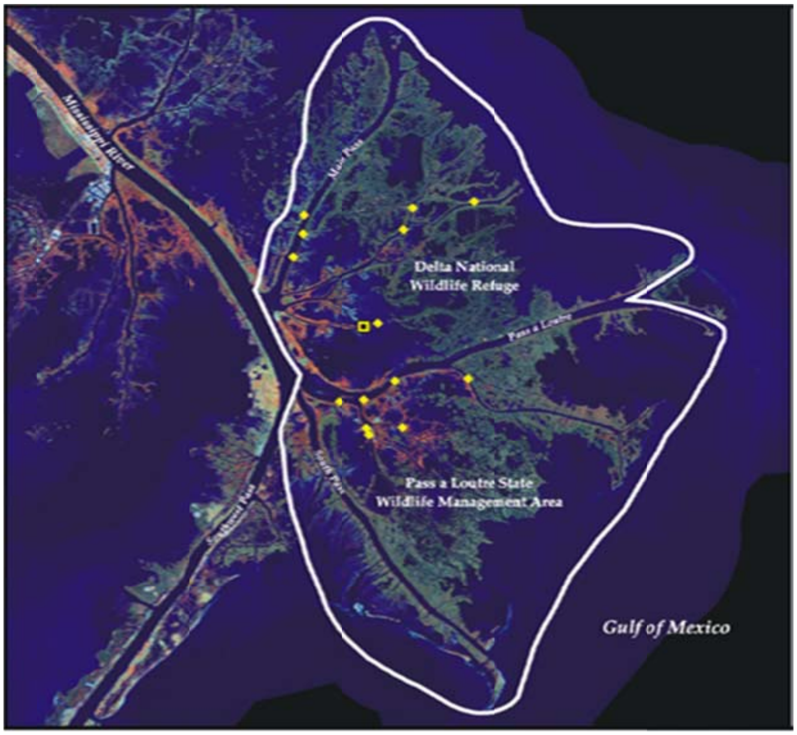

Figure 1-8. Delta wide Crevasses
[From Louisiana Coastal Wetlands Conservation and Restoration Task Force. 2004 (rev.)]

Figure 1-9. Photo of Violet Siphon (capacity 200 cfs)
(from Louisiana Governor's Office of Homeland Security and Emergency Preparedness 2010)

Figure 1-10. Photo of White's Ditch Siphon (capacity 200 cfs)
(from Center for Environmental Communications, Loyola University 2010)

Figure 1-11. Photo of Naomi Siphon (capacity 1,500 cfs) (Source: NOAA 2010)

Figure 1-12. Photo of West Pointe a la Hache Siphon (capacity 1,500 cfs) (from C.H. Fenstermaker & Associates, Inc. 2004)

Spillways and other control structures on the Mississippi River are used to divert floodwaters and distribute river flow. The Bonnet Carré and Morganza Spillways (Figures 1-13 and 1-14) are opened occasionally (Bonnet Carré 8 times, Morganza once) to divert floodwaters from the Mississippi River. The Old River Control Structure Complex (Figure 1-15) is operated continuously to maintain the distribution of flow between the Mississippi River and Atchafalaya Rivers.

Over recent years, there has been much discussion regarding the benefits and drawbacks of diversions, both large and small. Impacts of large diversions on estuarine and marine organisms are a concern, as well as the effects of high nutrients coupled with low sediment input on marsh vegetation. As with any significant change in the management of coastal ecosystems, river diversions will have both positive and negative effects. The challenge is to quantify these effects so that effective management decisions can be made.

Figure 1-13. Bonnet Carré Spillway during 2008 Opening (design capacity 250,000 cfs) (Source: G.E.C. Inc.)

Figure 1-14. Morganza Spillway (design capacity 600,000 cfs) (Source: G.E.C., Inc.)

Figure 1-15. Old River Control Structure Complex (Source: World News 2010)

The ability of the diversion to deliver Mississippi River sediments both in terms of total suspended solids and range of grain size is an integral part of the effectiveness of a river diversion. Grain size is important in marsh creation. Grain size is reduced in the lower portions of the river channel. This phenomenon is referred to as the *thinning of the sands* (Thorne *et al.* 2007a, b; Figure 1-16; Allison and Nittrouer 2004). Maintaining the navigation channel at an elevation of -45 feet reduces the river's ability to move the larger grain sediments that are available. Larger grain sizes are primarily carried in the bed load, but can become suspended during high river discharges. There is debate on whether or not these larger grain sizes are needed to help rebuild coastal wetlands. Dedicated dredging and placement have been suggested as an alternative method to *divert* the amount and grain size of sediment needed, while reducing the possible negative effects of large-scale water diversions.

1.1 Purpose

This report gathers and summarizes the existing data and information on river diversions and develops a review summary describing what is known from river diversion projects and research literature. This report presents the lessons learned and recommendations for future diversion operations based on the existing available literature.

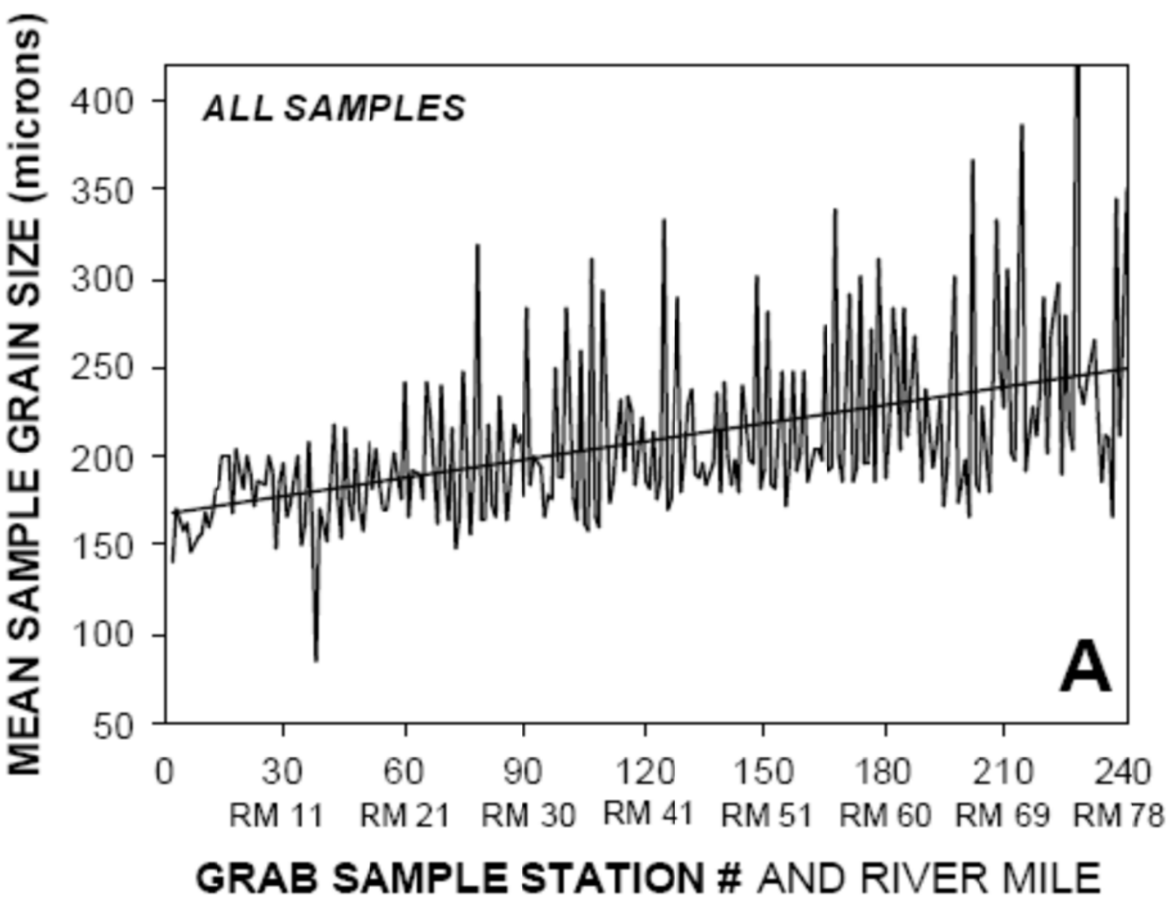

Figure 1-16. Grain size in grab samples from the Mississippi River by river mile (from Allison and Nittrouer 2004)

Scientific and technological uncertainties, as well as social, economic, and political implications have posed challenges to the development of Louisiana's coastal restoration program. Although not all of the existing diversions were designed for the same purpose, much can be learned about the operation, design, and success of the existing diversions that can help decision makers regarding the feasibility, design, and operation of proposed diversions.

This report is funded by the LCA Science and Technology (S&T) program. The Office of Coastal Protection and Restoration (OCPR), Louisiana Applied Coastal Engineering & Science (LACES) Division co-manages the LCA S&T Program for the State of Louisiana, with its USACE partner. For this report, LACES will use State funds cost-shared with USACE through the LCA S&T Program to organize pertinent questions and synthesize the data in order to summarize useful information from existing diversions that will aid project managers in the planning, design, and implementation of new diversion structures.

1.2 Objectives

The objectives of this report are to examine the available data, literature, and reports on existing river diversions and to develop a "Lessons Learned" document focusing on diversions that have been built in southern Louisiana. Specifically, this document summarizes the effects of diversions on coastal elements including: soils, vegetation, wildlife, and fisheries. Even though there is much information available that could pertain to a design and management of a diversion, the information mainly considered for this report were reports and papers that had data and information collected directly from an existing river diversion.

1.3 Literature Database

The initial step in the development of this report is to collect and organize the existing data and literature on coastal Louisiana, including river diversions. Access to the full array of literature related to river diversions in south Louisiana is difficult at present. The literature is a mix of traditional, peer-reviewed literature (white literature), as well as agency reports, conference, and meeting proceedings (grey literature). The collating of this body of literature in a central location (literature database) was necessary for this report, and will provide for future use by State and Corps Project Delivery Teams (PDTs).

The literature database developed for this report will be transferred and can be accessed through the Louisiana Department of Nature Resources through its Document Reference System (DRS). To date, 1,272 references have been incorporated into this database. This database has been developed so that literature references can be searched to develop a selected bibliography by the keywords listed below:

Accretion	Atchafalaya	Bay Study
Bonnet Carré	Biomass	Caernarvon
Coastal Land Loss	Crevasse	Data Only
Davis Pond	Diversions – General	Feasibility Study
Fisheries	Freshwater Inflow	Hydrodynamics
Hurricane Protection	Impacts	Levees
Marsh Creation	Modeling	Nutrients
Old River Control Structure	Plankton	Productivity
Proposed Diversion	Pulsing	Restoration
Riverine	Salinity	Sediment
Siphons	Splays	Survey
Water Quality	Wax Lake	West Bay
Wildlife	Vegetative/SAV	

Appendices A - D contain the literature queries for soils, vegetation, wildlife, and fisheries resources. The keywords used for each resource are as follows:

Resource	Keyword
Soils	Accretion, Atchafalaya, Bay Study, Bonnet Carré, Caernarvon, Coastal Land Loss, Crevasse, Davis Pond, Diversions – General, Freshwater Inflow, Marsh Creation, Old River Control Structure, Pulsing, Restoration, Sediment, Siphons, Splays, Wax Lake, West Bay
Vegetation	Atchafalaya, Bonnet Carré, Biomass, Caernarvon, Davis Pond, Diversions – General, Freshwater Inflow, Nutrients, Pulsing, Salinity, Wax Lake, West Bay, Vegetative/SAV
Wildlife	Wildlife
Fisheries	Fisheries, Plankton

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World News. 2010. Old River Control Structure. http://wn.com/Old_River_Control_Structure

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2.0 SOILS

The development of soils and land building processes are important elements in making decisions about river diversions. Mineral and organic inputs are critical for short- and long-term accretion and restoration of coastal Louisiana.

2.1 Mineral and Organic

Mineral sediment is necessary to promote the growth of marsh vegetation, which in turn produces the organic matter that forms organic soil. A limited amount of mineral sediment is being supplied to the marshes adjacent to the Mississippi River. Fresh, brackish, and saline marshes have different mineral requirements; higher salinity marshes generally require larger quantities of sediment for sustainability (Figure 2-1). Marsh loss will occur if the mineral sediment input is insufficient to meet these requirements (DeLaune *et al.* 2003). The introduction of freshwater to marshes which have been leveed off from the Mississippi River reduces the mineral sediment requirement for the growth of marsh vegetation as plant succession patterns shift from salt to brackish and freshwater habitats (DeLaune *et al.* 2003). Mineral and organic matter was found in higher abundances at sites nearest the freshwater input [Figure 2-2; DeLaune *et al.* 2003; Wetland Biogeochemical Institute (WBI) 2002]. Deposition is generally more mineral dominated near the diversion and more organic down basin (Wheelock 2003).

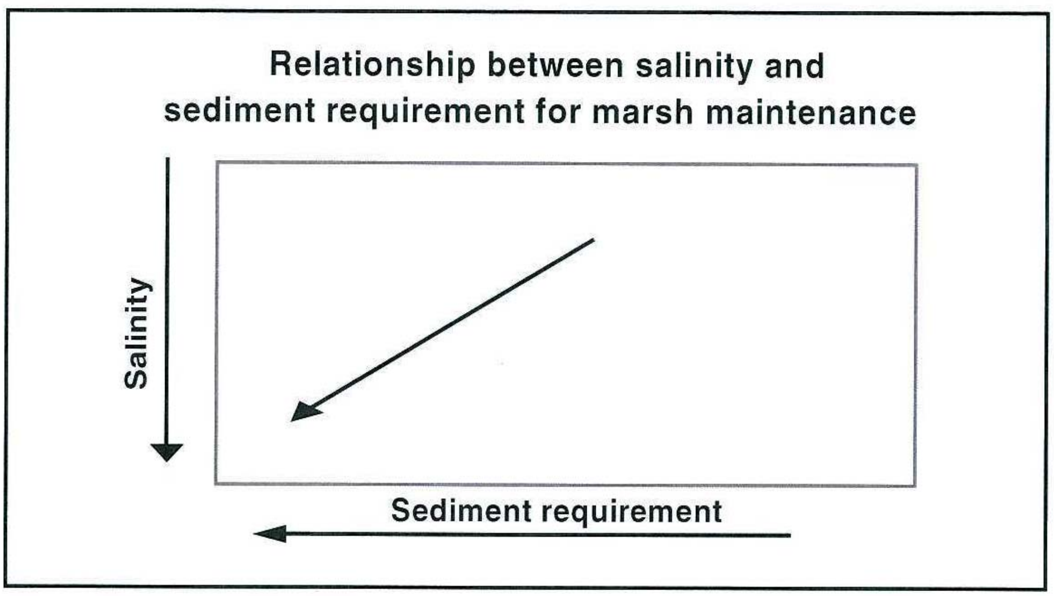


Figure 2-1. Relationship of Salinity to Sediment Requirement for Marsh Maintenance (from WBI 2002; DeLaune *et al.* 2003)

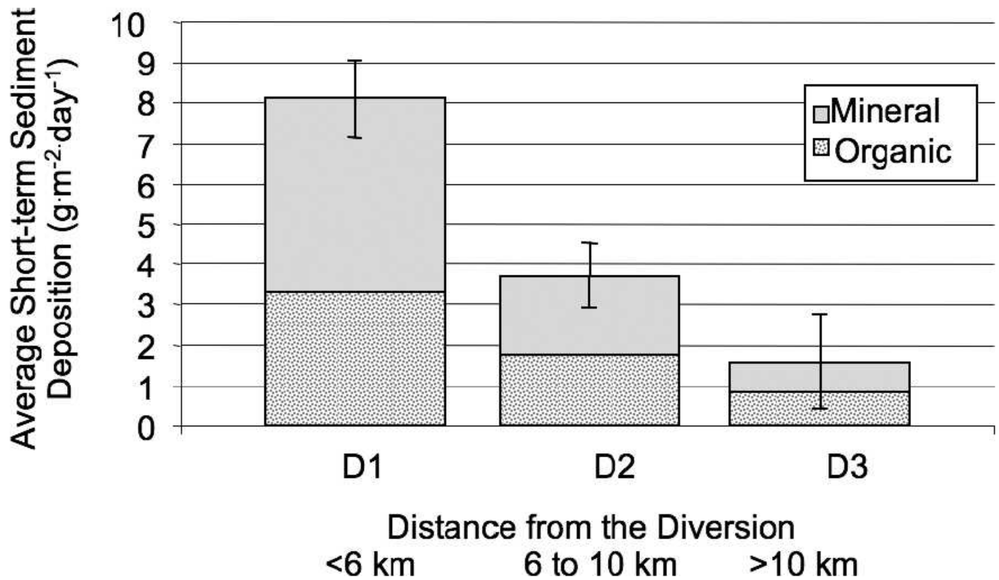


Figure 2-2. Short-term Sediment Trap Results for the Upper Breton Sound Estuary (from Wheelock 2003)

Land building in the deltaic environments relies primarily on the coarser grain sediments (Wheelock 2003). Organic sediments were important contributors to higher rates of accretion in certain ecosystems (Brantley *et al.* 2008; WBI 2002). While organic accretion is essential in adjusting marsh elevation to sub-decadal fluctuations in sea level, it has only a small effect over the long term (Smith 2009).

2.2 Accretion Short-Term/Long-Term Measurements

Accretion is the net effect of factors that increase local elevation (sediment deposition, vegetative deadfall, and root formation) and factors that counter elevation gain such as erosion, shallow subsidence, oxidation of organic material, and compaction. Each of these processes can occur at various depths in the marsh substrate ranging from less than 1 cm (sediment deposition, deadfall, oxidation, and erosion) to as deep as 10 cm (root formation, compaction, and shallow subsidence) (Wheelock 2003).

Sediment traps are used to assess short-term sediment deposition as an effective means of analyzing both spatial and temporal depositional patterns of mineral and organic matter (DeLaune *et al.* 2003; Wheelock 2003). Short-term sediment trap measurements capture net deposition that includes resuspended particles and are useful for identifying areas of high deposition. Many more samples can be collected in a short period of time using this technique (Day *et al.* 2009; DeLaune *et al.* 2003). However, the vertical marsh accretion determined from the feldspar method would overestimate the actual accretion rate representing the soil plant root zone (DeLaune *et al.* 2003; Wheelock 2003). The sediment trap deposition rates only indicate recent transport events and not the effects of burial, diagenesis, or below ground organic accumulation (Day *et al.* 2009). These measurements can also be affected by bioturbation, infauna and epifauna, mixing, and root formation (Smith 2009; Wheelock 2003).

Long-term (decadal scale) deposition rates are much lower than rates from short-term sediment traps; this likely reflects the decomposition of buried organic matter as well as compaction and compression of sediments (Day *et al.* 2009; Smith 2009). Long-term rates are measured from sediment elevation tables (SET) or from Lead-210 (^{210}Pb) and Cesium-137 (^{137}Cs) dating. Short- and long-term accretion rates should be compared since accretion is not a linear process (Smith 2009). Such comparisons are difficult and must be interpreted with caution since deposition above the marker horizon consists of loosely consolidated material which will eventually decay and compact the void space. These depositions fail to represent long-term sustainability (DeLaune *et al.* 2003; Smith 2009). Long-term measurements of accretion are more effective at estimating marsh sustainability and are most applicable for assessing coastal sustainability relative to sea level (Day *et al.* 2009; Smith 2009).

2.3 Atchafalaya Basin

2.3.1 Historic Development

During the late 1940s, approximately one-third of the Mississippi River flow shifted west to the newly developing Atchafalaya delta complex as part of the natural process of distributary lobe switching. This placed sediment into the Atchafalaya Basin and the diverted river waters and suspended sediment into the westward flowing currents of the coastal current system (Huh *et al.* 2001; Neill and Allsion 2005; Roberts 1998). A large dredge channel (initiated in 1942) is maintained at a depth of 20 ft (6.5 m) across the Atchafalaya Bay and onto the continental shelf to allow ocean-going vessels access to the Port of Morgan City, Louisiana via the Lower Atchafalaya River. At the entrance to the Atchafalaya Bay, dredge spoil is placed alongside the channel seaward of the oyster reef (Neill and Allison 2005). In additions, the Wax Lake Outlet was also dug in 1942 (Roberts 1998).

A subaqueous delta began to form at the mouth of the Atchafalaya River between 1952 and 1962 with the introduction of silts and fine sands into the bay. Prior to 1952, these sediments filled the lakes and bays within the Atchafalaya Basin Floodway system, north of the Atchafalaya Delta. Only prodelta clay deposition occurred in the Atchafalaya Bay before 1952 due to contact with higher salinity water (LCWCRTF 1993). Tidal bar and subaqueous bar accretion occurred from 1962 to 1972 due to the deposition of coarser materials into the Atchafalaya Bay (van Heerden and Roberts 1980).

In 1963, the Low Sill Structure was constructed at Old River on the Outflow Channel constructed at the point that linked the Mississippi River to the Red and Atchafalaya rivers. Discharge down the Atchafalaya River was then regulated at 30 percent of the Mississippi River and the Red River (Neill and Allison 2005; Roberts 1998). Additional structures (Auxiliary Structure, Overbank Structure, navigation lock and closure dam, and a hydropower plant and dam) were added in the Old River area in subsequent years to relieve pressure at other sites, to improve navigability, and provide hydropower.

By 1972, the bottom of Atchafalaya Bay had accreted to the point of near exposure at low tide over considerable areas opposite the Atchafalaya River mouth and to a lesser extent opposite the Wax Lake Outlet (Roberts 1998). In addition, transient mudflats were appearing and disappearing along the coast of the eastern Chenier Plain (Roberts 1998). In 1973, an abnormally high flood year, the Atchafalaya and Wax Lake deltas became subaerial features (Neill and Allison 2005; Roberts 1998; van Heerden *et al.* 1991). Subaerial evolution of the Wax Lake delta lagged behind the Atchafalaya because a small inland basin (e.g., Wax Lake) had to be filled before coarse sediments were efficiently bypassed to Atchafalaya Bay (Roberts 1998).

2.3.2 Atchafalaya and Wax Lake Deltas

A delta-switching event on the Atchafalaya River, the latest in a series of major Holocene diversions, is attempting to abandon the modern Balize (bird foot) delta of the Mississippi in favor of a new delta in Atchafalaya Bay and on the adjacent continental shelf. The Atchafalaya River course, to the Gulf of Mexico, is 300 km shorter than the current course of the Mississippi River. From a diversion perspective, this shorter course produces an obvious gradient advantage (Roberts 1998).

The Atchafalaya River empties into a shallow bay and low gradient inner shelf area that is more energetic than the shelf-edge Plaquemine lobe of the Mississippi River 180 km to the east (Neill and Allison 2005). Mississippi River sediment is discharged seaward, settling in the nearby deep water and is lost to coastal land building processes. In the Atchafalaya complex, land can be built rapidly due to the broad shelf and very shallow inshore areas (Huh *et al.* 2001). The river discharges into Atchafalaya Bay in southern Louisiana through two outlets, Lower Atchafalaya (70 percent of the discharge) and Wax Lake (30 percent) (Neill and Allsion 2005). Wax Lake Outlet was a channel constructed off the lower Atchafalaya River in 1942 across a natural ridge in to reduce the risk of flooding in Morgan City, Louisiana. In addition, a 4,000 foot rock weir was constructed across Grand and Six Mile lakes in 1987-1988 to regulate the distribution of flows between the Atchafalaya River (70 percent) and Wax Lake (30 percent). The USACE removed the weir in 1994-95 (Reuss 2004). The Wax Lake Outlet diverts about 30-40 percent of the Atchafalaya River water (approximately 10-12 percent of the Mississippi River discharge; Roberts *et al.* 2003).

The Atchafalaya and Wax Lake deltas have developed approximately 153 km^2 of area above the -0.6 m contour from 1981 to 1994 (Figures 2-3 to 2-6; Roberts and van Heerden 1981; Roberts 1998; Majersky *et al.* 1997). This delta has rapidly evolved through the processes of seaward channel extension and bifurcation as well as lobe fusion and upstream growth by coarse sediments (primarily fine sand). These processes are accomplished by the rapid growth of mid-channel bars and the sealing of feeder channels by subaqueous levee growth (Roberts and van Heerden 1981). Both deltas primarily consist of sand-rich facies (mostly distributary mouth bar and subaqueous levee deposits). Estimates of sand content from vibracores are 62 percent for the eastern Atchafalaya delta and 67 percent for the Wax Lake Delta (Roberts 1998).

Maintenance dredging has caused differences in the Atchafalaya and Wax Lake deltas. Since dredging ceased on the Wax Lake Outlet in 1980, the delta has been building naturally (Curole 2003). The Lower Atchafalaya River Navigation Channel, maintained for navigation by the

USACE, divides the Atchafalaya delta (van Heerden and Roberts 1980). Dredged material placement on channel banks has formed a proficient channel which carries sediment to the Gulf

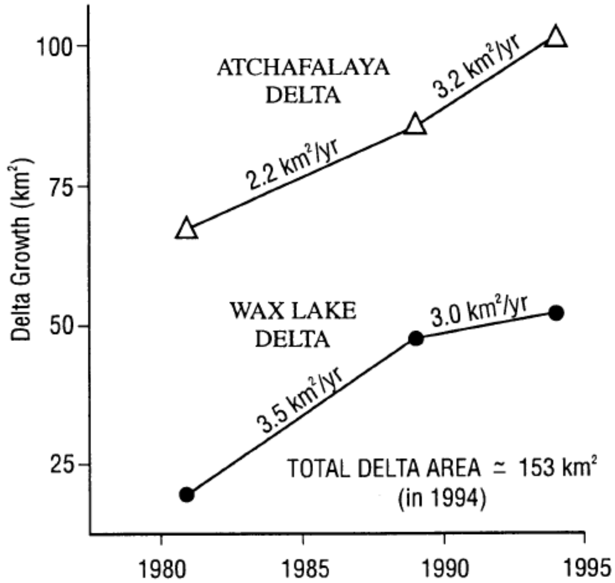


Figure 2-3. Growth of both the Atchafalaya and Wax Lake deltas measured in km^2 above the -0.6 m isobaths. Measurements were made for 1981, 1989, and 1994. Rates of change are indicated in km/yr between the measurements years (modified from Majersky *et al.* 1997 as cited in Roberts 1998).

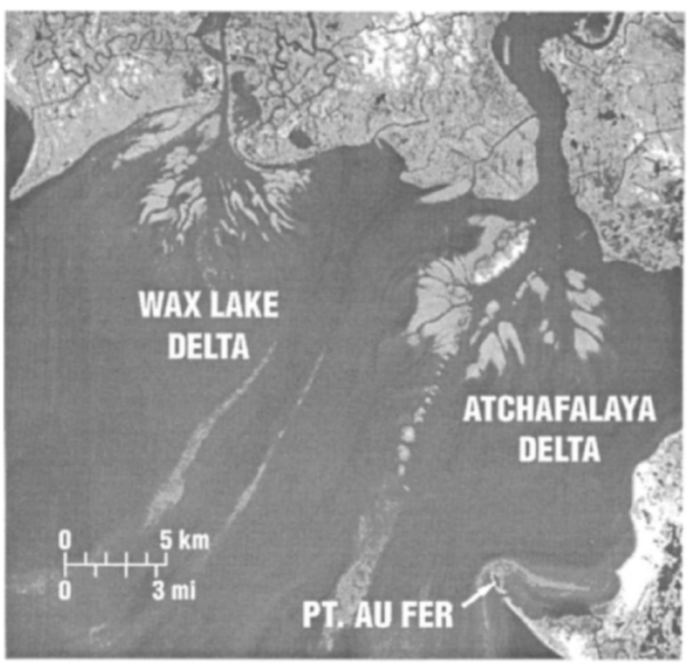


Figure 2-4. A SPOT satellite image (HRV3, near infra-red) taken 22 January 1988 (1704GMT) of Atchafalaya Bay showing the subaerial morphology of the Wax Lake and Atchafalaya bayhead deltas (from Roberts 1998)

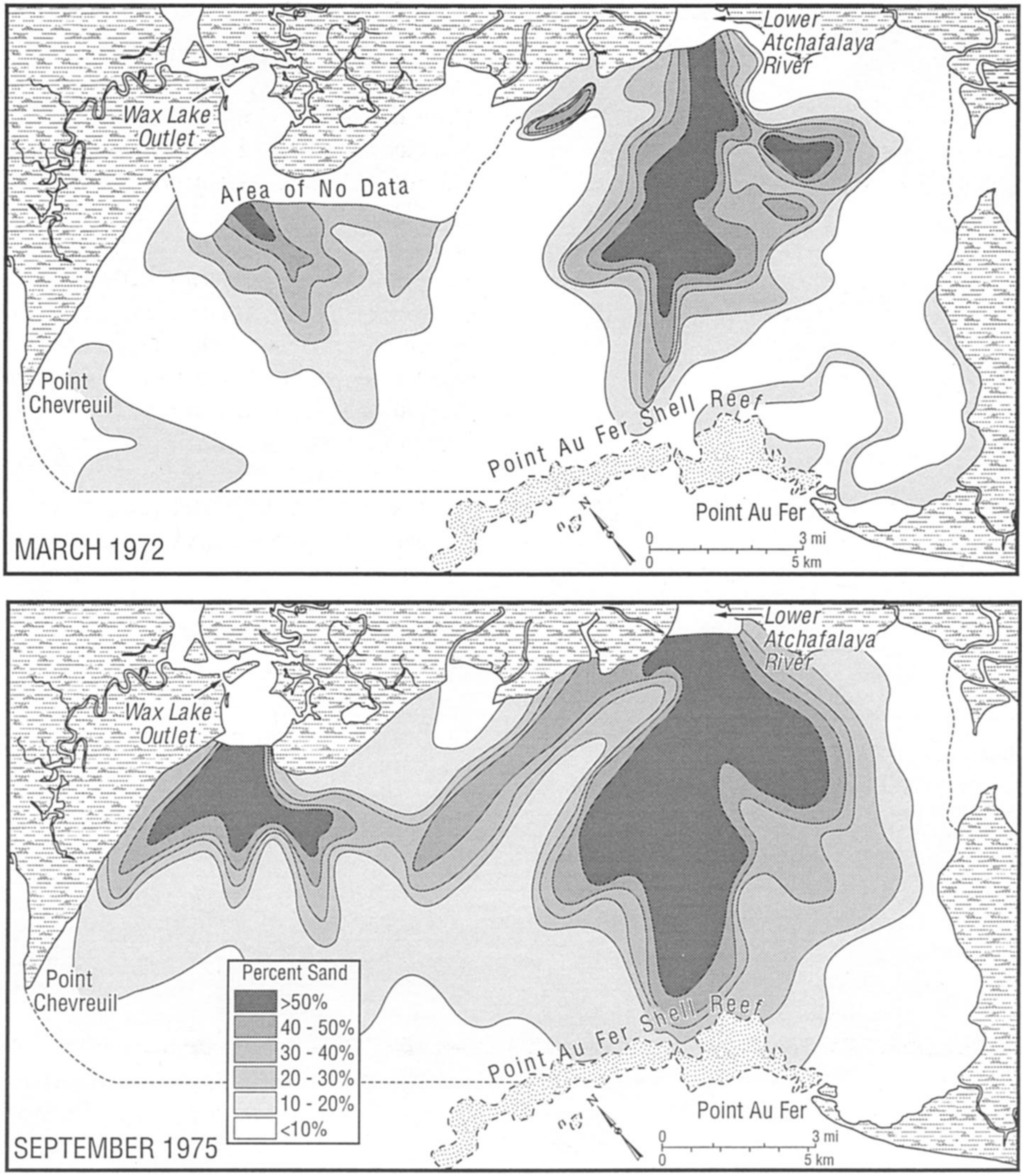


Figure 2-5. Distribution of sand concentration for Atchafalaya Bay bottom sediments as determined from USACE (New Orleans District) samples (477 samples in 1972 and 160 samples in 1975) (from Roberts 1998)

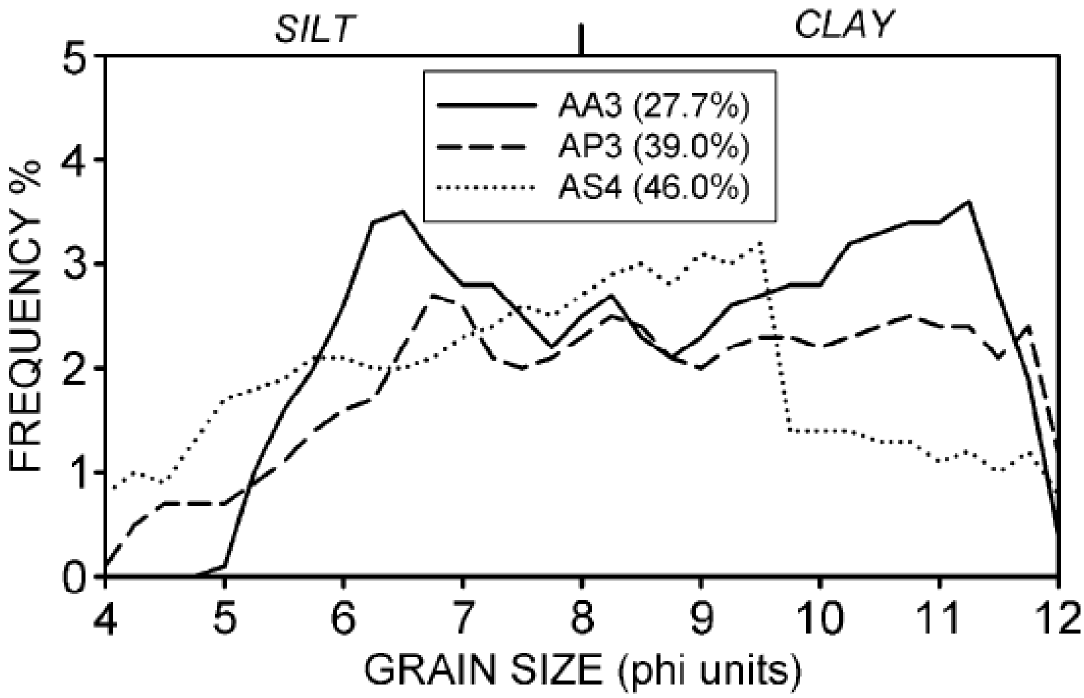


Figure 2-6. Detailed granulometry of the mud fraction for the homogenized top 20 cm of three cores displaying decreasing silt/clay ratios shown in Figure 2-7. The highest silt/clay ratio corresponds to the highest coarse silt content (core AA3, 14 percent), moderate in AP3 (10 percent), and low coarse silt (3 percent) in AS4. Trends are reversed for the finest grain sizes (smaller than 10 ϕ) and for the percentage of the mud fraction finer than 12 ϕ (shown in parenthesis in the legend. (from Neill and Allison 2005)

of Mexico and hampers the delta-building process for the surrounding areas (van Heerden and Roberts 1980). The distributary channels in the eastern part of the delta have reduced the cross-section area and effectiveness and reduced the sediment delivery to the surrounding delta areas (van Heerden and Roberts 1980).

Systematic monitoring has shown that a direct correlation exists between growth of the delta and flood duration and volume (Roberts and van Heerden 1981). Analysis of LANDSAT imagery shows that during 1976 through 1978, average discharge years, Wax Lake experienced a net loss of subaerial expression. The cumulative effects of subsidence, compaction, and winter erosion attributed to this loss (Roberts and van Heerden 1981). Aerial photographs of a section of the eastern Atchafalaya Delta reveal that land loss was reversed during a major flood in 1979 (Roberts and van Heerden 1981).

The deltas at the Lower Atchafalaya River and Wax Lake have elevated water levels near the coast during flood events, creating a *backwater effect*. Water laden with sediment is discharged into surrounding marshes due to the presence of these deltas (Roberts and van Heerden 1981). These water level changes are forced by a variety of events ranging from hurricanes and winter storms to wave run-up (Roberts 1998). A similar response results from wave setup prior to cold-front passage (Roberts and van Heerden 1981).

2.3.3 Sediment Transport in Atchafalaya Bay

Critical differences exist between the coastal accumulation of fine-grained sediment (clays and silts) and sand-sized sediment. The sands of dunes, beaches, and barrier island complexes are dispersed landward and seaward by extreme waves, storm surges, and currents. These environments are rebuilt and advance landward during calmer prevailing conditions. Sandy beaches occur on a chain of eroding barrier islands and at the distributary mouths or headlands east of the Chenier Plain. In contrast, fine-grained sediment accumulates at the open coast, downdrift from the active distributaries and in sheltered bays. Fine-grained sediments discharged into the ocean flocculate due to salinity and evolve into a slurry, or dense fluid, which settles out beneath the surface waters (Huh *et al.* 2001).

On average, fine sediments are continuously supplied to the Louisiana western coasts by the mean westward drift that occurs opposite Atchafalaya Bay and near the Chenier Plain coast as a very turbid band of water near the coast, locally termed the *mudstream* (Neill and Allison 2005; Roberts 1998; Wells and Kemp 1982). This westward drift of sediments results in deposition of fluid mud on the inner shelf and the simultaneous progradation of the shoreline along sections of the downdrift eastern Chenier Plain (Roberts 1998).

2.3.4 Accretion of the Chenier Plain

Since the first accretion along the eastern Chenier Plain coast was documented during the late 1940s to early 1950s, Atchafalaya Bay, the surrounding marshlands and adjacent shelf, and downdrift coasts have experienced a dynamic influx of sediment as a result of the latest Holocene delta switching event (Roberts 1998; Wells and Kemp 1982). This influx has reversed the centuries-old state of coastal erosion and retreat and reactivated the dormant processes of mud accumulation along this coast (Figures 2-7 - 2-9; Neill and Allison 2005; Huh *et al.* 2001; Roberts 1998). The sedimentary buildup of the Chenier Plain is progressively extending westward, closing Gulf access channels and building a consolidated mud sheet that extends seaward and westward (Huh *et al.* 2001).

A regional sediment sorting process at the periphery of the Mississippi River delta and delta plain results in a westward decrease of sand and coarse silt (Huh *et al.* 2001; Neill and Allison 2005; Roberts 1998). The coarsest material available (very fine sand, 3.50 Φ) is transported southeast by intense flow due to cold front passages, whereas most of the suspended load of finer sediments is moved down current (westward) (Neill and Allison 2005; Roberts 1998).

During the 1950s to the 1980s, mud arcs and linear mudflats increased and transient features occurred in an increasing westward direction (Roberts 1998; Wells and Kemp 1982). The mud flats of the eastern Chenier Plain are prograding seaward as well as progressively growing in a westerly direction (Huh *et al.* 2001; Roberts 1998). This fine-grained sediment accumulation continues to evolve and affect inshore and coastal conditions (Huh *et al.* 2001).

The river channel shifts ultimately distribute the sediments and initiate delta lobe developments in the delta plain (Huh *et al.* 2001). The meteorology, energetic weather systems, and associated coastal currents redistribute the sediment and reshape the coastal geomorphology (Huh *et al.*

2001). Sections of the coast fronted by fluid muds accrete rather than eroding from waves (Roberts 1998). Storm surges and wave action transport the fluid mud and sea water as a two-layer sheet onto the shore face and coastal marshes. The return flow of water to the Gulf outruns the more viscous fluid mud that becomes stranded (Huh *et al.* 2001).

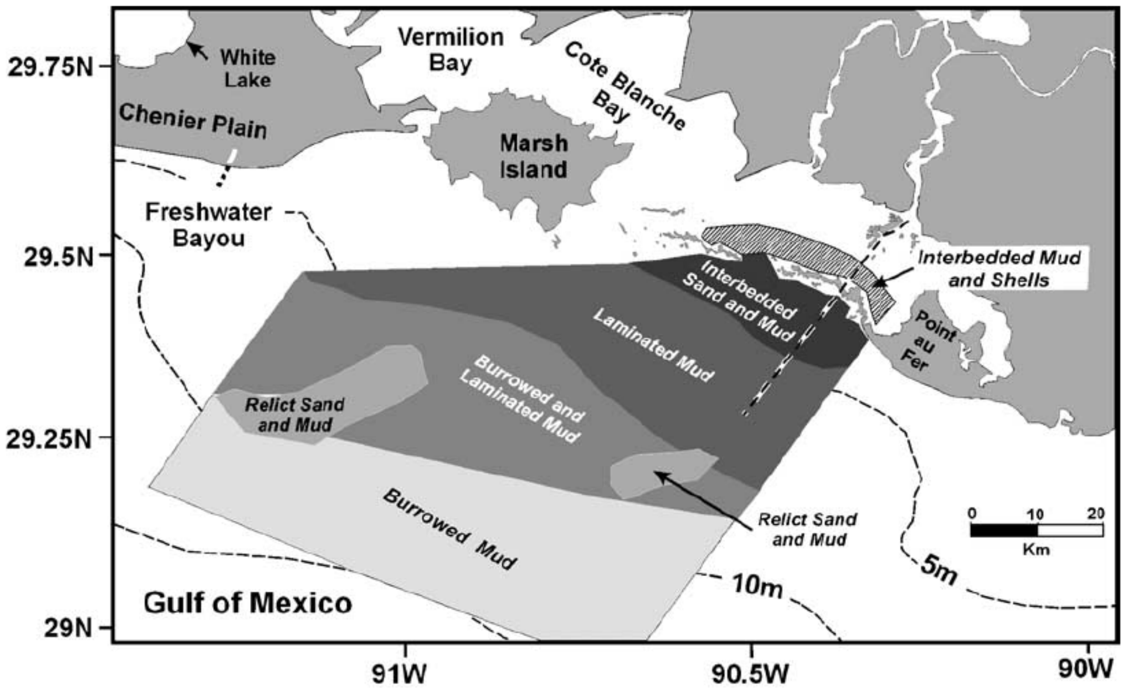


Figure 2-7. Facies map of the spatial extent of facies observed in surface sediments in the cores. The facies pattern is strongly related to sediment accumulation rates, with decreased sediment accumulation rates associated with increase degree of homogenization from bioturbation. Preferential sorting along the dispersal system controls whether sand layers are present in the cores (from Neill and Allison 2005)

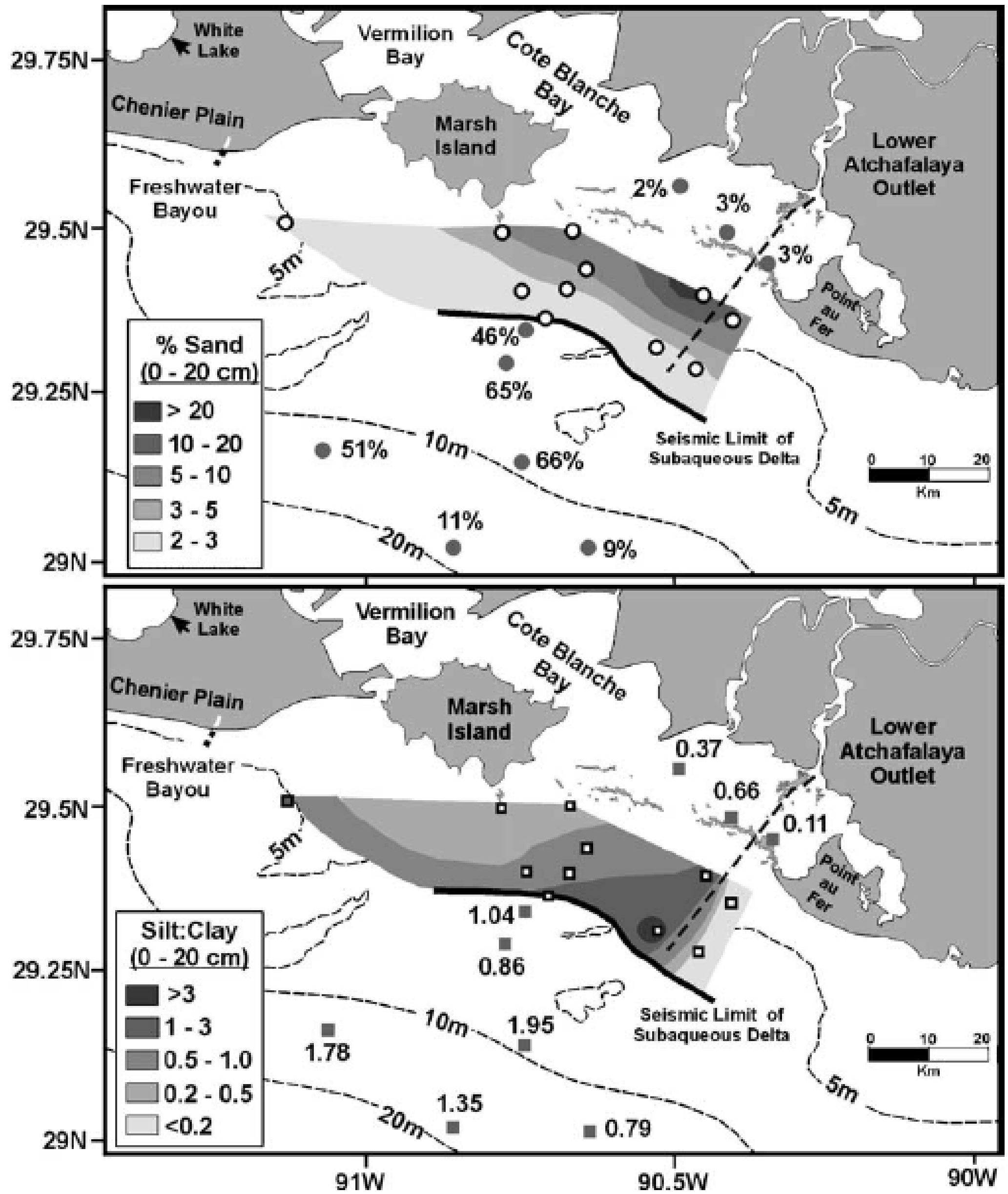


Figure 2-8. Maps of sand percentage (upper panel and silt to clay ratio (lower panel) averaged for the top 20 cm at each core site. Sand content drops off sharply with distance from the eastern bay outlet to the shelf, in keeping with an overall westward dispersal pattern associated with the predominant coastal currents. Sand contents are high but variable over the relic shoal area seaward of the seismic limit of the modern subaqueous delta. The silt content, like that of sand, show evidence of a westward pattern of preferential sorting the moves coarse material along the dispersal pathway (from Neill and Allison 2005)

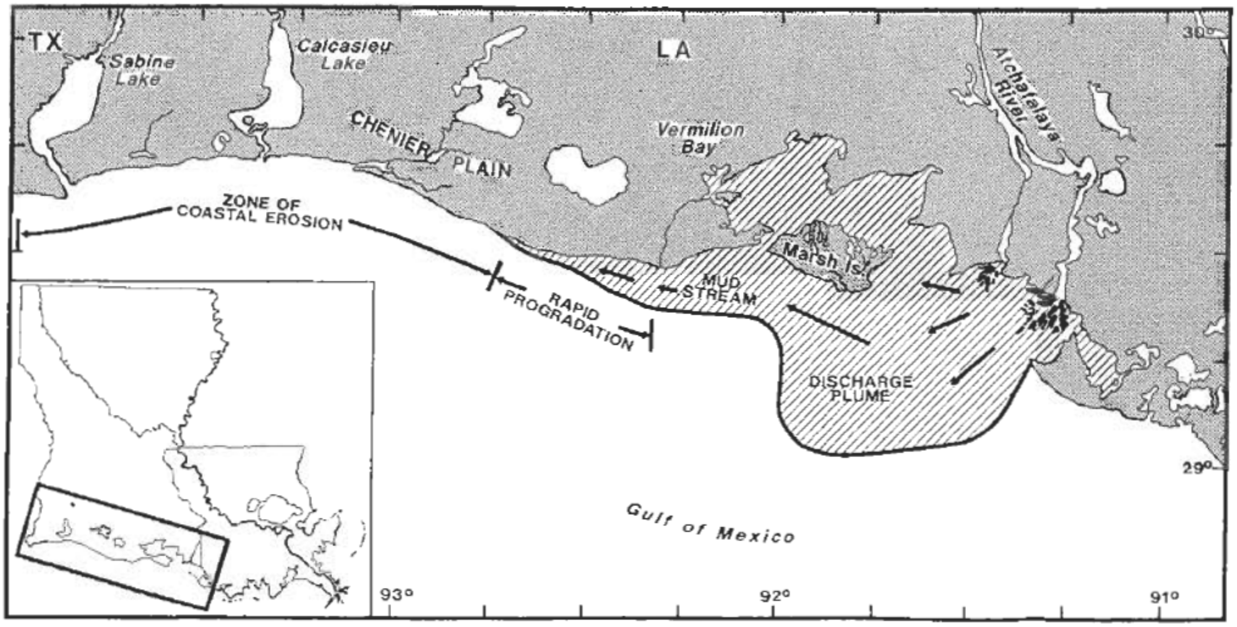


Figure 2-9. The Atchafalaya-Chenier Plain sedimentary system with river discharge that provides sediment for accretion in the eastern-most portion of the Chenier Plain coast (from Huh *et al.* 2001)

Cold front passages appear to provide the primary conditions for sedimentation and coastal progradation (Roberts 1998). Storm surges during hurricanes are much more rare (every two to three years) than those from cold fronts (30 to 40 each year) (Huh *et al.* 2001). Hurricanes have a higher rate of energy transfer along the coast. Cold fronts have a more uniform direction of approach, repeated wind and wave forcing patterns, larger spatial scales, and a much higher repeat frequency (Huh *et al.* 200; Roberts 1998).

Strong southeast winds, that precede cold fronts, resuspend sediments driving the westerly coastal mud-stream and elevating water levels along coastal areas (Figures 2-10 and 2-11). The heavier mud is left behind during post-frontal winds, water levels fall along the coast, and water is rapidly transported out of coastal bays (Roberts 1998). The newly deposited mud is stabilized through five main processes: (1) free drainage from the gravitational compaction of the newly deposited mud layer; (2) drying from evaporation by the strong, cold, dry winds that follow a cold front passage; (3) daytime solar desiccation baking of the mud-cracked polygons; (4) conversion of the muddy, fine-grained shore face to a cobble beach; and (5) colonization by dense growths of *Panicum*, a tall cane with an interlocking root structure (Huh *et al.* 2001, Roberts 1998).

Plants affect sedimentation by acting as baffles during mudflat flooding, stabilizing the mudflat and reducing erosion. The accreting mudflats are quickly colonized by marsh plants that protect accreting mudflats from infrequent, occasionally intense storm waves (Roberts 1998).

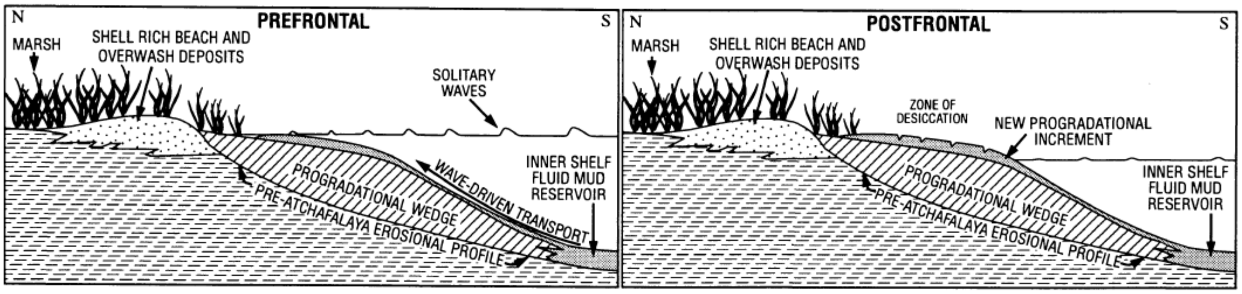


Figure 2-10. Schematic Representation of Processes of Mudflat Accretion and Stabilization during Pre-frontal and Post-frontal Conditions (From Roberts 1998)

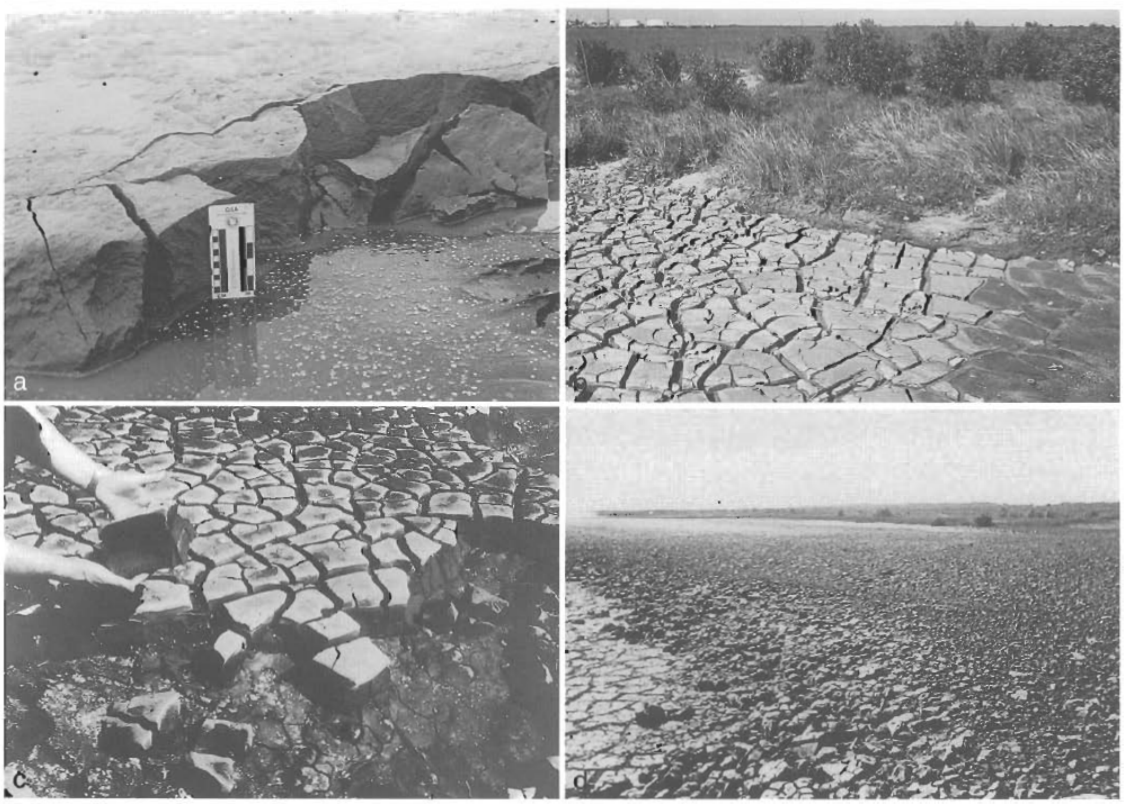


Figure 2-11. Stabilization of Fluid Mud Deposits: (a) Fresh Sheet of Fluid Mud Deposited; (b) Drying from Evaporation; (c) Desiccation; (d) Cobbling (from Huh *et al.* 2001)

2.4 Crevasses: Natural and Artificial

Crevasses may form on the Mississippi River in at least three ways (Gammill *et al.* 1990). Most frequently, crevasses are formed when a break in the levee during flood stages creates a depositional environment colonized by marsh flora. Artificial breaks in the levee can be created to facilitate the colonization of new marsh by vegetation. A third type of crevasse formation is a result of natural levee deterioration that begins with conversion of marsh to open water behind the levee in conjunction with erosion and natural degradation of the levee. This process compromises the strength of the levee, making it susceptible to breakage from the lagoon side during severe weather events. The first two modes of crevasse formation are constructive and new marsh is created; the last process is destructive and marsh is not created (Gammill *et al.* 1990).

Historically, crevasses are formed on the side of the river that is least protected from wave and storm activity (Gammill *et al.* 1990). The pass width at the crevasse region is directly related to increasing distance from the headwaters of the pass. Elevation gain is impacted by the crevasse angle of orientation and width. Wider crevasses and crevasses oriented at 60 degree angles from their parent channels gained elevation and created subaerial land at rates faster than narrower crevasses oriented 90 degrees from parent channels (Table 2-1); Gossman 2009). Deeper areas take longer to fill because they require more sediment and subaerial expression of the crevasse splay may be delayed (Rodrigue 2004). Abnormally high river stages cause more shoaling than normal in the main channel which results in additional dredging. This additional shoal material, combined with high river flows, increases the volume of sediments introduced into the crevasses areas (Bernard 2009).

Table 2-1. Mean elevation (NAV88 (ft)) and change in elevation for 12 crevasses receiving areas within the MR-09 project area. Asterisks (*) indicate that the crevasse was re-dredged in Phase II (2205) (From Grossman 2009)

Crevasse	Angle	Width	2000 Elevation	2003 Elevation	2008 Elevation	2000-2003 Change	2003-2008 Change	Total Change
6	90°	wide	-0.74	0.34	0.42	1.09	0.07	1.16
7	60°	narrow	-0.08	0.74	1.16	0.82	0.42	1.24
8	60°	narrow	0.07	0.56	0.59	0.49	0.03	0.52
9*	90°	narrow	0.38	0.81	0.64	0.43	-0.17	0.26
11*	60°	wide	-0.7	0.89	1.25	1.59	0.36	1.95
12*	90°	narrow	0.32	0.35	0.63	0.03	0.28	0.31
15	90°	wide	-1.17	0.2	0.16	1.36	-0.04	1.32
20	60°	narrow	-0.75	0.59	1.01	1.34	0.42	1.75
31	60°	wide	-0.3	0.66	0.92	0.96	0.27	1.23
36	60°	wide	0.06	0.76	0.71	0.7	-0.05	0.65
38	90°	wide	0.6	1.1	1.29	0.5	0.19	0.69
51	90°	narrow	-0.46	-0.65	-0.62	-0.19	0.03	-0.16
Average			-0.23	0.53	0.68	0.76	0.15	0.91

The total land gain for the Delta Wide Crevasses (State Project Number MR-09) project was 499 acres, at a rate of approximately 23 ac/year per crevasse (Table 2-2; Bernard 2009). Crevasse 31 had the largest land gain (124 ac) and only one had a lost; crevasse 53 lost 18 acres.

Table 2-2. Land area (ac) for 22 crevasses in the Delta Wide Crevasses (MR-09) project area (from Grossman 2009)

Crevasse	2001	2002	2007	Change	Relative gain/loss	Rate (ac/year)
6	116	150	171	55	47.4%	7.9
7	24	28	30	6	25.0%	0.9
8	5	8	10	5	100.0%	0.7
9	39	45	45	6	15.4%	0.9
11	116	131	157	41	35.3%	5.9
12	21	28	40	19	90.5%	2.7
15	19	26	26	7	36.8%	1.0
20	28	28	39	11	39.3%	1.6
24	3	4	5	2	66.7%	0.3
27	7	10	29	22	314.3%	3.1
31	67	90	191	124	185.1%	17.7
36	125	136	181	56	44.8%	8.0
38	102	99	181	79	77.5%	11.3
45	47	51	54	7	14.9%	1.0
47	3	5	9	6	200.0%	0.9
51	21	24	23	2	9.5%	0.3
53	33	36	15	-18	-54.5%	-2.6
54	41	47	57	16	39.0%	2.3
81	10		29	19	190.0%	2.7
CO-2	2	7	19	17	850.0%	2.4
NC-1	5	6	11	6	120.0%	0.9
NC-3	6	11	17	11	183.3%	1.6
Totals	840	970	1339	499	59.4%	71.3
Average	38	46	61	23	59.4%	3.2

2.4.1 Cubit's Gap

Cubit's Gap was an artificial crevasse created in1862 when a cut was made through a narrow portion of the levee. The gap widened to carry about 10 percent of total river flow. Sedimentation deposited in the open waters of Bay Rhondo created splays. These splays became vegetated and in 1935, Delta National Wildlife Refuge, which contains 48,000 acres, was established.

Sediment diversions would be more successful it they were designed after natural crevasses (Allison and Nittrouer 2004) and other successful crevasses such as Delta Wide Crevasses and Cubit' Gap. Natural crevasse exit channels are deep to capture significant sand, since the thickest portion of the sand sheet (moving as large bedforms) is in water depths >20 m (Allison and Nittrouer 2004). Natural crevasses have a relatively short life span (decades) due to shallowing of the exit channel as elevation increases progressively beyond the exit channel. The riverine end of the diversion would need to be oriented upriver or river-oblique to intercept significant sand moving in a downriver vector. Crevasses should be designed to retain significant energy flowing through the river end of the sluice or tunnel to avoid settling of significant suspended mud during the low discharge period of the year (Allison and Nittrouer 2004).

2.4.2 West Bay

The West Bay uncontrolled river diversion, is a large, artificially-induced, uncontrolled crevasse that delivers an average of 20,000 cfs of water and sediment into West Bay. The diversion was created in late 2003 north of Cubit's Gap by dredging a 440-foot-wide, 25-foot deep, 2,600-foot long channel on the right descending bank of the Mississippi River. Although sediment profiles provide evidence of episodic deposition within West Bay with the potential for long-term retention, Hurricane Katrina eroded sediment and shoreline and receding flood waters replaced it with bedded deposits. Historical subdeltas appear to have experienced similar conditions. Since the hurricane, the initial stages of subdelta formation have begun; this is evidenced by diversion scour, increased flow capacity, formation of distributary channels, and delivery of fine sediments to a depositional front (Andrus 2007). However, major portions of the fine sediment delivered to West Bay appear to bypass the bay and are delivered to the Gulf of Mexico. Coastal wind and wave attack, bay bottom depths, and a lack of estuarine enclosure work against rapid subaerial land development (Andrus 2007).

Potential growth estimates for West Bay were estimated to range from 51 to 143 acres per year by comparing delta growth estimates with Wax Lake (Andrus 2007). These estimates suggest that delta-building processes at West Bay may continue build the sub-aerial delta for 100 to 150 years (Andrus 2007). Andrus (2007) estimated that peak wetland development could be decades away.

The Breaux Act Task Force voted to close the West Bay diversion to avoid spending additional money to dredge a nearby shipping anchorage every three years. The project was built in a reach of the Mississippi River near Pilottown that has been historically used as an anchorage area by riverboat pilots. The anchorage has been experiencing silting. A recent study by the USACE

Engineering Research and Development Center (ERDC) determined that the lateral bar along the right descending bank that extended throughout the anchorage area was developing prior to the construction of the West Bay diversion, and this bar would have continued to develop to some degree without construction of the diversion (Little 2010). Deepening of the navigation project appears to correspond to the development of the lateral bar downstream of Cubit's Gap. Although the construction of the diversion has likely contributed to increases in deposition rates in the anchorage area (mainly between the diversion and Cubit's Gap), deposition rates in the anchorage area downstream of Cubit's Gap do not appear to have been influenced by the construction of the diversion. The outlets in the study area are believed to be a major factor in observed channel morphology and deposition trends between Venice and Head of Passes (Little 2010). Before the West Bay Diversion was opened, an agreement was signed between the CWPPRA Task Force and the navigation industry to dredge if the project caused sediment to accrete in the anchorage making it too shallow to anchor deep-draft vessels.

2.5 Caernarvon

The Caernarvon Freshwater Diversion is located at the northern end of the Breton Sound Basin, near a crevasse that occurred during the 1927 flood (Smith 2009). The diversion is the most important source of allochthonous mineral sediments for regional marshes, even though it was designed primarily to modify salinities in the estuary (Cable *et al.* 2007; Snedden 2006; Snedden *et al.* 2007). The rates of accretion and resultant surface elevation of Breton Sound wetlands vary due to changing processes and pulsing events. Sediment cores indicate that depositional events occur; however, due to insufficient data, interpretation of events is difficult. The important effect of powerful storms and river floods on marsh elevation are indicated by the abundance of facies changes associated with these event layers (Smith 2009).

Sediment inputs were 1 to $1.3x10^5$ metric tons annually during two late-winter to early-spring pulsed river events (Cable *et al.* 2007; Snedden *et al.* 2007). Half of the sediment delivery occurred during the pulses and almost 90 percent of the loading occurred within four months when the river discharge peaked due to snowmelt and high precipitation in the upper Midwest (Cable *et al.* 2007). Sediment discharge to the Breton Sound estuary was governed by the magnitude of the diversion and by the total suspended solids (TSS) concentration in the Mississippi River at the time of discharge (Figure 2-12; Snedden *et al.* 2007). Diversions coinciding with river flood events delivered more sediment to Breton Sound than those occurring during relatively low river discharges (Snedden *et al.* 2007). Higher levels of TSS were found during diversions during the rising limbs of river flood events (Snedden *et al.* 2007).

Sediment deposition in the Breton Sound estuary varies by season, with distance from the diversion, and with proximity to a major waterway (Cable *et al.* 2007; Day *et al.* 2003; Wheelock 2003). The impact of the diversion, as shown by deposition and accretion rates, was greatest near the diversion and decreased with increasing distance from the diversion (Cable *et al.* 2007; WBI 2002; Smith 2009). In the upper marsh, the Caernarvon Diversion project may be contributing to wash-in of topsoil from beyond Breton Sound or the redistribution and mixing of sediment within Breton Sound (Smith 2009).

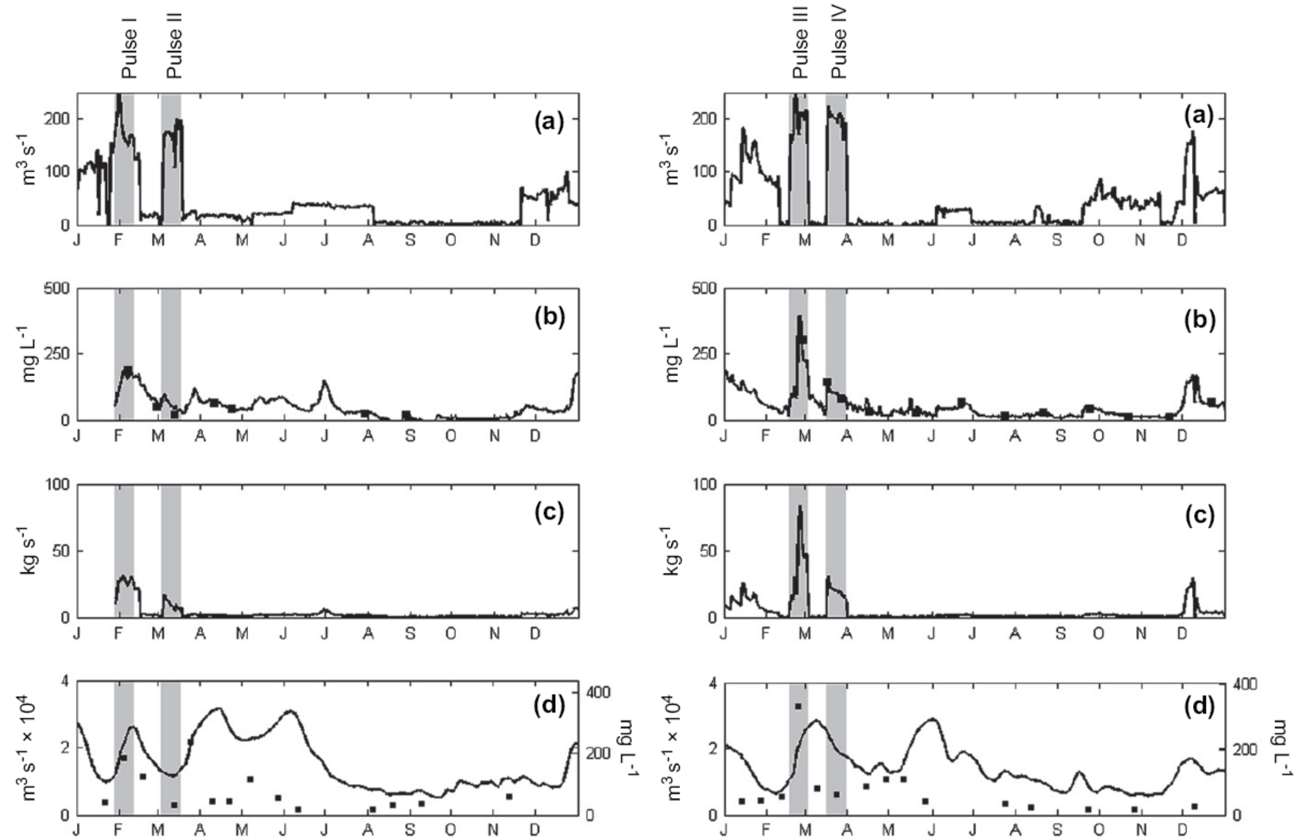


Figure 2-12. Time Series of Diversion Parameters for 2002 (left) and 2003 (right) (a) Diversion discharge; (b) TSS concentrations in the diversion outfall channel estimated with turbidity probe (line) and obtained through laboratory analysis of discrete water samples (squares); (c) sediment flux through the river diversion; (b) and (d) Mississippi River discharge (line) and river TSS concentrations (squares) at Belle Chase, Louisiana(from Snedden *et al.* 2007)

Fluvial pulses are significant sediment delivery mechanisms for interior marshes within close proximity to the diversion. Deposition associated with diversion-induced overland flow was primarily limited to within 6 to 10 km of the diversion. During low discharges (less than 100 $m^3 s^{-1}$), fluvial inputs were confined to the main flow channels in the upper estuary, but large pulses (greater than180 $m^3 s^{-1}$) induced sheet flow over the marsh surface, resulting in periods of elevated marsh water levels and large residuals in the upper estuary water budget (Cable *et al.* 2007). Greater amounts of fine sands are suspended in the water column during the rising limb of the flood hydrograph (Thorne 2000). Water discharging overbank and entering the vegetated marsh during these events flowed over the marsh surface and returned to the channels at some location down estuary instead of returning to the channels at the same location where it overbanked (Snedden *et al.* 2007). Pulsed discharges deliver large quantities of river sediments to the upper estuary and transport the fluvial materials to subsiding wetland areas located in the upper receiving basin (Cable *et al.* 2007).

Ephemeral short-term sediment deposition is driven by overland flow and is highly variable due to prevailing winds and tides (Cable *et al.* 2007). Wind direction was a major controlling factor in providing both TSS and water levels high enough to deliver sediment to the marsh (Day *et al.* 2003). Sustained south winds can impede diversion flow and hold sediment in the northern section of the estuary (Day *et al.* 2003; Wheelock 2003). Cold fronts and the associated northern winds encourage resuspension and transport of sediments to southern areas of the estuary (Wheelock 2003).

Exterior marsh sites received more total and allochthonous sediment than interior marsh sites (Cable *et al.* 2007). Sites located further from the diversion receive minimal sediment (WBI 2002). Marine and riverine dominated transport methods exert an equal influence on sediment deposition during late winter and early spring (Cable *et al.* 2007; Wheelock 2003).

Caernarvon is enhancing the stability of the marsh (WBI 2002). About 10 to 20 percent of the total sediment load likely reaches the surface of the marsh in the upper estuary (Day et al 2009). All Caernarvon sites appear to be keeping pace with regional relative sea level rise (RSLR) according to short term accretion rates (Lane *et al.* 2006; WBI 2002; Moerschbaecher 2008). This vertical marsh accretion was associated with soil organic matter accumulation (WBI 2002).

Wheelock (2003) suggested that the volume of sediment being delivered by Caernarvon was adequate for land building, but the grain size distribution and transport mechanism to the marsh surface were not. The composition of suspended sediment loads delivered to the Breton Sound Basin was primarily fine-grained clays and silts and not the coarser-grained sediments primarily responsible for land-building in deltaic environments. Smith (2009) found that although Caernarvon's effect on accretion rates was positive, in the long term, it was insufficient to enable marsh surface elevation to keep pace with accelerated RSLR. Current sediment loading rates are minor compared to those from previous controlled and uncontrolled Mississippi River diversions (Snedden 2006; Snedden *et al.* 2007). Estuarine sediment budgets indicate land-building processes are 66 percent deficient relative to the combined effects of sea level rise, subsidence, and erosion, even assuming 100 percent capture efficiency (Cable *et al.* 2007; Snedden 2006).

Because of the limited Mississippi River input, the threat to the sustainability of Breton Sound is evident by the conditions of the abandonment stage of the delta cycle, disturbance from human activity, and the accelerated relative sea level rise (Smith 2009). Although Caernarvon is undersized for its receiving basin (Lane *et al.* 2006), it has a much greater discharge capacity than was originally estimated. This increased discharge could improve restoration effectiveness (Lane *et al.* 2006). The current slow land-building in the Breton Sound estuary are likely due, in part, to the combined effects of inadequate transport to marsh surfaces and fine-grained sediments (Wheelock 2003). Under the current conditions, plant stress and increased flooding will continue to allow the surface elevation to fall below the tidal range, resulting in peat collapse and sediment erosion throughout most of Breton Sound (Smith 2009).

During the 2005 hurricane season, the storm surge and wave field associated with Hurricanes Katrina and Rita eroded 527 km^2 of wetlands within the entire Louisiana coastal plain, including the Caernarvon and Wax Lake Delta areas (Figure 2-13; Howes *et al.* 2010). Low salinity wetlands were eroded more than higher salinity wetlands. A weak zone (shear strength 500–

1450 Pa) was observed ~30 cm below the marsh surface in low salinity wetlands, coinciding with the base of rooting. High salinity wetlands had no such zone (shear strengths > 4,500 Pa) and contained deeper rooting (Howes *et al.* 2010). Storm waves during Hurricane Katrina produced shear stresses between 425–3,600 Pa, sufficient to cause widespread erosion of the low salinity wetlands. Vegetation in low salinity marshes is subject to shallower rooting and is susceptible to erosion during large magnitude storms (Figure 2-14; Howes *et al.* 2010).

2.6 Freshwater Siphons

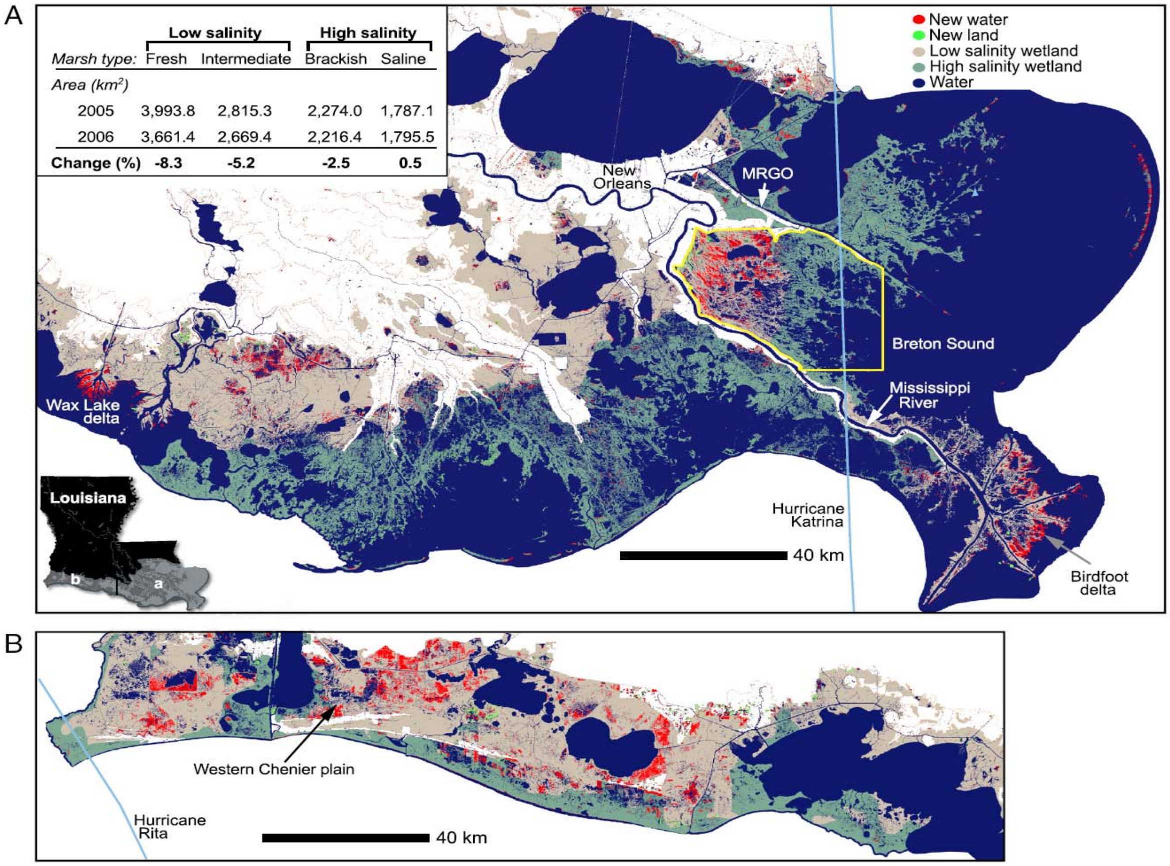
Siphons have minimal impacts on water levels in the project areas and initial concerns about erosion from the flow are not substantiated (Raynie *et al.* 2002). This may be due, in part to improper sizing of the structures. The siphon at the West Point a la Hache was found to be appropriately sized, while the structure at the Violet Diversion is undersized for its receiving basin (Lane *et al.* 2006). West Point a la Hache lost 460 acres of land from 1991 to 1999 during the siphon operation (Boshart and MacInnes 2000).

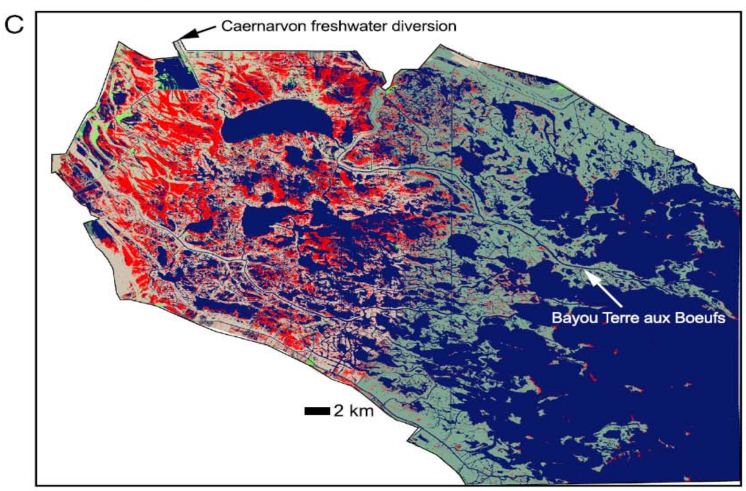
The siphon field study concluded that for the benefit of sediment transport and deposition, an inherent component of freshwater diversions, to be fully utilized the sediment needs to be distributed throughout the marsh (Roberts *et al.* 1992). Even though the Violet study site nearest the diversion is very close to a sediment source, it is hydrologically disconnected from it by canals, spoil banks, and weirs. It had the highest rate of elevation loss of any site in the study. Spoil banks have been found to decrease the net flux of materials to and from nearby wetlands. When water does reach these areas, the spoil banks block water from leaving, making these areas prone to excessive inundation.

The full potential of restoration benefit is not realized without proper hydrologic restoration and outfall management (Lane *et al.* 2006). If proper measures for outfall are not implemented, the deposition of sediment will mostly occur in the outfall channel and banks of the major distribution channels and the majority of the sediments will be transported through the wetlands (Roberts *et al.* 1992).

2.7 Bonnet Carré

The Bonnet Carré Spillway deposits sediment (mostly silt and sand) during each opening (Figure 2-15). In a major flood, the river can deposit more than 12 million cubic yards of sediment on Spillway lands. In addition, the Spillway’s forebay area experiences significant deposition during each high water event on the river (USACE 2009). During the 1973 opening, an area of silty sand (an average of 19 cm thick) was deposited near the mouth of the Spillway (Crocker 1988). For the 31 days of opening, assuming sediment water content at 60 percent, the total wet sediment volume would amount to 9.1 million tons. Spread over the entire Lake Pontchartrain area of 640 mi^2, the mean thickness would be 0.42 cm (Figures 2-16 and 2-17; Manheim and Hayes 2002).





	Dominant Vegetation	Mean Salinity (ppt)	Equivalent Salinity Class
Fresh	*Sagittaria sp., Panicum hemitomon*	0	Limnetic (0-0.5 ppt)
Inter-mediate	*Sagittaria sp., Sp. patens*	4	Oligohaline (0.5-5 ppt)
Brackish	*Sp. patens, Sp. alterniflora*	10	Mesohaline (5-18 ppt)
saline	*Sp. alterniflora*	18	Polyhaline (18-30 ppt)

Figure 2-13. (A and B) Land loss in the Louisiana coastal plain. Low salinity (fresh and intermediate combined) marsh experienced more than twice as much land loss by percent than high salinity (brackish and saline combined) marsh. The failure of low salinity wetlands was focused in the interior regions of Breton Sound, the western Chenier Plain, and the more exposed regions of the Birdfoot and Wax Lake Deltas. (C) Zoom in on Breton Sound. Vegetation type and conditions defining each zone are given in the bottom table (from Howes *et al.* 2010)

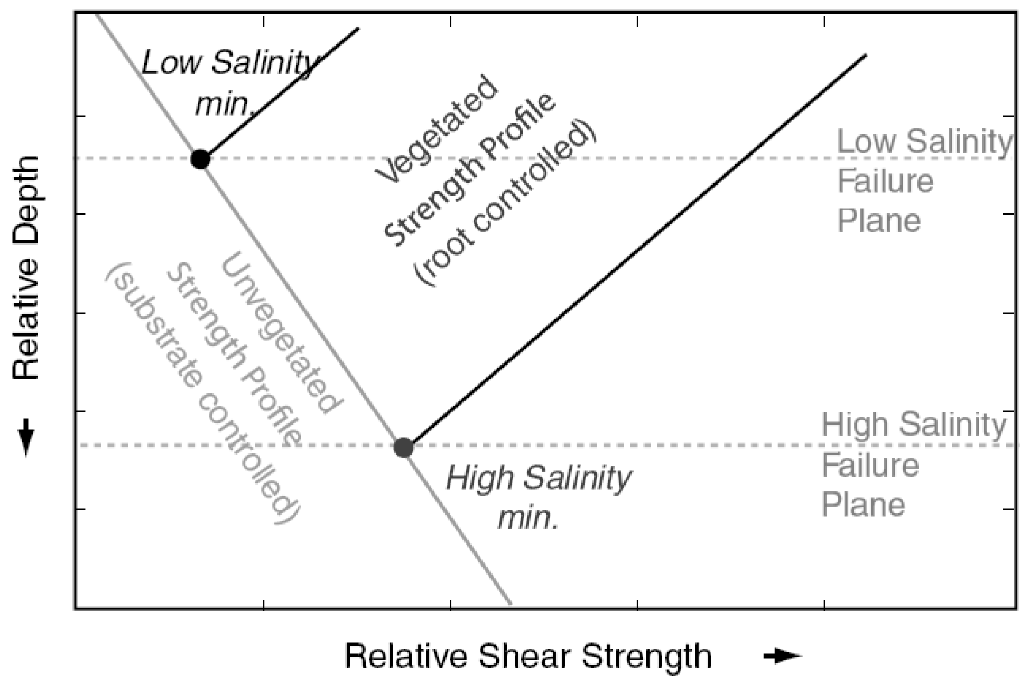


Figure 2-14. A conceptual model of soil strength in freshwater and saline marshes based on field data (from Howes *et al.* 2010)

Figure 2-15. Sediment Accretion from 2008 Bonnet Carré Spillway Opening (from USACE 2009)

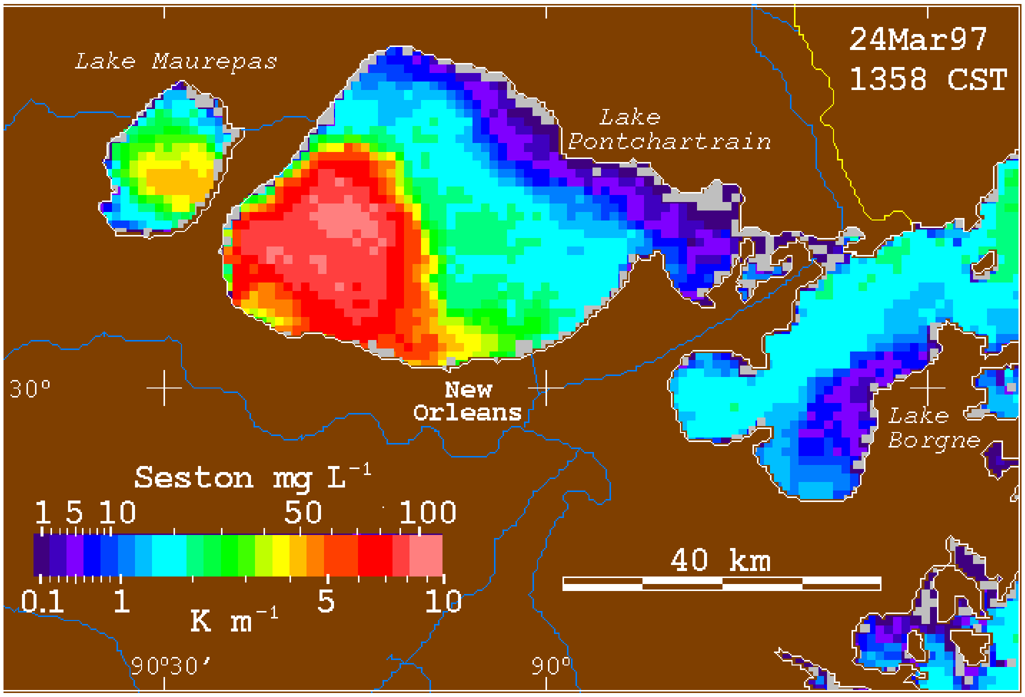


Figure 2-16. Estimates for March 24, 1997 of suspended sediment concentration (seston) in Lake Pontchartrain interpreted from Stumpf's remote sensing data during 1997 Bonnet Carré Spillway opening (from Manheim and Hayes 2002)

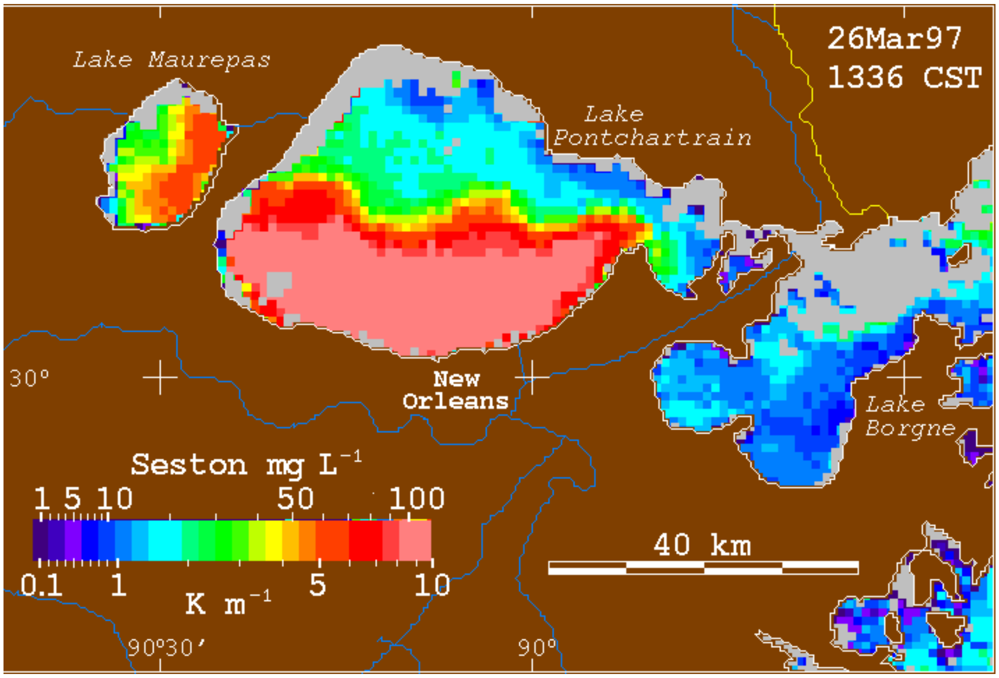


Figure 2-17. Estimates for March 26, 1997 of suspended sediment concentration (seston) in Lake Pontchartrain interpreted from Stumpf's remote sensing data during 1997 Bonnet Carré Spillway opening (from Manheim and Hayes 2002)

2.8 Effluent Water

The long-term input of secondarily treated effluent to a wetland ecosystem filters nutrients, increased plant productivity, and increases accretion downstream of the discharge location (Brantley *et al.* 2008). Increased leaf litter and aboveground net primary production for the freshwater forest system and accretion rates were both high downstream of the effluent discharge. Accretion rates downstream of the outfall were significantly higher than the reference location; however, the high accretion rate observed downstream of the outfall may be in part due to the mineral soils already present at the study site, as this has been shown to increase relative elevation rates in coastal areas (Brantley *et al.* 2008).

When the primary source of mineral sediments to the Pointe au Chene swamp was eliminated due to the completion of levees along the Mississippi in the 1930s, post-1963 mineral accumulation rates in the treatment site were higher than or within the range of published rates for coastal salt marshes in this region, and were comparable to accumulation rates for other bottomland hardwood forests (Rybczyk *et al.* 2002). It had been hypothesized that little or no mineral sediments above the 1963 ^{137}Cs horizon would be found. In contrast to mineral-matter accumulation, organic matter accumulation rates increased significantly during the 1988 to 1993 period, which can be attributed to effluent-stimulated organic matter accretion after March 1992. The background accretion balance deficit in the treatment site was -7.9 mm yr^{-1}. Accretion balances remained negative during the post-effluent period at all three sites; however, in the treatment site, the deficit was only -0.9 mm yr^{-1} and fell well within one standard error of estimated RSLR rate. The rates of sediment accretion in general, and organic matter accumulation, in particular at this site, increased and approached the estimated rates of RSLR in the treatment site after effluent applications began (Rybczyk *et al.* 2002).

Management or re-introduction of nutrient-enhanced effluents to wetland ecosystems can maintain plant productivity, sequester carbon, and maintain coastal wetland elevations in response to sea-level rise (Brantley *et al.* 2008). Estimates of accretion balance should be viewed with caution; however, because short-term accretion measurement methods (feldspar horizon markers for example) fail to fully integrate long-term but significant decomposition, dewatering, and compaction processes (Rybczyk *et al.* 2002). When estimating accretion balance deficits, other factors may also contribute. Subsidence rates are highly variable, even in a single basin. RSLR measured in a waterway may not represent RSLR in shallower wetlands of interest in a study. A long enough period of time to integrate compaction and decomposition to estimate RSLR, will give the best estimates. The time spanned by accretion estimates should also be long enough to integrate most decomposition and some of the compaction and dewatering processes (Rybczyk *et al.* 2002).

2.9 Lessons Learned

- Diversions that appeared to build the most land are those that move large amounts of sediment, such as the Atchafalaya Delta, Cubit's Gap, and the Delta Wide Crevasses Project.

- Mineral and organic matter was found in higher abundances at sites nearest the freshwater input.

- Sediment deposition was mineral dominated near the diversion and became more organic down basin.

- The Atchafalaya and Wax Lake deltas have developed approximately 153 km^2 of area above the -0.6 m contour from 1981 to 1994.

- The Atchafalaya and Wax Lake deltas have rapidly evolved through the processes of seaward channel extension and bifurcation as well as lobe fusion and upstream growth by coarse sediments (primarily fine sand).

- Maintenance dredging has caused differences in the Atchafalaya and Wax Lake deltas. Since dredging ceased on the Wax Lake Outlet in 1980, the delta has been building naturally.

- For the Atchafalaya Delta, dredged material placement on channel banks has formed a proficient channel which carries sediment to the Gulf of Mexico and hampers the delta-building process for the surrounding areas.

- Systematic monitoring has shown that a direct correlation exists between growth of the delta and flood duration and volume.

- Strong southeast winds, that precede cold fronts, resuspend sediments driving the westerly coastal mud-stream and elevating water levels along coastal areas. The heavier mud is left behind during post-frontal winds, water levels fall along the coast, and water is rapidly transported out of coastal bays.

- The total land gain for the Delta Wide Crevasses (State Project Number MR-09) project was 499 acres, at a rate of approximately 23 acres/year per crevasse.

- Elevation gain is impacted by the crevasse angle of orientation and width. Wider crevasses and crevasses oriented at 60 degree angles from their parent channels gained elevation and created subaerial land at rates faster than narrower crevasses oriented 90 degrees from parent channels.

- Deeper areas take longer to fill because they require more sediment and subaerial expression of the crevasse splay may be delayed. Abnormally high river stages cause more shoaling than normal in the main channel which results in additional dredging. This additional shoal material, combined with high river flows, increases the volume of sediments introduced into the crevasses areas.

- Land is still being lost in the outfall of the West Pointe a la Hache siphon.

- Cubit's Gap, an artificial crevasse created in1862, essentially created 48,000 acres of land that became Delta National Wildlife Refuge in 1935.

- The Bonnet Carré Spillway deposits sediment (mostly silt and sand) during each opening. In a major flood, the river can deposit more than 12 million cubic yards of sediment on Spillway lands. In addition, the Spillway's forebay area experiences significant deposition during each high water event on the river. During the 1973 opening, an area of silty sand (an average of 19 cm thick) was deposited near the mouth of the Spillway.

- Vegetation in low salinity marshes is subject to shallower rooting and maybe more susceptible to erosion during large magnitude storms.

2.10 Recommendations from the Literature

There were several recommendations in the literature. These are categorized by planning, project management, engineering and design, construction, and operations and maintenance, and monitoring.

2.10.1 Planning and Project Management

- All phases of project management must be coordinated and must share information, not only to maximize the benefits on a project-by-project basis, but also to carry the information learned from past projects into the development of future projects (Raynie *et al.* 2002).

- Project goals should be quantified as much as possible to aid evaluation of project effectiveness (Raynie *et al.* 2002).

- Reference areas were not included during the project planning or developmental stages but should be addressed in the future with the Coast-wide Reference Monitoring System (CRMS) (Raynie *et al.* 2002).

- Instead of attempting to restore a large, highly impacted area, perhaps work within a regressed saltmarsh landscape that is sustainable, even if it is much smaller in area (Swarzenski 1998).

- Other strategies should be employed in conjunction with diverted Mississippi River water, such as restoring suspended sediment loading in the Mississippi, installing numerous smaller-scale sediment diversions, and local hydrological restoration (Smith 2009).

- One preservation strategy is increasing Mississippi River input to replicate pre-20th century conditions of delta progradation (Smith 2009). To preserve all of Breton Sound's land surface area, the equivalent to sixteen diversions similar to the Caernarvon Diversion project, each diverting 4.5×10^5 metric tons sediment/yr, would be needed to contribute 10 mm long-term accretion annually, allowing the marsh surface elevation to keep pace with modern rates of relative sea level rise. (Snedden 2007, Smith 2009).

2.10.2 Engineering and Design

- Gated structures provide for greater flexibility in operations and should be the preferred technique for freshwater diversions (Raynie *et al.* 2002).

- The most important lesson we should learn in the selection and design of future outfall management projects is to properly consider the structural integrity of existing topographic features (i.e., spoil banks, cheniers, etc.) that project structures will depend on to function (Carter and Bernard 2004). In the event that they can be compromised through subsidence, increased water velocity, or erosion during the 20-year life of the project, then proper consideration should be given to the maintenance efforts and costs, and these costs should be included in the selection criteria (Carter and Bernard 2004).

- Engineering strategies should place as much focus on receiving area configuration and trapping efficiency as sediment delivery in order to maximize sediment retention (Andrus 2007).

- Landscape modifications such as spoil banks and weirs reduce the benefits of river water introduction by limiting wetland-water interaction and should be removed or breeched as part of outfall management in conjunction with river diversion implementation for effective wetland restoration (Lane *et al.* 2006; Raynie *et al.* 2002; Roberts *et al.* 1992). One aspect of this management should be design of secondary, tertiary, and micro-drainage conduits that provide the optimum drainage density for the area of influence, particularly with regard to siphons (Roberts *et al.* 1992).

- Sediment diversions would be more successful it they were designed after natural crevasses (Allison and Nittrouer 2004) and other successful crevasses such as Delta Wide Crevasses and Cubit' Gap. The riverine end of the diversion would need to be oriented upriver or river-oblique to intercept significant sand moving in a downriver vector. Crevasses should be designed to retain significant energy flowing through the river end of the sluice or tunnel to avoid settling of significant suspended mud during the low discharge period of the year (Allison and Nittrouer 2004).

2.10.3 Construction

- Close supervision and inspection of the construction contractor is required during construction to ensure proper placement of the material and construction of the project feature (Grandy 2009).

- When possible, crevasses should be constructed and maintained using hydraulic dredges, as opposed to bucket dredges (Grandy 2009). This allows for immediate and beneficial impact of the sediments dredged from the crevasse and longer term benefits from distribution of water, sediments, and nutrients into the receiving basin (Grandy 2009).

2.10.4 Operations and Maintenance

- Politics have a very important role in operations of diversion projects (Raynie *et al.* 2002). Concern about lawsuits involving diversion projects contributed substantially to the failure to implement a maintenance plan (Raynie *et al.* 2002).

- Operating diversions has been a challenge as many different resource user groups are affected by diversion structures (Raynie *et al.* 2002). This has resulted in conservative use of the structures, which limits the ability to evaluate the potential benefits (Raynie *et al.* 2002).

- The current pulsed diversion management plans could be optimized by timing the pulsing events to coincide with rising limbs of the Mississippi River flood events in late winter and early spring, or by increasing the discharge allowed through the diversion, particularly during frontal events would optimize sediment availability with adequate transport mechanisms to marshes (Cable *et al.* 2007; Wheelock 2003).

- LDNR should maintain operation and maintenance control over operations of diversion projects to ensure consistency with restoration objectives (Raynie *et al.* 2002). Some of the water control structures are currently being operated without a contract (Carter and Bernard 2004).

- A consistent plan for operation and maintenance is needed for diversion projects (Raynie *et al.* 2002). Although current procedures are adequate, a more permanent method of operations is desired (Carter and Bernard 2004).

- For the siphons, a simplified priming system (i.e. fixed vacuum pump) needs to be installed to allow the individual pipes to be quickly placed back in service when they lose prime (Raynie *et al.* 2002). Output from the siphons would be increased substantially (Raynie *et al.* 2002). Also, the siphons would then be available for service during much of the low river season when they are often not currently available (Raynie *et al.* 2002).

2.10.5 Monitoring

- Suspended sediment and discharge measurements were discontinued because their sampling frequency was not sufficient to yield accurate and reliable data (Rodrigue 2004). However, it is suggested that funding for these variables be provided for future projects (Rodrigue 2004). The quantity and quality of sediment being transported into the project area can be combined with land gain data and used to model and increase predictive capabilities of crevasse splay development (Rodrigue 2004).

- The state should evaluate and develop a statewide policy for addressing water hyacinths in diversion projects (Carter and Bernard 2004). One monitoring station in Caernarvon is suspected to have been destroyed by a moving mass of water hyacinths, resulting in three months of data being lost.

- Security of monitoring stations can be an issue at diversion projects– a Caernarvon station was vandalized and offline, losing a month's worth of data (Carter and Bernard 2004).

- Measuring and modeling sediment elevation can be a good short-term indicator that a diversion project is successful (Rodrigue 2004). Although the endpoint for determining project success is land gain measured from aerial photography, the elevation data can identify project success earlier than photography and also show additional benefits (i.e., subaqueous infilling) (Rodrigue 2004).

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3.0 VEGETATION

3.1 Emergent Vegetation Distribution and Composition

Many factors affect vegetative species distribution and composition. The ability of a plant to adapt to varying levels of salinity as well as the frequency and duration of flooding affects species composition. A pulse of high salinity water into a freshwater/brackish system can negatively affect salt intolerant species. Individual species adaptations to salt stress and flooding play important roles in determining the presence and abundance of species. Plants which are adapted to deal with longer rates of inundation may be more susceptible to slight changes in porewater salinity.

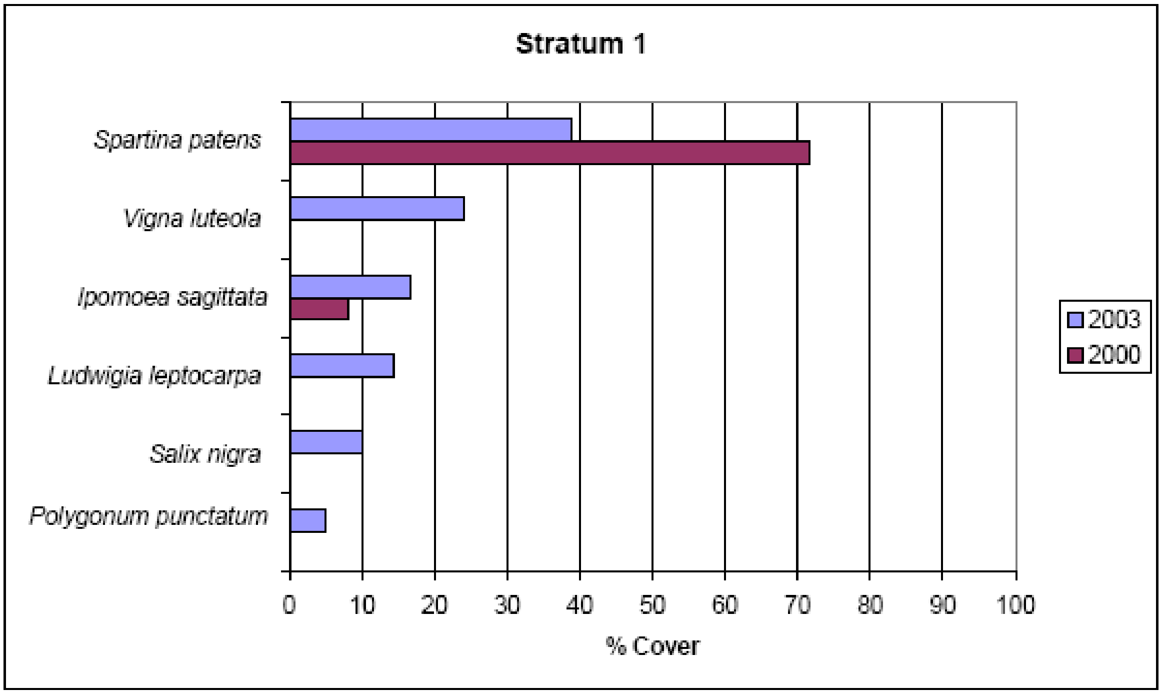
Competition, herbivory and storms can affect species composition. Marshes can take a long time to recover from such disturbances. Species compositions, especially at lower salinity sites, will likely change as the process of recovery continues (Moerschbaecher *et al.* 2008). Over time, a more diverse assemblage of plants may become established due to increased dispersal as well as changes in the competitive vigor of the plants already present. Alternatively, an increased frequency of large storm events can lead to the elimination of freshwater plants with low tolerances to salinity (Moerschbaecher *et al.* 2008).

Major contributors to the loss of coastal marsh and associated vegetation include salt-water intrusion from subsidence and sea-level rise. Diversions reduce salinity and offset accretion by providing sediment and nutrients which enhance land building and plant growth (CPRA 2010a; Nyman *et al.* 1993; Twilley and Nyman 2002; Delaune 2002).

3.1.1 Caernarvon

Salinity is a dominant factor influencing plant species composition near Caernarvon; however, salinity is not a stressor for species such as saltmeadow cordgrass. Three factors that decrease production are nutrient deficiency, elevated salinity, and water logging (Twilley and Nyman 2002). Adequate soil nutrients were present at each site during the study suggesting that soil nutrients did not limit plant growth (Moerschbaecher *et al.* 2008).

Saltmeadow cordgrass was the dominant species throughout the Caernarvon area in 2000 (pre-operation). However, in 2003 (post-operation) the saltmeadow cordgrass in the area near Caernarvon was replaced by big pod sesbania (*Sesbania herbacea*) and hairypod cowpea (*Vigna luteola)* (Figure 3-1; Carter and Bernard 2007). Saltmeadow cordgrass was dominant in all strata in 2000. In 2003, saltmeadow cordgrass was dominant in all strata, except stratum four. However, the mean cover of saltmeadow cordgrass was reduced across all strata and species richness was increased across all strata (except stratum 4). In stratum four, hairypod cowpea, a vine supported by emergent vegetation, dominated in both occurrence and percent total cover. The dominant non-vine vegetation in stratum four was big pod sesbania followed by saltmeadow cordgrass (Carter and Bernard 2007). The decrease of saltmeadow cordgrass and the increase in species richness in most strata do not necessarily equate to project effectiveness and more likely indicate the vegetation community was recovering from a drought. More data will be needed to determine project effects, since the 2003 post-operation survey was conducted only a year post-operation. However, vegetation



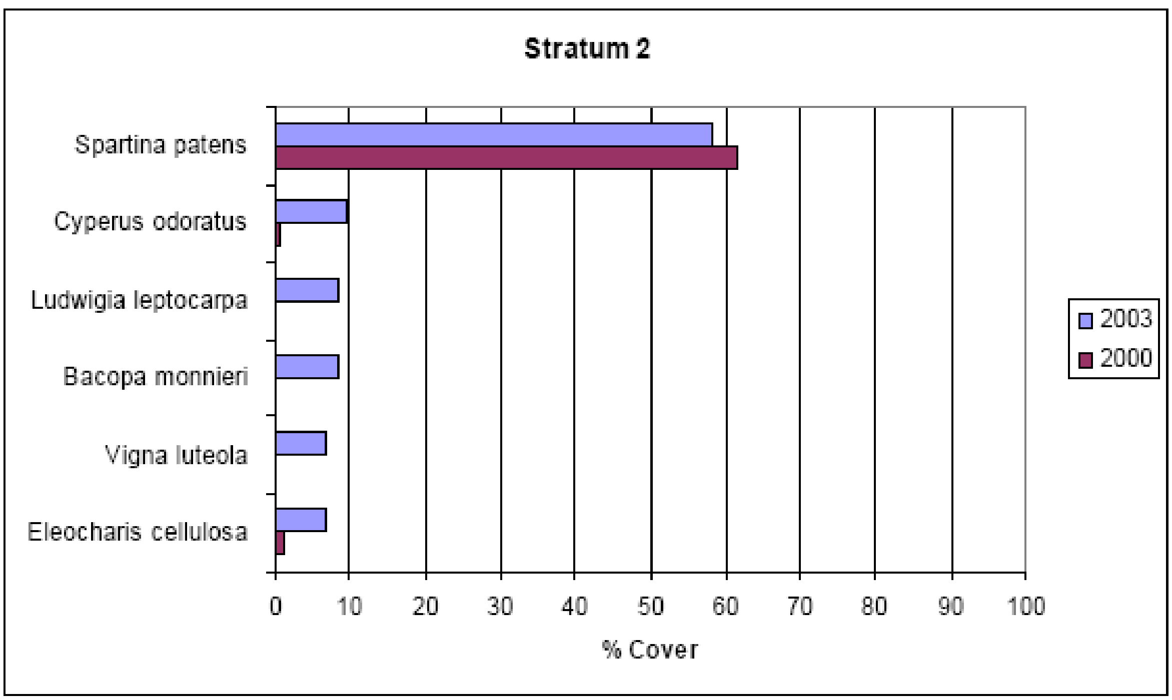
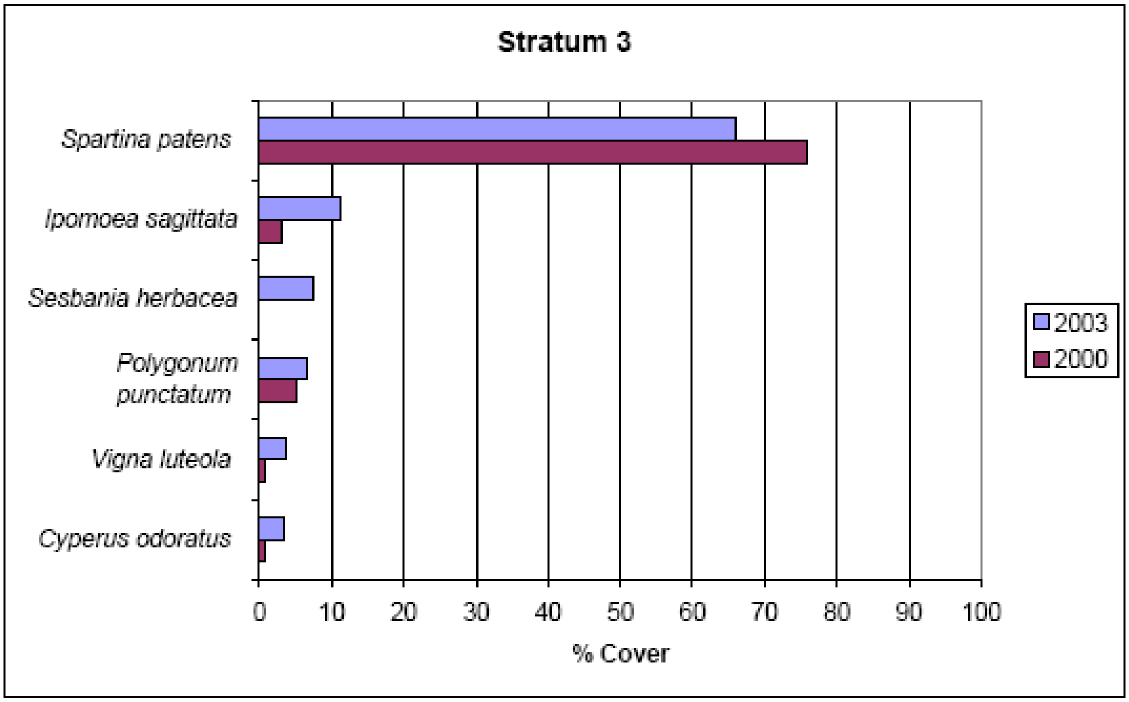


Figure 3-1. Mean percent cover of dominant vegetative species across all 4-m^2 plots during 2000 (pre-construction) and 2003 (post-construction) vegetation surveys for strata 1-4 of the Caernarvon Outfall Management Project. (from Carter and Bernard 2007)



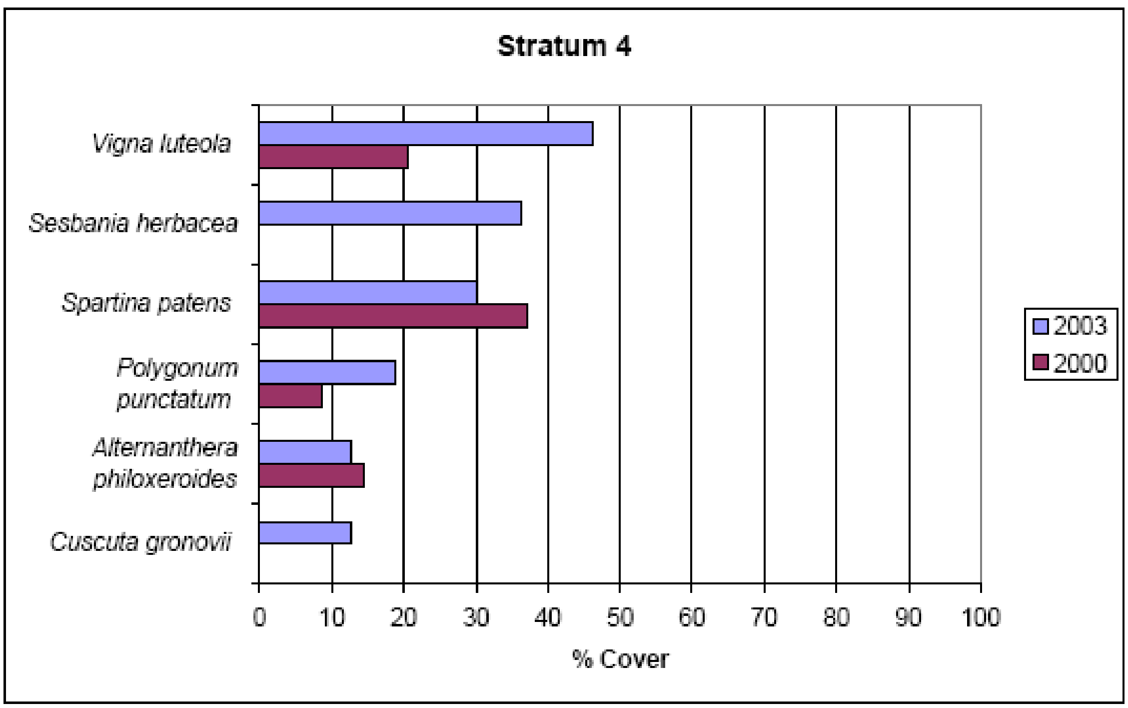


Figure 3-1 - continued. Mean percent cover of dominant vegetative species across all 4-m^2 plots during 2000 (pre-construction) and 2003 (post-construction) vegetation surveys for strata 1-4 of the Caernarvon Outfall Management Project (from Carter and Bernard 2007)

type mapping does show the Caernarvon area is becoming increasingly fresher since the diversion began operating (Chabreck and Linscombe 2001).

Proximity to the Caernarvon Diversion and hydrological connectivity are major influences on plant species composition (Moerschbaecher 2008). Six sites were sampled in the Caernarvon vicinity and were located near, mid, and far from the diversion (Figure 3-2). One near site was a fresh/intermediate marsh strongly influenced by Caernarvon. This site had the greatest variety of species. Switchgrass (*Panicum virgatum*), knotweed *(Polygonum* sp.), and alligatorweed (*Alternanthera philoxeroides*) were the dominant species, followed by saltmeadow cordgrass. The other near site was folded laterally from the effects of Hurricane Katrina and the increased elevation due to the folding, plus an adjacent spoil bank resulted in hydrologic isolation. The folded near site was never observed to have standing water and was dominated by a thick mat of hairypod cowpea and morning-glory (*Ipomoea* sp.) (Moerschbaecher 2008).

Mid site marshes near Caernarvon were dominated by saltmeadow cordgrass and chairmakers bulrush (*Scirpus* = *Schoenoplectus americanus*) (Moerschbaecher 2008). These intermediate marsh species result from the mixing of freshwater with saltwater. Far sites were dominated by smooth cordgrass (*Spartina alterniflora*), saltmeadow cordgrass, and needlegrass rush (*Juncus roemerianu*s). Saltwater is influencing far site species composition more than at the near or mid sites since saline species such as smooth cordgrass are present. Chairmakers bulrush and saltmeadow cordgrass dominated at the Control site; saltgrass (*Distichlis spicata*) occurred less frequently. The intermediate marsh species at the Control site indicate saltwater is present in quantities that limit species diversity more than at the near site. The Control site appears to be intermediate marsh comparable to the vegetative makeup of the mid sites (Moerschbaecher 2008).

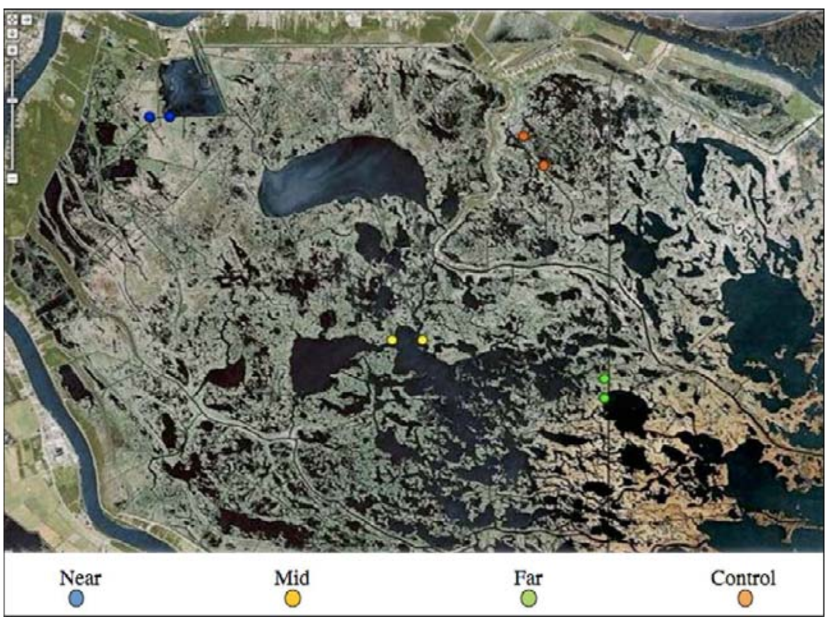


Figure 3-2. Vegetative Study Sites Sampled near Caernarvon in Breton Sound Estuary (from Moerschbaecher 2008)

Vegetative species composition at the different sites near Caernarvon reflected salinity levels on a gradient away from the diversion (Moerschbaecher 2008). Freshwater marsh species found at the near sites were not present at the mid, far, and control sites. The far sites contained smooth cordgrass which was absent from the near sites and less abundant at the mid and control sites. Saltmeadow cordgrass occurred over the whole salinity range (Moerschbaecher 2008).

Another major factor affecting species composition at each site is the frequency and duration of flooding (Moerschbaecher 2008). The adaptations of individual species to salt stress and flooding play important roles in determining the presence and abundance of species along the estuarine gradient in Breton Sound. Plants which have adapted to longer rates of inundation may be more susceptible to slight changes in porewater salinity. Alligatorweed was present at the near station but absent from other sites (Moerschbaecher 2008). Porewater salinity levels of 1.5 psu and higher decrease plant vigor of maidencane *(Panicum hemitomon)* and lead to the localized decline of the species (Willis and Hester 2004).

Vegetation habitat in the Breton Sound Basin changed from 1978 to 2000 (Figure 3-3; CPRA 2010a). Freshwater marsh was not observed in 1978; however, in 2000, 628 acres were documented. Since 1978, brackish and saline marsh decreased, and intermediate marsh increased by 10,582 acres (CPRA 2010a).

3.1.2 Delta Wide Crevasses

The Delta Wide Crevasses project constructed uncontrolled sediment diversions southeast of Venice, Louisiana (Bernard 2009). Vegetation surveys of subaerial splays created by six crevasses constructed in 1999 were conducted in 1999 and 2002 and 2007 (post-construction). Total percent vegetative cover was lower in 2007 than in 1999 and 2002 at five of the six crevasses surveyed (Figure 3-4). The mean percent cover of one crevasse (20) increased from 4 percent in 2002 to 82 percent in 2007 (Bernard 2009).

Lower plant diversity is observed in the late stages of succession as the most stable competitive species begin to dominate (Bernard 2009). Primary succession can be observed by combining the elevation and vegetation data; new plant growth follows land creation. In 1999, a non-diverse group of pioneer plants were observed. Post-construction of the crevasses (2002), a more diverse community of competitive species became dominant (Bernard 2009).

Percent cover data of individual species across all plots in the Delta Wide Crevasses project area which dominated the 1999 and 2002 surveys suggests a shift in species composition [Figure 3-5; Bernard (2009)]. Percent cover of species such as bulltongue arrowhead (*Sagittaria lancifolia media=falcata*), broadleaf arrowhead (*Sagittaria latifolia*), coco yam (*Colocasia esculenta*), and chairmakers bulrush, decreased in the 2007 survey. Percent cover of other species has increased; common reed (*Phragmites australis*), hairypod cowpea, and cattail (*Typha* sp.) have increased from 1999 to 2007. Species diversity, increased from 1999 to 2007 at four of the six crevasses; diversity decreased at crevasses 38 and 51 (Bernard 2009).

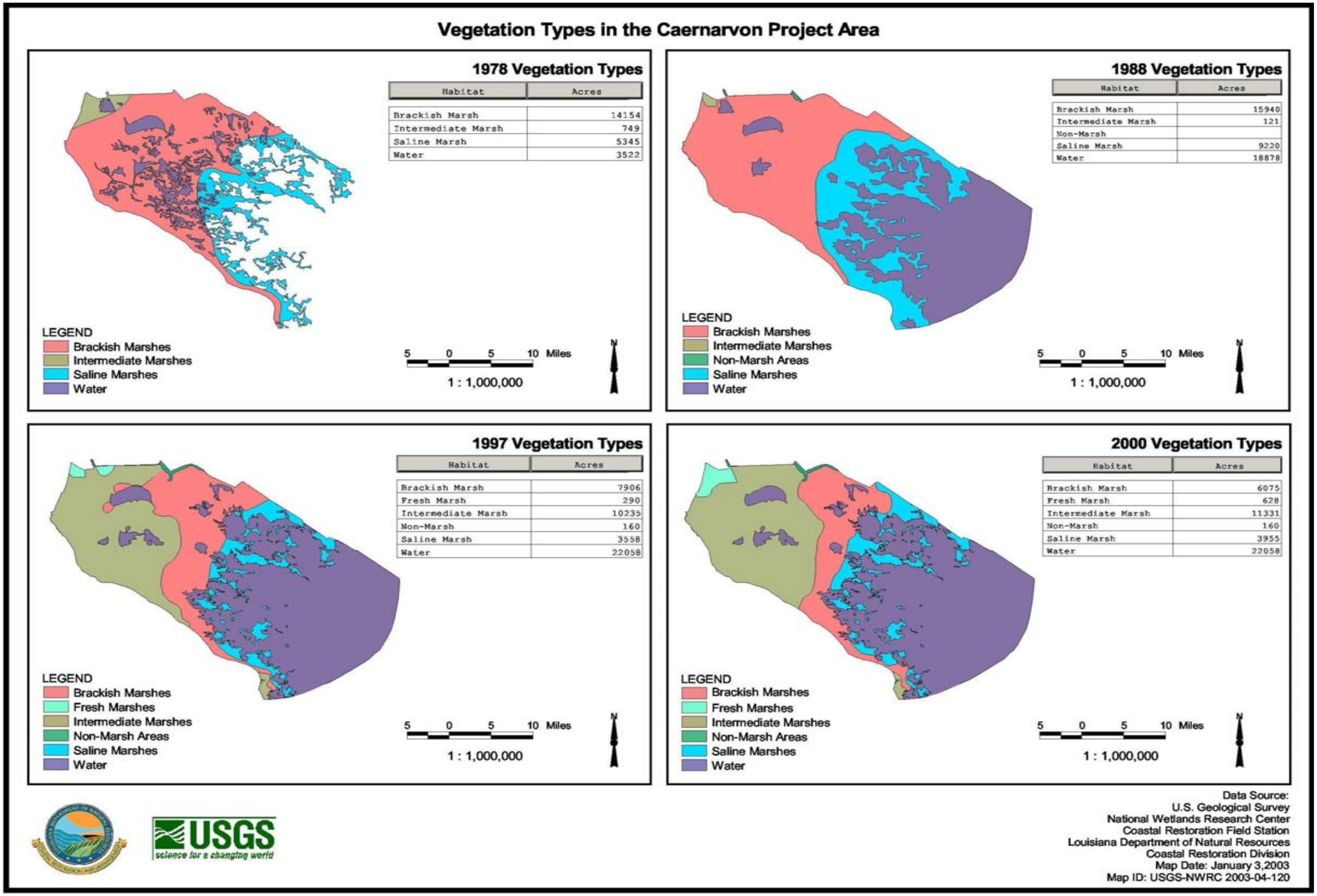


Figure 3.3. Vegetation types in the Caernarvon Project Area (from CPRA 2010a).

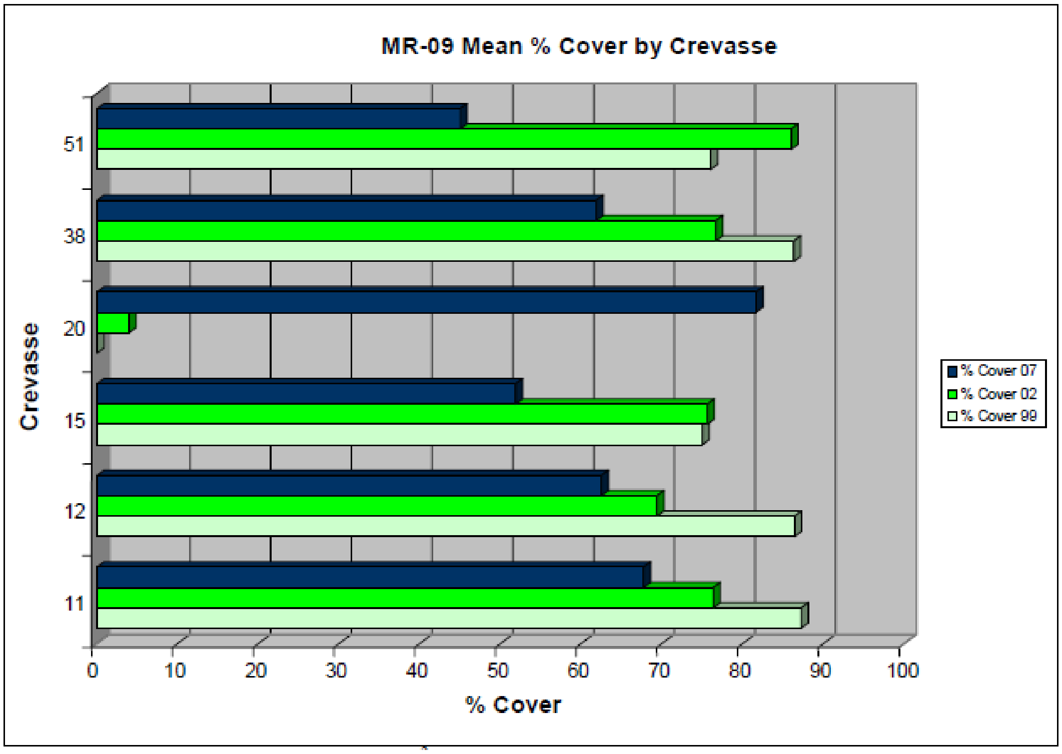


Figure 3-4. Mean percent cover of 4-m plots for six selected crevasses constructed within the Delta Wide Crevasses project area August 1999, 2002, and 2007 (from Bernard 2009)

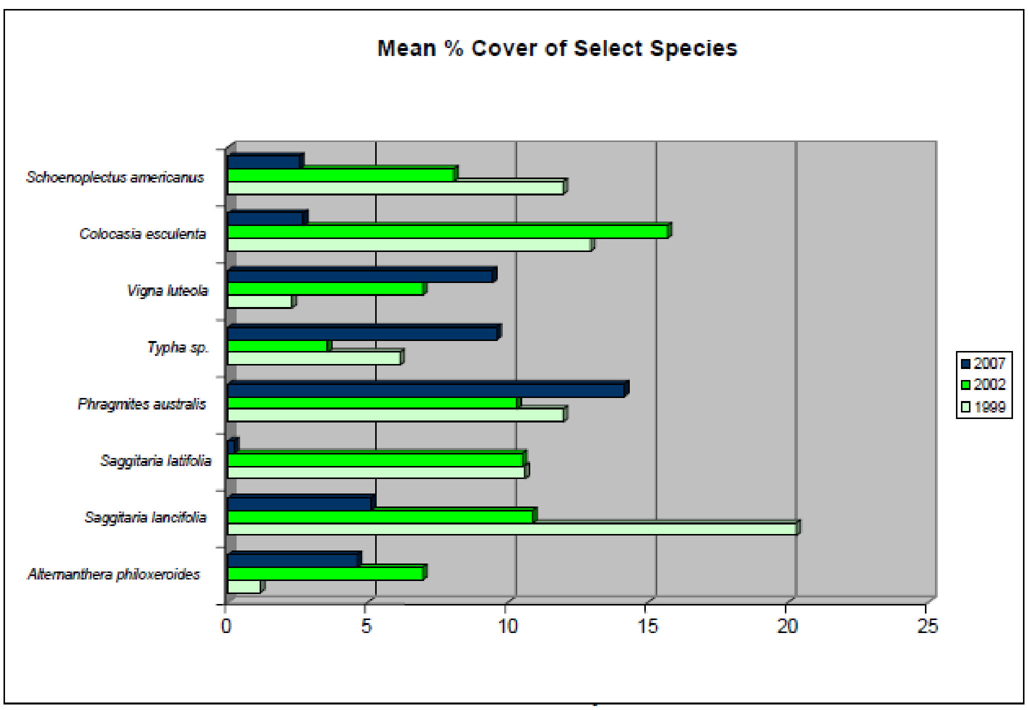


Figure 3-5. Mean percent cover of selected species across all 4-m plots within the Delta Wide Crevasses project area during August 1999 and 2007 (from Bernard 2009)

3.1.3 Atchafalaya Delta

The natural islands within the Atchafalaya delta are primarily covered by three types of vegetation (Sasser and Fuller 1998). The most extensive vegetation coverage (64 percent) is the arrowhead *(Sagittaria* sp.) community which generally occur at the lowest intertidal elevation and includes broadleaf arrowhead, delta arrowhead (*Sagittaria platyphylla*) and chairmakers bulrush. The second most extensive coverage (19 percent) is woody vegetation, primarily black willow (*Salix nigra*) which occurs on the upstream end of the delta lobes and along the island edge where elevation and sand content are high. Cattail is the third vegetation type (10 percent) and occurs at intermediate elevations and includes broadleaf cattail (*Typha latifolia)*, variable flatsedge (*Cyperus difformis*), spikerush (*Eleocharis* sp.), chairmakers bulrush or softstem bulrush (*Schoenoplectus tabernaemontani* = *Scirpus validus*), and valley redstem (*Ammannia coccinea*) (Curole 2003).

Three general categories of species development were reported in the Atchafalaya Delta (Sasser and Fuller 1988):

1) Species which have increased over time and converged on certain elevational zones: looseflower water-willow (*Justicia ovata*), coco yam, rice cutgrass (*Leersia oryzoides*), dotted smartweed (*Polygonum punctatum*), chairmakers bulrush, and hairypod cowpea.

2) Species which have been relatively stable over time with elevational shifts attributable to local erosion or accretion: black willow, Indian jointvetch (*Aeschynomene indica*), spikerush, maidencane, bulltongue arrowhead, softstem bulrush, and southern cattail (*Typha domingensis*).

3) Species which present over a wide range initially, eventually disappearing at low elevations: broadleaf arrowhead, valley redstem, variable flatsedge (*Cyperus difformis*), hydrocotyle (*Hydrocotyle* sp.), climbing hempvine (*Mikania scandens*), delta arrowhead, and chickenspike (*Sphenoclea zeylanica*).

3.2 Submerged Aquatic Vegetation (SAV)

3.2.1 Caernarvon

Submerged aquatic vegetation (SAV) coverage was higher in the area most affected by Caernarvon diversion (Day *et al.* 2009). SAV had significantly ($P<0.00001$) elevated coverage in the inflow versus the reference area (unaffected by Caernarvon) in the Breton Sound estuary. By lowering salinities, diversions generally expand the area suitable for SAV. The relative frequency of SAV increased across the total Caernarvon area, except for an area located east of the diversion near Bayou Mandeville which carried 66 percent of the total diversion flow south of Lake Lery from 2000 to 2003. Except for these small strata, the SAV plant diversity of the entire Caernarvon area increased (Day *et al.* 2009).

Freshwater releases through the Caernarvon Diversion have increased the amount of submerged aquatic vegetation (SAV) coverage (Rozas *et al.* 2005). All 34 open-water sites sampled by Rozas *et al.* (2005) contained SAV (rooted vascular plants or macroalgae); whereas only 59 percent of the open-water sites in the reference area contained aquatic plants. Aerial coverage was approximately 66 percent in the Caernarvon inflow area and 18 percent in the reference area. Most SAV sites contained Eurasian watermilfoil *(Myriophyllum spicatum)* and small pondweed *(Potamogeton pusillus)*. Widgeongrass *(Ruppia maritima)*, southern waternymph *(Najas guadalupensis)*, and coontail *(Ceratophyllum demersum)* were common, but less abundant. Macroalgae, an unidentified green alga and a stonewort *(Nitella* sp.), also were widespread in the study area. Sixteen inflow sites and 12 reference sites contained macroalgae, and macroalgal coverage was complete at three inflow sites and one reference site. Three inflow sites and nine reference sites contained only macroalgae and no SAV (Rozas *et al.* 2005).

The three most common SAV species observed near Caernarvon were watermilfoil, widgeongrass, and southern waternymph. Widgeongrass decreased in abundance by 4.74 percent and watermilfoil increased in abundance by 3.86 percent from pre-construction (1989 and 1990) to post-construction (1991 to 1994). However, none of these differences were significant. The occurrence of coontail in 1993 and 1994 indicates a trend towards a fresher habitat (USACE-LDWF 1998).

Salinity from storm surges due to hurricanes in 2002, 2005 and 2008 reduced much of the SAV near Caernarvon CPRA 2010a).

3.2.2 Davis Pond

An immediate increase in SAV was observed in Lake Cataouache (2006-2009) after an increase in the flow from Davis Pond (Figure 3-6, CPRA 2010b). Water hyacinth (*Eichhornia crassipes)* and hydrilla (*Hydrilla verticillata*) are commonly seen in the lake. The extent of dieback of SAV over the winter months varies from year to year (CPRA 2010b).

3.3 Phytoplankton

The introduction of fresh water into estuaries has broad effects on phytoplankton productivity (Lane *et al.* 2001). Salinity, suspended sediments, and nutrients can interact to affect phytoplankton communities (Day *et al.* 2003). Pulsed river water events can increase nutrient levels, potentially resulting in enhanced primary production, phytoplankton community shifts, and bloom formation (Bargu *et al.* 2011). River nutrient loading can alter the phytoplankton community and potentially lead to eutrophication (Day *et al.* 2009). Nutrients in diverted water can increase algal growth; making estuaries areas of potentially high primary production (Lane 2003). This growth could impact water quality by lowering dissolved oxygen levels (Miao *et al.* 2006).

Figure 3-6. Aquatic vegetation growth in Lake Cataouatche (from CPRA 2010b)

Light limitation is the primary control of phytoplankton growth. Suspended sediments cause light attenuation; this confines the photic zone to a small fraction of the water column (Lane 2003; Lane *et al.* 2001). High riverine discharge can suppress phytoplankton concentrations and chlorophyll *a* concentrations are inversely related to suspended sediment concentrations. Chlorophyll *a* is the principal photosynthetic pigment and is common to all phytoplankton; therefore, chlorophyll *a* can be used as a measure of phytoplankton biomass. Once suspended sediment concentrations decline, phytoplankton levels increase (Lane 2003). Phytoplankton productivity in estuaries is often higher at intermediate salinities where suspended sediment has dropped out of the water column but high nutrient concentrations are still available (Lane *et al.* 2001).

High nitrogen loading to coastal aquatic systems can increase algal production and reduce dissolved oxygen (DeLaune and Jugsujinda 2003; White *et al.* 2009). Assimilation into particulate organic matter (i.e. organic nitrogen and chlorophyll *a*) by phytoplankton is one of the common transformations of nitrogen oxides (NOx; Lane *et al.* 2001). Other nutrients linked to plankton primary productivity include dissolved reactive phosphorus (DRP) and silica (Si). Similar to the distribution of nitrate, dissolved reactive phosphorus was highest within the Bonnet Carré Spillway plume. This increased loading of inorganic nutrients could eventually provide a trigger for a phytoplankton bloom (White *et al.* 2009). In Breton Sound, rapid river-assisted flushing probably prevents widespread development of algal blooms in response to introductions of the nutrient-rich river water. However, the introduction of river water to isolated coastal lakes with longer residence times can lead to eutrophic conditions and in some cases, cause harmful algal blooms (Wissel *et al.* 2005).

3.3.1 Caernarvon

Variations in river input rates create a dynamic and turbulent environment that favors specific groups of phytoplankton. The community composition of phytoplankton shifts in response to seasonal changes in river input rates, and responds quickly to changes in environmental conditions such as nutrients, salinity and turbulence. Phosphorus availability and the distance from Caernarvon were important during these changes in river input rates. The phytoplankton community was dominated by diatoms, chlorophytes, and cyanobacteria and varied spatially, seasonally, and interannually. The phytoplankton community shifted from cyanobacteria during most of the year to chlorophytes in response to changes in environmental conditions (Czubakowski 2010). The phytoplankton community of the Breton Sound estuary appears to be moderated by temperature during high river input and nutrient availability during low river input. Cyanobacteria were highest during summer and fall when temperatures were high and flushing was low (Czubakowski 2010; Day *et al.* 2009).

Year-round algal blooms were not observed in the area around Caernarvon, although moderate eutrophication occurs at some sites (Day *et al.* 2003). This area is relatively well-flushed by riverine pulses and other weather events (Day *et al.* 2003; Wissel *et al.* 2005). Seasonal and spatial patterns in chlorophyll *a* and phytoplankton availability were very strong near Caernarvon. The estuary receives most of its sediment input and high loadings of nutrients during the spring, but high turbidity and colder temperatures during this time limit phytoplankton productivity (Lane 2003). During high discharges, chlorophyll *a* concentrations were low near Caernarvon; this was likely because high suspended sediment concentrations caused high light attenuation. In the mid-estuary, chlorophyll *a* often increased after suspended sediment concentrations decreased. During low discharge periods, this mid-estuary production was most likely supported by the regeneration of nutrients supplied during the high discharge (Day *et al.* 2003). As temperatures rise in the summer and fall, nutrients are regenerated by benthic metabolism, releasing dissolved nutrients back into the photic zone where they support phytoplankton production. This decoupling between riverine input and peak phytoplankton productivity has been observed in many estuaries (Lane 2003). Chlorophyll *a* concentrations near Caernarvon were low during pulsed discharge but higher in the mid-estuary during warmer months (Figure 3-7; Day *et al.* 2009).

3.3.2 Davis Pond

As of 2005, Davis Pond has not negatively impacted water quality in terms of algal blooms (CPRA 2010b). A hypereutrophic event in Lac Des Allemands during August 2004 was likely related to high chlorophyll *a* due to a lack of rainfall, low turbidity, and high temperatures.

3.3.3 Bonnet Carré

Increased phytoplankton growth has been noted after Bonnet Carré Spillway openings. During the April 2008 Spillway opening, a freshwater plume formed by the strong river input had

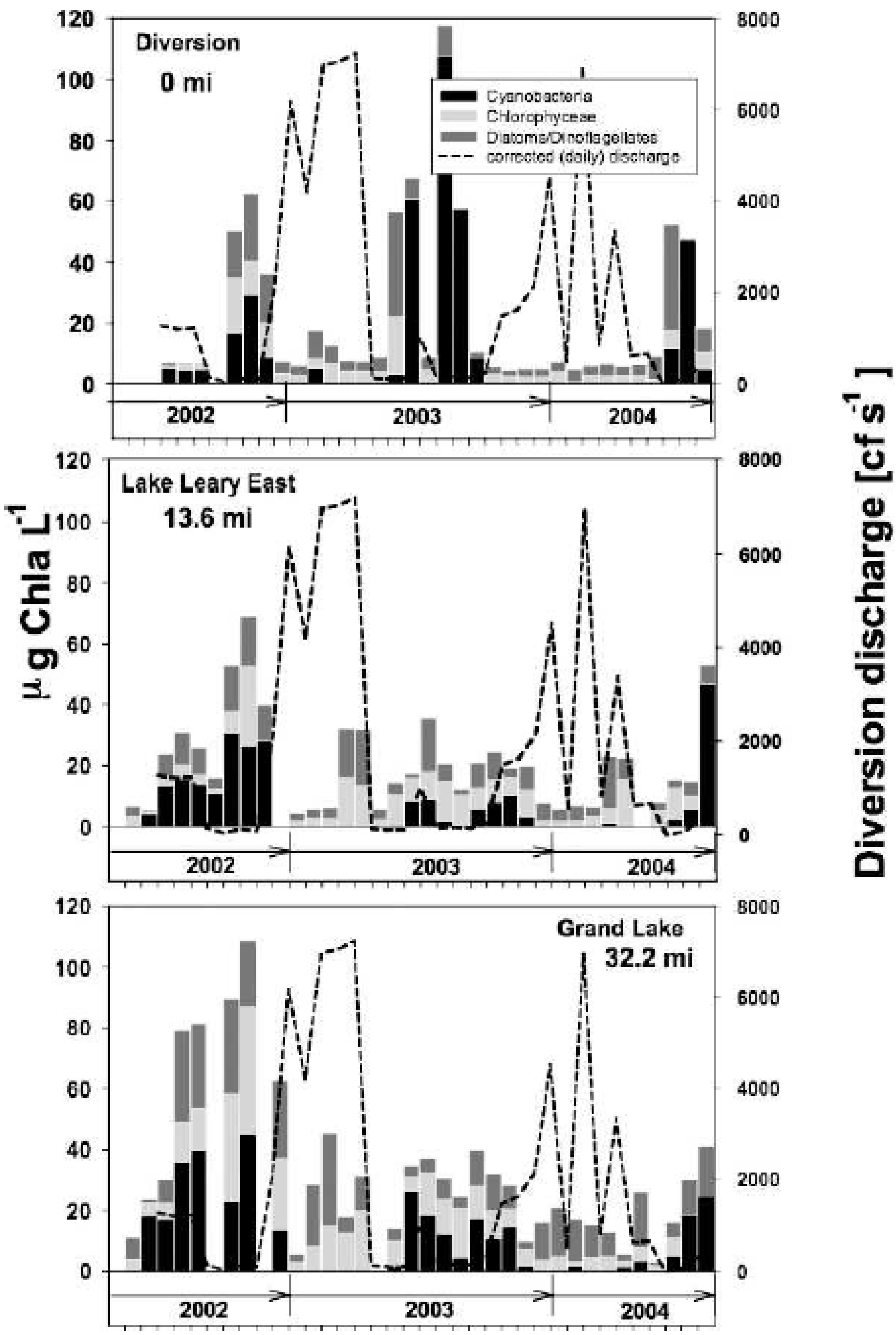


Figure 3-7. Spatial, seasonal, and interannual variability of the phytoplankton community structure are shown for three stations with increasing distance from the diversion (Breton Sound estuary, February 2002 - September 2004). Chlorophyll *a* concentrations of the three major groups cyanobacteria, chlorophyceae, and diatoms or dinoflagellates) are given as stacked bars for the monthly surveys along with diversion discharge (dashed line) averaged for 5 days prior to phytoplankton sampling (from Day *et al.* 2009)

limited mixing with Lake Pontchartrain (Bargu *et al.* 2011). Lake Pontchartrain nitrate and dissolved reactive phosphorus concentrations were increased to more than five times the lake background in the plume stations (Bargu *et al.* 2011). Although the dissolved nutrients were higher, plume stations contained lower algal biomass as indicated by chlorophyll *a* values but high diversity compared to outside the plume (White *et al.* 2009). Chlorophyll *a* concentrations were significantly negatively correlated with nitrate, dissolved silica, and phosphorus concentrations. More dominant plume-related factors (lower temperature and high TSS) may have inhibited phytoplankton productivity because high amounts of dissolved nutrients generally stimulate primary productivity (White *et al.* 2009).

Phytoplankton composition changes after the 2008 Spillway opening were similar to those of the 1997 opening (Mize and Demcheck 2009). Blue-green algae dominated the phytoplankton community in 2008, but were less severe than in 1997, when a large blue-green algae bloom resulted in lake-wide recreation health advisories (Dortch *et al.* 1999; Mize and Demcheck 2009). River water with highly visible sediment loads was near the south shore of the lake during the peak flow of April 2008 event shows and not fully mixing with water in the north-central portion of the lake (Figure 3-8). Satellite imagery of Lake Pontchartrain from May 2008 showed evidence of spring runoff conditions and high sediment loading from several streams into the northern portions of the lake and Lake Borgne. This spring runoff from streams along the north shore of Lake Pontchartrain may have contributed to the changes in water quality in the north-central portion of the lake. The combination of reduced freshwater inflows (both diversion closing and end of spring north shore runoff into the lake) and substantial nutrient concentrations in the lake created optimal conditions for nuisance cyanobacteria growth (Mize and Demcheck 2009).

Major surface blooms of blue-green algae did not occur after the 1973, 1975, 1979, and 1983 Spillway openings. No major blue-green algal blooms were noted in years between and after these openings (Poirrier and King 1998). Algal blooms occur in Lake Pontchartrain when the spillway is not open. A small surface accumulation of the blue-green alga *Anabaena circinalis* was observed near Mandeville in June 1993, and large surface accumulations of blue-green algae occurred in late June 1994. A major bloom of blue-green algae occurred from late June through mid July 1995 and surface accumulations were present over most of the lake during the peak of the bloom. No blue-green algal blooms occurred in 1996 (Poirrier and King 1998).

Increased plant nutrient levels from development within the basin, particularly on the north shore, and unusual weather may be the cause of the blooms (Poirrier and King 1998). The blue-green algal blooms and associated events are indicative of high levels of plant nutrients (Poirrier and King 1998). Even short-term nutrient-pulse events, like a temporary release of river water into the lake may have cascading effects on water quality and phytoplankton communities (Mize and Demcheck 2009). In estuarine receiving waters like Lake Pontchartrain, water quality changes and corresponding phytoplankton community compositional changes are frequently consequences of nitrogen enrichment of the system (Mize and Demcheck 2009). Nitrogen is the growth-limiting nutrient for the phytoplankton community in Lake Pontchartrain, and nitrogen-limited systems normally favor the cyanobacteria that presents as blue-green algae (Mize and Demcheck 2009).

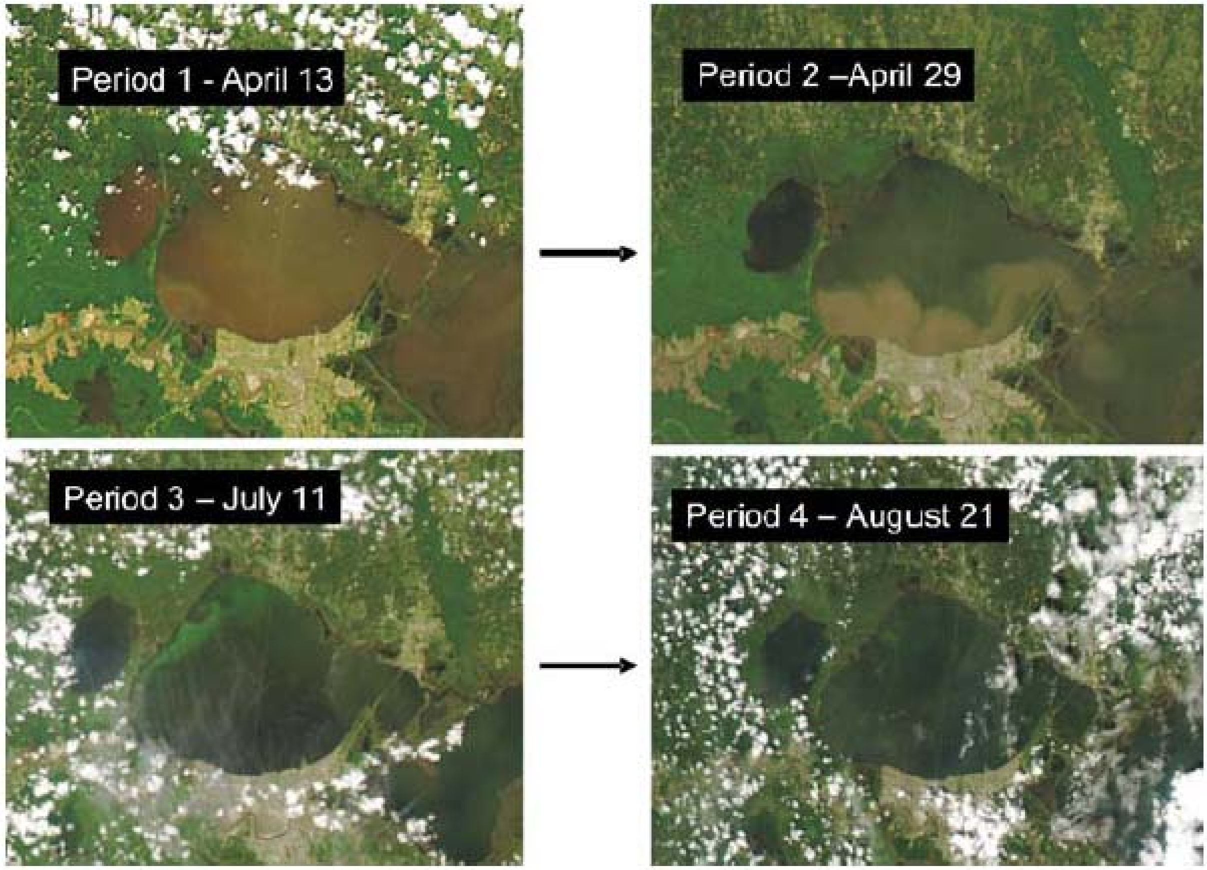


Figure 3-8. National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroadiometer (MODIS) imagery (NASA 2008) showing Lake Pontchartrain during the four sampling periods (from Mize and Demcheck 2009)

Algal blooms may be more common in Lake Pontchartrain than they were in the past. The distribution and density of the blooms are difficult to quantify because algae accumulated at the surface and moved with wind (Poirrier and King 1998). At times algae were present throughout the estuary, and at other times they were concentrated near shore depending upon wind direction. Duckweeds were often present with the blooms suggesting that movement of floating algae from wetlands may have contributed to the surface blooms. Increased concentrations of nutrients in river water may explain why blooms have occurred after recent Spillway discharges, but did not occur after past discharges. Increased nutrient loading from development in the basin, increased water clarity due to the cessation of shell dredging, and the retention time for nutrients and freshwater are also contributing factors to these blooms. Whatever the source of algal blooms, the solution to controlling them is reducing nutrient loading (Poirrier and King 1998).

Phytoplankton communities in Lake Pontchartrain were affected by the spillway opening (Figure 3-9; Mize and Demcheck 2009). Nutrient concentrations decreased rapidly after the spillway closure as the plume dissipated; the plume and lake water gradually mixed together after the spillway was closed, indicated by the reduction of the horizontal salinity gradient

(Bargu *et al.* 2011). Water-quality data also indicated this gradual reversion to pre-diversion lake conditions by June to July, but shifts in the phytoplankton composition were still evident through August 2008 (Mize and Demcheck 2009).

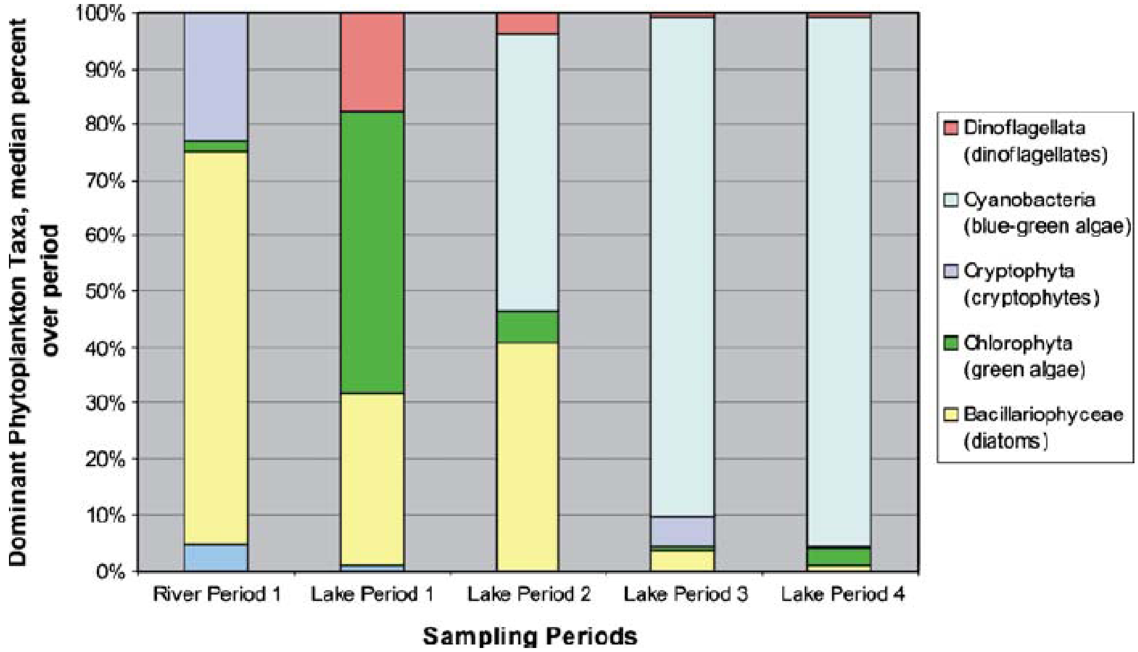


Figure 3-9. Composition of dominant phytoplankton taxa for the Bonnet Carré Spillway, and four sampling periods at five sites in Lake Pontchartrain and adjacent waterways in southeastern Louisiana, April to October 2008 (from Mize and Demcheck 2009)

Two main types of phytoplankton communities affect the estuarine ecosystem differently. Diatoms are the usual food for filter feeding fishes and zooplankton. The non-diatom based community is typically dominated by flagellates, which are poor food for most grazers and may include noxious or toxic species (Lane *et al.* 2001). Most of the harmful algal species are non-diatoms (Lane *et al.* 2004). Diatoms require a dissolved inorganic Si:N molar ratio of about 1:1. A ratio lower than 1:1 (silica deficiency) may exacerbate eutrophication by reducing the potential for diatom growth in favor of noxious flagellates.

During the 1994 experimental opening of the spillway, silica concentrations were significantly lower at the edge of the freshwater plume than in the water flowing through the spillway, possibly because diatomic phytoplankton incorporated the silica entering Lake Pontchartrain. The dissolved inorganic Si:N molar ratio of water in the spillway was 1.3, while at the freshwater plume edge the ratio ranged from 1.4 to 3.0. These Si:N ratios suggest that there was an adequate supply of silica to support a diatom-based phytoplankton community at the plume edge (Lane *et al.* 2001).

Diatoms and chlorophytes dominated the system during the 2008 spillway opening (Bargu *et al.* 2011; Mize and Demcheck 2009). The plume was primarily dominated by freshwater species of centric diatoms; stations outside the plume were dominated by brackish species of centric diatoms (White *et al.* 2009). After the spillway closure, over time the dominant species shifted from diatoms to toxic cyanobacteria; this corresponded to more stable, warmer, and nutrient-limited water conditions (Bargu *et al.* 2011; Mize and Demcheck 2009).

3.4 Factors of Influence on Vegetation

Diversions have been used to restore the natural process of overbank flooding during high water. River diversions deliver freshwater that lowers salinity, mineral sediments that contain nutrients as well as increase bulk density, and iron that precipitates sulfide (Carpenter *et al* 2007; Moerschbaecher 2008). A common assumption is that river water quality has not changed appreciably since the river last flowed unencumbered into the estuaries, but this assumption is not always correct (Swarzenski *et al.* 2008). Seasonality is important to the operation of the freshwater sources and therefore the delivery of constituents, especially during the winter and spring. Nutrients and freshwater input are dependent on seasonal nutrient concentration in the river source water (Hyfield *et al.* 2008).

Fresh water is the primary process for nutrient delivery to many aquatic systems, and rivers are important sources of fresh water, sediment, and nutrients to coastal systems (Hyfield *et al.* 2008). Efficient nutrient removal occurs at low discharges, but the removal efficiency decreased rapidly with increasing loading rates (Lane *et al.* 1999). The low removal efficiency at high loading rates during high discharges may result from shorter residence times of water in the estuary, allowing less time for biogeochemical processes to occur (DeLaune *et al.* 2003; Lane *et al.* 1999).

3.4.1 Nutrients

Nutrients were quickly assimilated over the first 20 km near Caernarvon and were generally lower at sites further from the diversion (Day *et al.* 2009; Moerschbaecher 2008; Twilley and Nyman 2002). This is in part because increases in overmarsh flow enhances sediment retention and increases in temperature increases nutrient uptake (Day *et al.* 2009). As diverted river water passed through the estuary, significant changes in nutrient concentrations and stoichiometric nutrient ratios (Lane *et al.* 2004; Day *et al.* 2009). Nutrient concentrations generally decreased as river water passed through the estuary and over the marsh (Lane *et al.* 2001). It is unlikely that all marshes will respond equally to similar increases in nutrient loads (Turner 2010). Greater flushing and lower water residence times occurred near and far from the diversion due to riverine inputs from the Caernarvon diversion and high frequency tidal inundation. Increasing the frequency and volume of riverine discharge could potentially impact the mid sites (Moerschbaecher 2008).

Nutrients are actively deposited and/or transformed as riverine derived water passes through an estuarine system (Lane 2003). Important estuarine sinks for nutrients include direct burial of particulate nutrients, plant uptake and subsequent burial of organic nutrients, and denitrification. These processes are significant sinks for nutrients in the Breton Sound system (Hyfield *et al.* 2008). However, regeneration of nutrients may occur during the summer as water temperatures rise, so this nutrient uptake may not be a permanent loss pathway (Lane *et al.* 2004).

Spillways and their surrounding wetlands can be used to decrease nutrient and sediment concentrations of diverted river water before the water reaches lakes. This can buffer the lakes from possible side-effects of diverting nutrient-rich waters (Lane *et al.* 2001). Forested wetlands are effective sinks for nutrients, and nutrient concentrations may decrease in forested spillways (Lane *et al.* 2001).

3.4.1.2 Nitrogen

Nitrogen is the major limiting nutrient in Louisiana' salt marshes; the rate of the nitrogen supply influences the composition of the plant community (Twilley and Nyman 2002). The major source of inorganic nitrogen to estuaries is nitrate from river diversions (Hyfield *et al.* 2008). Excess nitrogen is of greatest consequence downstream of diversions because it is the limiting nutrient in flooded soils and estuarine environments (Gardner 2008).

Nitrogen can exhibit more dynamic behavior than other nutrients. Nitrogen oxides comprise 90 percent of the dissolved inorganic nitrogen input from diversions. Nitrogen oxides also show a seasonal trend. Large fluxes in nitrogen oxides from Caernarvon waters are associated with high discharges during late winter–early spring (Day *et al.* 2009; Moerschbaecher 2008). Maximum concentration of nitrogen oxides occurred during the summer and minimum concentrations occurred during the winter (November to March) near Caernarvon (Day *et al.* 2009) and the Atchafalaya River (Smith *et al.* 1985).

Freshwater diversions can significantly alter riverine nutrient concentrations and ratios; and reduce the overall amount of nitrogen exported (DeLaune *et al.* 2005, Lane *et al.* 2004). The Breton Sound wetlands act as a sink for nitrogen (Day *et al.* 2009; Lane *et al.* 1999). Nitrogen removal fluctuates due to variations in temperature, nitrate concentration, and the amount of over-marsh flooding (Hyfield *et al.* 2008).

Nitrogen transformation can be carried out by biological and non-biological processes. Important processes of the nitrogen cycle include fixation, mineralization, nitrification, and denitrification. Nitrogen availability can affect the rate of key ecosystem processes, including primary production and decomposition. Ammonification, ammonia mobilization, and assimilatory nitrogenous oxide reduction may also be dominated by microbial activities, but these may also be performed by macroorganisms (Day *et al.* 1989).

Nitrate concentrations are substantially reduced in the estuarine environment due to denitrification, assimilation, and reduction (Lane 2003). Over-marsh flow efficiently removes nitrate because the water slows and warms (Day *et al.* 2009). The capacity of a ponded wetland to remove nitrate in diverted river water is strongly influenced by discharge rate. A wetland cannot remove all the nitrates during a large peak, but nearly all the nitrate can be removed during a steady, lower discharge (DeLaune *et al.* 2005; Yu *et al.* 2006). Diverted water must be discharged at rates capable of providing sufficient time for the marsh soils to denitrify the nitrate, to achieve a specific nitrate reduction objective (Yu *et al.* 2006).

Denitrification is a major process for removing nitrate in diverted river water (Lane *et al.* 2004; Day *et al.* 2009; DeLaune *et al.* 2005). Denitrification is carried out by denitrifying bacteria that use nitrate as an electron acceptor to oxidize organic matter anaerobically. Temperature plays a critical role in denitrification and nitrification rates (Yu *et al.* 2006). Denitrification rates increase with increasing temperature and high nitrate concentrations (Hyfield *et al.* 2008). Switching from aerobic to anaerobic conditions results in a rapid decrease in nitrogen oxide concentration (Figure 3-10) due to denitrification (Miao *et al.* 2006). Initial and average flux rates of nitrogen oxide were higher under aerobic conditions than under anaerobic conditions (Miao *et al.* 2006). Since denitrification is controlled by the availability of nitrate in an anaerobic environment, much of the seasonal change in denitrification rate can be attributed to changes in inorganic nitrogen oxide status of the water (Smith *et al.* 1985). Denitrification rates are greater in areas of fluctuating redox potential (flooding and draining cycles) than in areas where the redox is continuously high or continuously low, and is an important mechanism for the oxidation of ammonia to nitrate and subsequent denitrification (Lane *et al.* 2004).

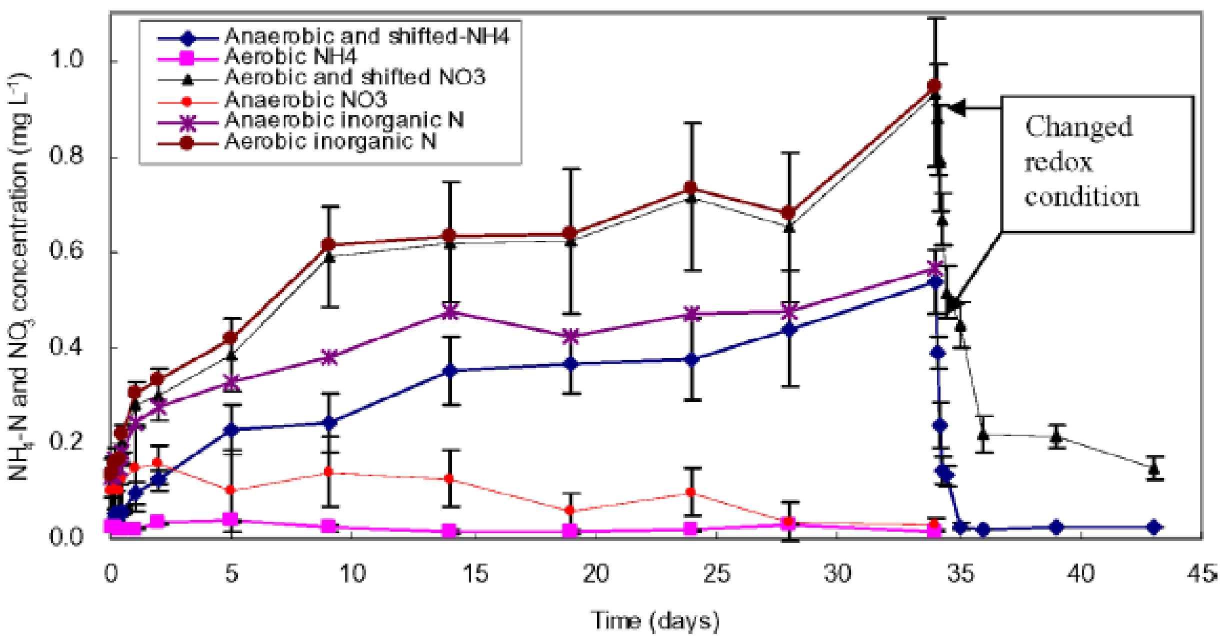


Figure 3-10. Changes in ammonium nitrate, and inorganic N concentration for the water column under different redox conditions from sediment cores of Lake Cataouatche (*n* = 6) (from Miao *et al.* 2006)

Another transformation of nitrogen oxide is assimilation into particulate organic matter (i.e., organic nitrogen and chlorophyll *a* by phytoplankton) (Lane *et al.* 2001). Vascular plants as well as algae incorporate nitrogen oxide into cellular mass (Lane *et al.* 1999). Nitrogen uptake by marsh plants decreases as salinity increases (Moerschbaecher 2008; White *et al.* 2009). More efficient nutrient uptake and higher productivity should occur near diversions due to the salinity gradient (Moerschbaecher 2008). Nitrate levels at Davis Pond also decreased with distance from the diversion (Delaune *et al.* 2005; Moerschbaecher 2008).

Another potential pathway for nitrogen loss is reduction to ammonia (NH_3) (Lane *et al.* 1999; Lane *et al.* 2004). However, this is not a permanent reduction of nitrogen because ammonia can oxidize back to nitrate.

Ammonium (NH_4^+) is an important source of nitrogen for many plant species, particularly plants growing on hypoxic soils. Ammonium concentrations fluctuated with nitrogen oxide concentrations; negligible concentrations of ammonium occurred during periods of high nitrogen oxide, and high concentrations occurred during periods of low nitrogen oxide. This suggests that regeneration is a source of ammonium throughout the Breton Sound basin (Day *et al.* 2009; Miao *et al.* 2006). Atmospheric deposition was the primary source of ammonium to the estuary (Hyfield *et al.* 2008). As much as 50 percent of nitrate applied to marine sediments can be reduced to ammonium (Lane *et al.* 1999). These processes are biologically driven and are positively correlated to temperature; higher nitrogen oxide concentrations occur during winter, when these biological processes are at their slowest rate (Lane *et al.* 1999).

Ammonium regeneration is highest on or in the sediments; ammonium was the predominant form of inorganic nitrogen in sediment collected from Four League Bay off the Atchafalaya Bay (Smith *et al.* 1985). The regeneration of ammonium was caused by the decomposition of organic matter in the Breton Sound estuary, which acted as a source for ammonium (Lane *et al.* 1999). Ammonium is also released from the sediment to the water column, a reduction of nitrogen oxide to ammonium. This release can be significantly greater under anaerobic condition than aerobic conditions due to the lack of nitrification as a result of the absence of oxygen (Miao *et al.* 2006). Under aerobic conditions and once the nitrifying microbial population became established, ammonium released from the sediment did not build up in the water column due to nitrification (Miao *et al.* 2006).

Ammonium concentrations were highest at sites near Caernarvon during months of high flow; however, concentrations at the far site were less variable (Moerschbaecher 2008). A spatial pattern was also observed within basins and within core samples. Porewater concentrations of ammonium increased with depth (Figure 3-11) and ammonium concentrations were greater at the upstream and transition sites compared to the downstream site (Figure 3-12; Twilley and Nyman 2002). A lack of any strong seasonal trend in ammonium concentrations was observed near Caernarvon by Moerschbaecher (2008). Smith *et al.* (1985) reported that the concentration of ammonium had a distinct seasonal pattern with maximum concentrations during the summer and minimum concentrations during the winter (November to March).

3.4.1.3 Phosphorus

Phosphorus enters the estuary from runoff of weathering of soil and rock or from point-source discharges including sewage treatment plants (Day *et al.* 1989). Phosphorus is usually buffered in estuarine systems and is taken up when concentrations are high and released when concentrations are low (Lane *et al.* 2004). A rapid reduction of phosphorus occurs as salinity increases during the flocculation of iron (Fe), manganese (Mn), aluminum (Al), organic carbon and humic substances. Flocculation and the subsequent deposition of dissolved organic and inorganic matter during the mixing of river and sea water is an important removal mechanism for phosphorus. Other important mechanisms for the removal of phosphorus from the water column are plant uptake, microbial incorporation, and soil fixation. Phosphorus is readily adsorbed onto the surface of sediments and is lost from the water column as sediments are deposited on bay bottoms and surrounding marshes. The fixation of phosphorus to soil is more extensive and less reversible under alternating flooding-draining than under conditions of continuous flooding or continuous soil moisture (Lane *et al.* 2004). Burial is the only mechanism by which phosphorus is permanently lost from the system (Lane *et al.* 1999).

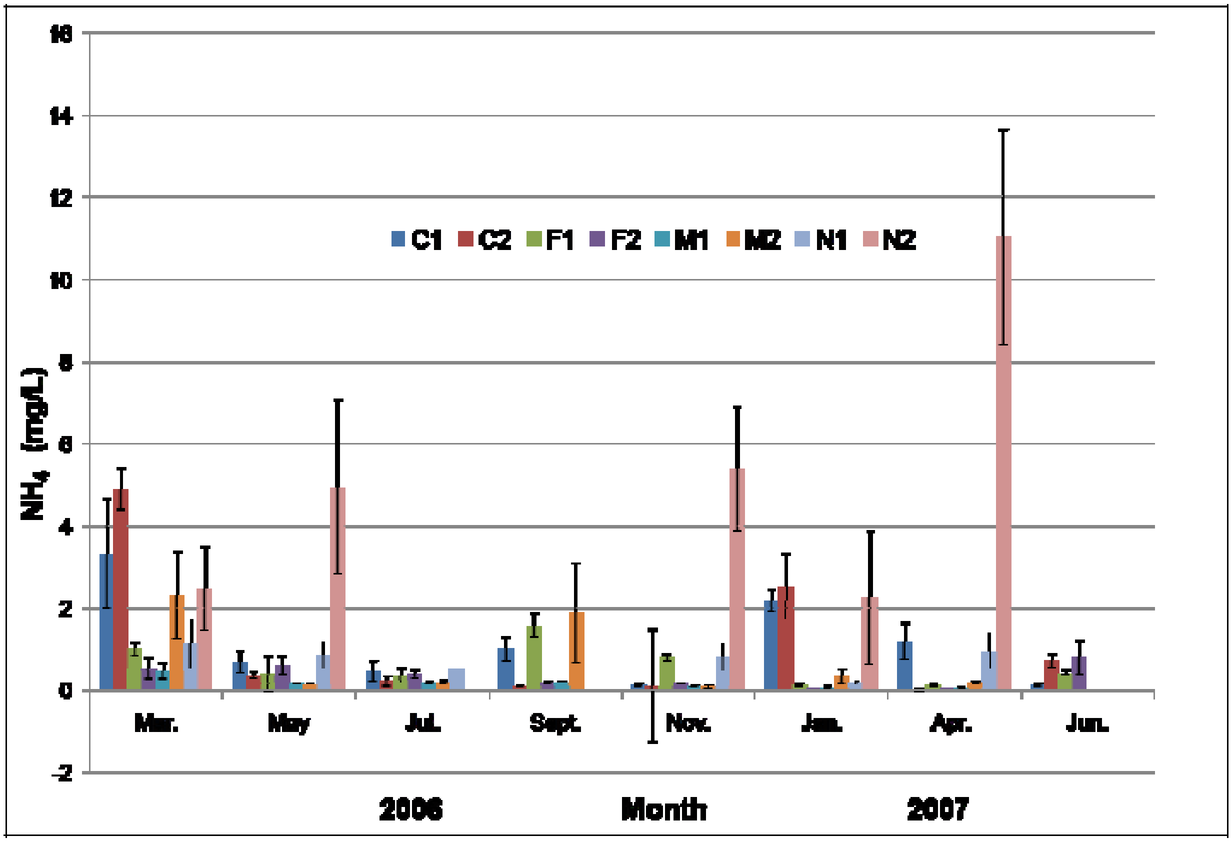


Figure 3-11. Mean porewater NH4 concentrations at each site in the Breton Sound Estuary during the study period (from Moerschbaecher 2008)

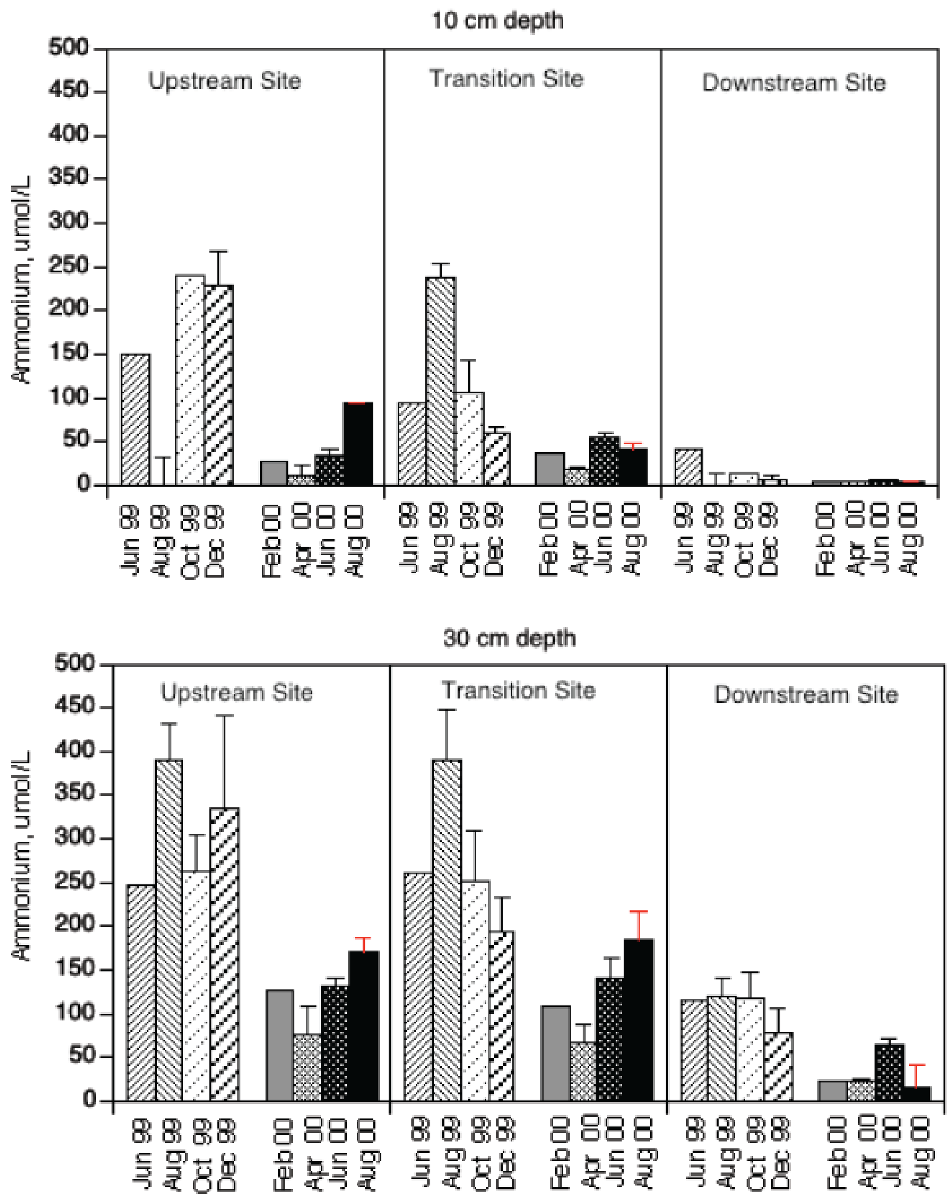


Figure 3-12. Ammonium concentrations in porewater at three sites downstream from the Caernarvon outfall at two depths during each survey (from Twilley and Nyman 2002)

Concentrations of phosphate (PO_4) during late spring and early summer were typically higher towards Caernarvon and at the marine end of the estuary (Moerschbaecher 2008; Day *et al.* 2009). Lower phosphate values occurred during late winter and early spring (Day *et al.* 2009), although Moerschbaecher (2008) found phosphate peaked during March. After this initial peak in March, concentrations decreased and leveled for the rest of the study period (Figure 3-13; Moerschbaecher 2008).

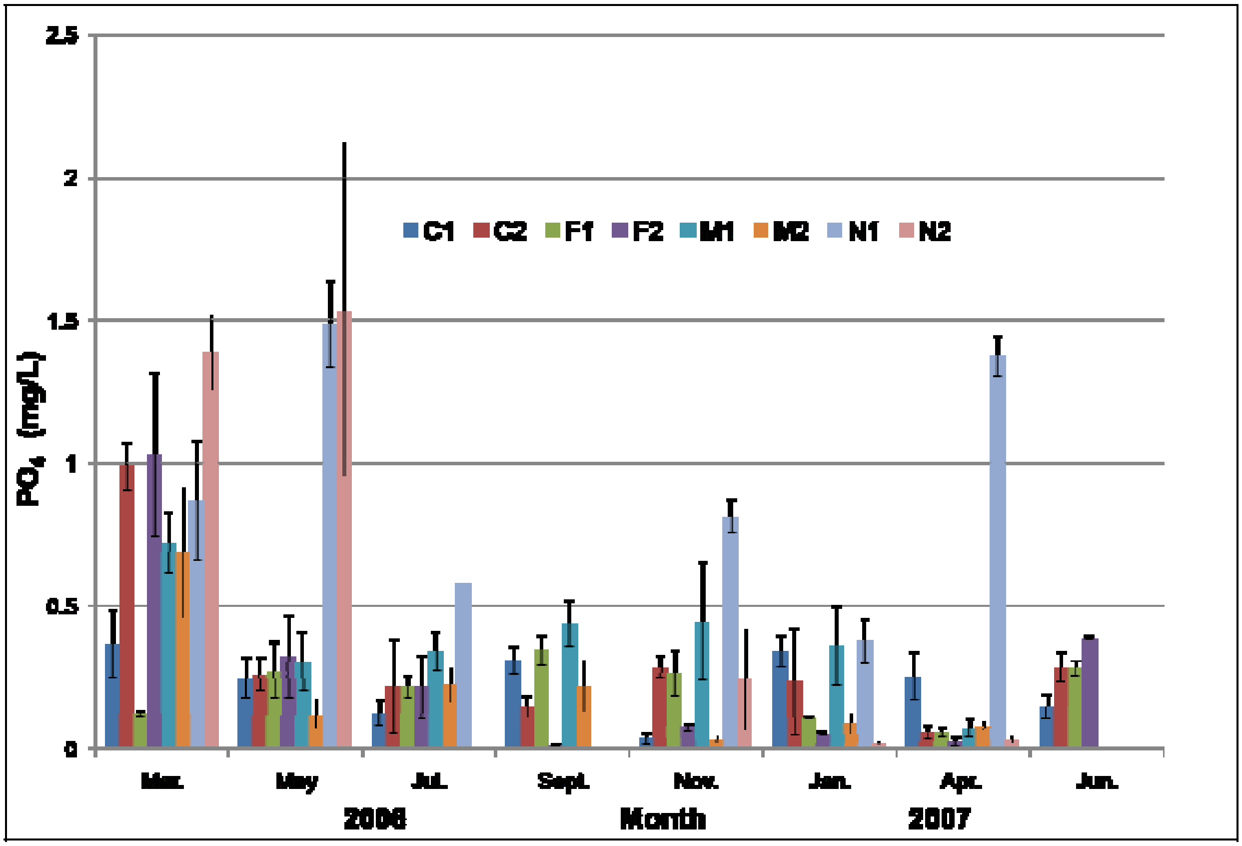


Figure 3-13. Mean porewater phosphate concentrations at the study sites (from Moerschbaecher 2008)

Total phosphorus concentrations were higher during the summer and lower during the winter (Day *et al.* 2009). Total phosphorus was also higher during high discharge periods (Day *et al.* 2009). Phosphate concentrations showed the same general patterns as ammonium. Porewater concentrations increased with depth at all three sites, and at each depth (10 and 30 cm), concentrations were greater at the upstream and transition sites compared to the downstream site. No significant seasonal differences occurred within sites (Twilley and Nyman 2002).

The Breton Sound estuary acted conservatively with respect to total phosphorus. The highly charged phosphate anion (PO_4-), when at high concentrations, was readily sorbed by clay and detrital organic particles. At lower concentrations, phosphate anions were released into the water, thus maintaining moderate ambient concentrations. This buffering process occurs in two distinct steps: sorption/desorption of phosphate anions directly onto particle surfaces occurs rapidly (minutes-days); then slow (days-months) diffusion of phosphate anions toward the interior of the particles. Cyclic aerobic and anaerobic conditions in the top several centimeters of the wetland soil also affect the sorption and release of phosphate (Lane *et al.* 1999). Maintaining the oxygen status of Lake Cataouatche would result in less phosphorus release to the water column, thereby decreasing the internal sediment load (Miao *et al.* 2006). Phosphorus concentrations released from the sediment to the water column under anaerobic conditions were significantly greater than the fluxes measured under aerobic conditions. Under anaerobic conditions, both dissolved reactive phosphorus and total phosphorus concentration in the water column were highly correlated with iron concentration. Under aerobic conditions, no significant or negative relationship existed between phosphorus and iron concentration. In coastal sediments or other areas with high concentrations of sulfides, the opposite trend (greater solubility under aerobic conditions) was observed for many metals (Miao *et al.* 2006).

3.4.1.4 Nutrient Ratios

A strong seasonal change in porewater nutrients occurred near Caernarvon, particularly at the 10-cm depth, which resulted in very distinct changes in nitrogen to phosphorus (N:P) ratios, reflecting the effect of plant uptake on these spatial concentrations (Twilley and Nyman 2002). Bulk nutrient gradients were particularly evident with total phosphorus, and less with carbon and nitrogen. As riverine water flows through an estuarine system, dissolved inorganic molar silicate to nitrate (Si:N) ratios increase and N:P ratios decrease (Lane 2003). Primary nutrients, such as nitrogen and phosphorus, decrease with depth in marsh soils, while sulfides increase with depth and exhibit strong seasonal differences (Twilley and Nyman 2002). Total sulfide contents in sods of smooth cordgrass have been shown to limit growth by preventing nitrogen uptake and root development (Twilley and Nyman 2002).

The Breton Sound estuary acted as a sink for dissolved silicon and nitrogen, but at different rates, changing the stoichiometric nutrient ratio of water passing through the estuary (Lane *et al.* 2004). Porewater N:P levels in upstream and downstream sites were the same, indicating little nutrient resource gradient occurs in response to Caernarvon (Twilley and Nyman 2002). A seasonal change in the upstream and downstream porewater nutrient concentrations occurs in response to diversion pulses. Bulk nutrient sediments are important and pulsed diversions are a significant factor in the stability of these marsh ecosystems (Twilley and Nyman 2002). Annual mean N:P ratios in the Breton Sound Estuary displayed an overall nitrogen limitation for all sites. According to the Redfield ratio, N:P should be 16 based on molar concentrations needed to provide adequate nutrients for plant growth. At concentrations below this value, plants may be nitrogen limited, and above this value plants are phosphorus limited. Significant changes in stoichiometric nutrient ratios are attributed to high removal rates of nitrate (Day *et al.* 2009).

3.4.1.5 Silicon

Silicon is the crystalline base of clay minerals and quartz, it occurs in dissolved form primarily as silicic acid. Silicic acid forms the basis of diatom shells. Silicon enters estuaries in runoff water containing weathering products and from sewage discharge (Day *et al.* 1989). Silicate concentrations were higher in the upper and lower Breton Sound basin during the summer. Low concentrations occurred during the winter and early spring within the lower estuary. Like phosphorus, silica is readily absorbed onto the surface of sediments and is lost from the water column as sediments are deposited (Lane *et al.* 2004). Silicate levels were higher in the upper and lower basin during the summer; however, higher concentrations occurred during the winter during periods of high Caernarvon discharge (Day *et al.* 2009). Dissolved silicon is lost through assimilation into diatom tests and sinking and adsorption onto sediments deposited into the estuary (Lane *et al.* 2004). Low spring temperatures result in little to no benthic regeneration of dissolved inorganic silicon. Regeneration of silicon is slow relative to both nitrogen and phosphorus. Regeneration of biogenic silica is primarily a chemical phenomenon, whereas the regeneration of nitrogen and phosphorus is biologically mediated by grazers and bacteria (Lane *et al.* 2004).

3.4.1.6 Sulfur

The most abundant oxidizing agent in most estuaries is sulfate (SO_4^{2-}), which is reduced to sulfide (S^{2-}) through assimilatory and dissimilatory sulfate reduction (Day *et al.* 1989). Saltwater, combined with more reduced soil conditions, leads to the production of sulfides. Freshwater from Caernarvon helps to maintain low sulfide concentrations (Moerschbaecher 2008). The increased frequency and volume of riverine discharge could potentially decrease sulfide levels.

Sulfide concentration was significantly correlated to belowground biomass ($P<0.05$, $R^2=0.13$). Sulfide concentrations during the growing season appeared to be correlated to lower biomass at the sites least affected by the diversion. The relationship between sulfide concentration and biomass production of smooth cordgrass, the dominant vegetation in the area, is presented in Figure 3-14 (Moerschbaecher 2008). Introductions of river water may decrease chloride concentrations and increase habitat space for organic–rich freshwater marshes.

Sulfur concentrations in Penchant Basin maidencane marshes that have been inundated by water from the Atchafalaya River in conditions simulating a diversion for more than 40 years appear to differ (Swarzenski *et al.* 2008). The diverted water promotes sulfur accumulation in the Penchant Basin, compared to reduced levels in similar marsh in the Barataria Basin. The elevated sulfur levels in the Penchant Basin area do not appear to originate from marine sources, but from the frequent river influx during overland flow. Swarzenski *et al.* (2008) suggested that the elevated sulfur in the Bayou Penchant area may make this maidencane marsh unsustainable.

3.4.2 Salinity

Salinity is an important determinant of salt marsh growth (Day *et al.* 1989). The lowering of salinity alone stimulated plant growth of saltmeadow cordgrass (DeLaune *et al.* 2005). Twilley and Nyman (2002) suggested that fresh water alone is not the only mechanism that will enhance vegetated growth in the Caernarvon Outfall Area. Salinity reduction alone, even in the absence of sediments, did not promote biomass production (Twilley and Nyman 2002). Increased salinity did not repress aboveground biomass to any significant extent (Figure 3-14, Twilley and Nyman 2002). However, belowground biomass decreased with increasing salinity (Figure 3-15; Twilley and Nyman 2002). The effects of salinity on root biomass production nullified the stimulated growth observed at higher sediment additions in the low salinity treatment. Under low salinity, sediment additions significantly increased total biomass production, both above and below ground (Figure 3-15; Twilley and Nyman 2002). Shoot biomass decreased even more substantially with salinity, as shown by an increase in root:shoot ratios (Figure 3-16; Twilley and Nyman 2002).

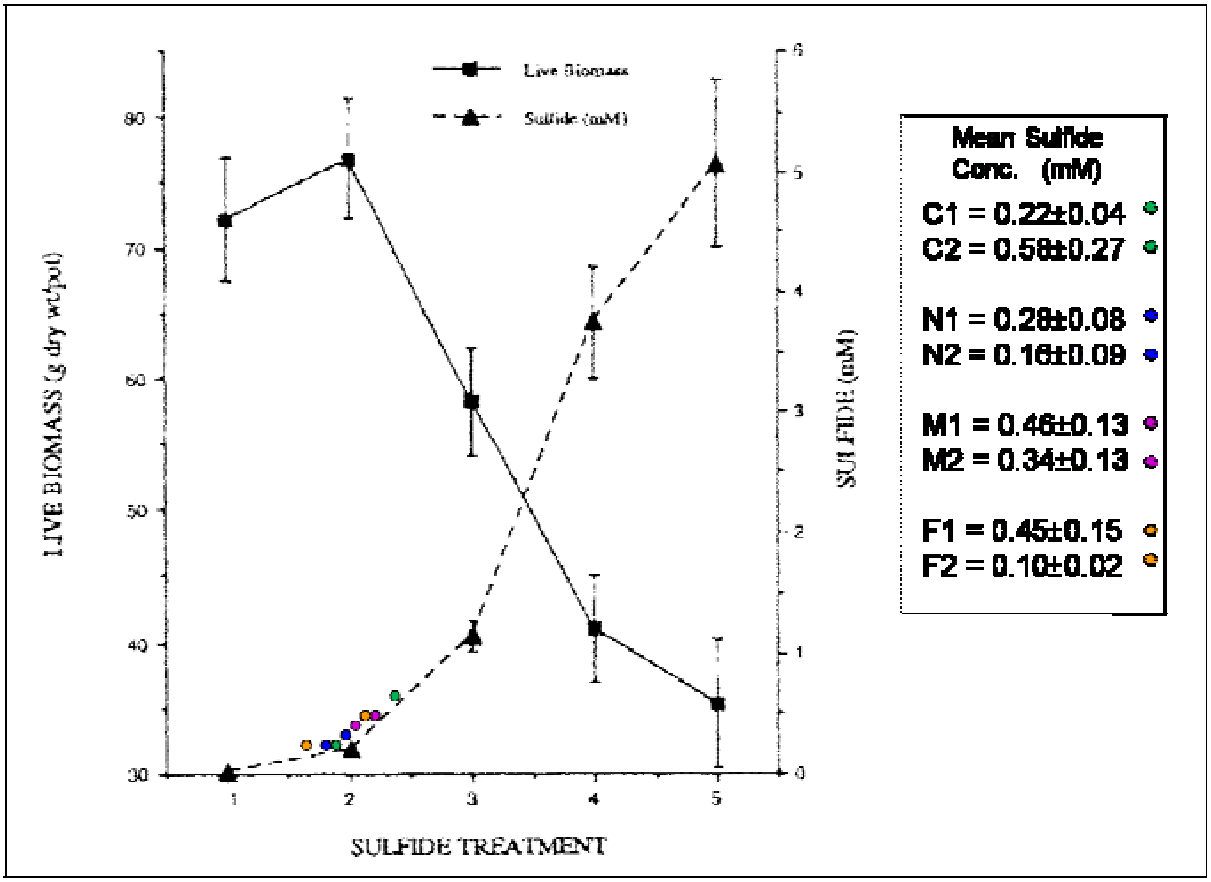


Figure 3-14. The growth response (biomass production) of smooth cordgrass to varying sulfide concentrations (Modified from Mendelssohn and Morris (2000) as cited by Moerschbaecher 2008)

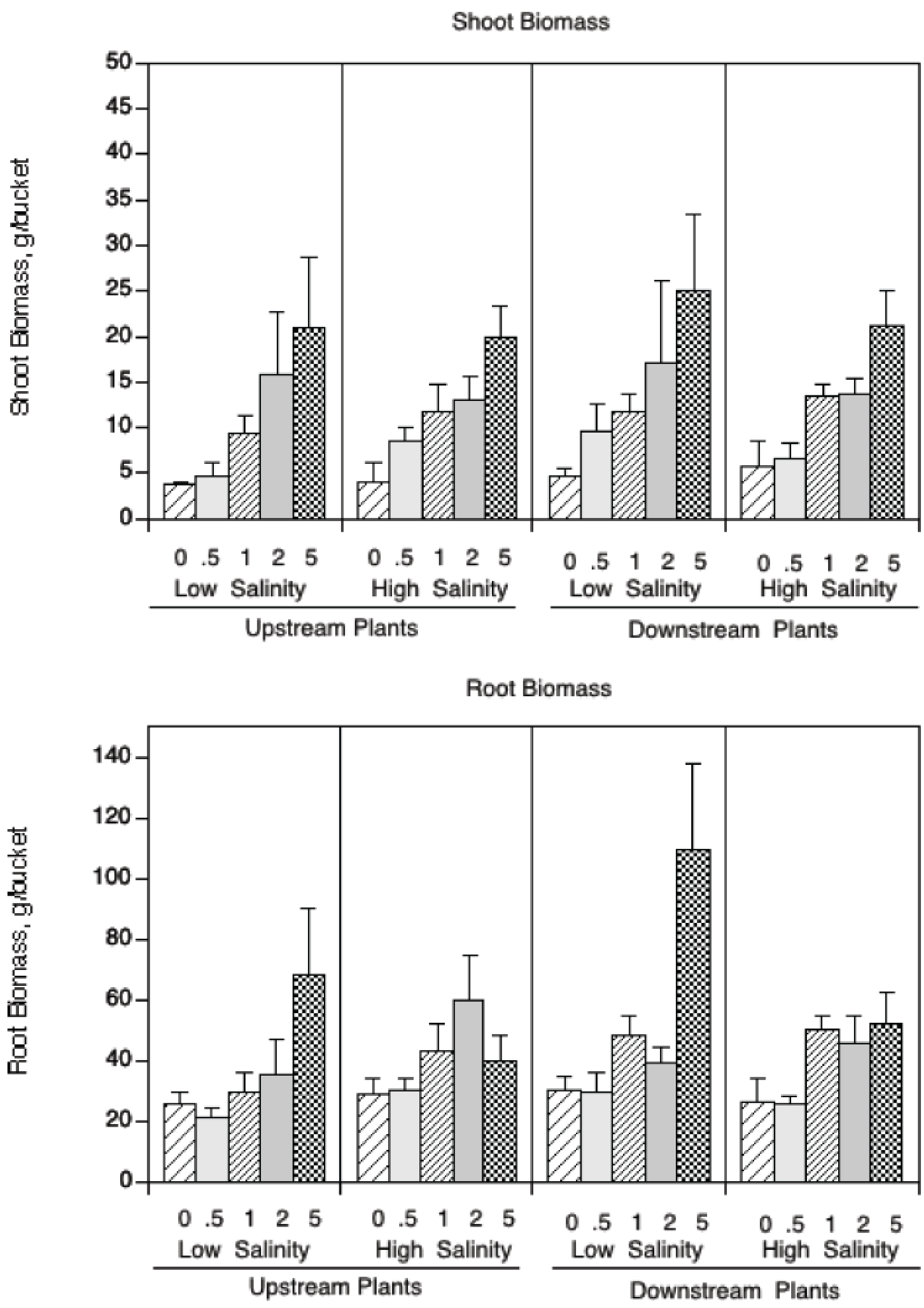


Figure 3-15. Shoot biomass (upper panel) and root biomass (lower panel) ecotypes from upstream and downstream sites under different enrichments of sediment (in liters) at low and high salinity treatments (from Twilley and Nyman 2002)

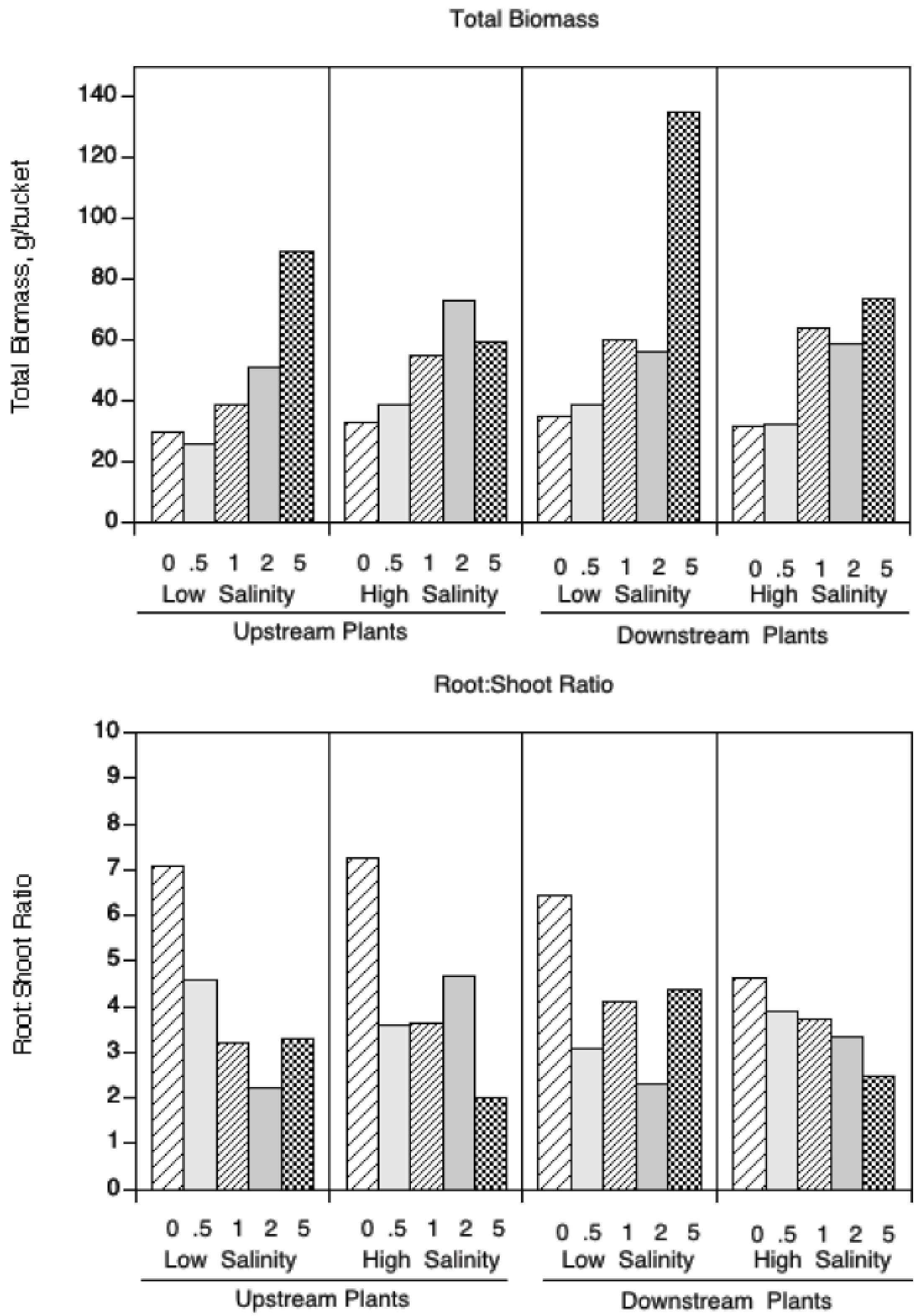


Figure 3-16. Total biomass (upper panel) and root:shoot ratio (lower panel) ecotypes from upstream and downstream sites under different enrichments of sediment (in liters) at low and high salinity treatments (from Twilley and Nyman 2002)

The reintroduction of Mississippi River water into saltmeadow cordgrass marshes of Breton Sound should enhance plant growth and improve marsh stability (DeLaune *et al.* 2005). Lowering salinity and increasing nutrient input will enhance nutrient uptake and biomass production of saltmeadow cordgrass according to greenhouse studies using soil–plant plugs extracted from a saltmeadow cordgrass marsh receiving diverted Mississippi River water (DeLaune 2002; DeLaune *et al.* 2005). Biomass production more than doubled in treatments receiving added nutrients (DeLaune 2002). However, there was an interaction between nutrients and salinity (DeLaune 2002; DeLaune *et al.* 2005). Although the fertilizer treatment had significantly greater plant biomass production at 0 ppt salinity than at 8ppt salinity, plant growth was higher in both fertilized treatments (0 and 8 ppt) than in the control (Figure 3-17; DeLaune 2002; DeLaune *et al.* 2005).

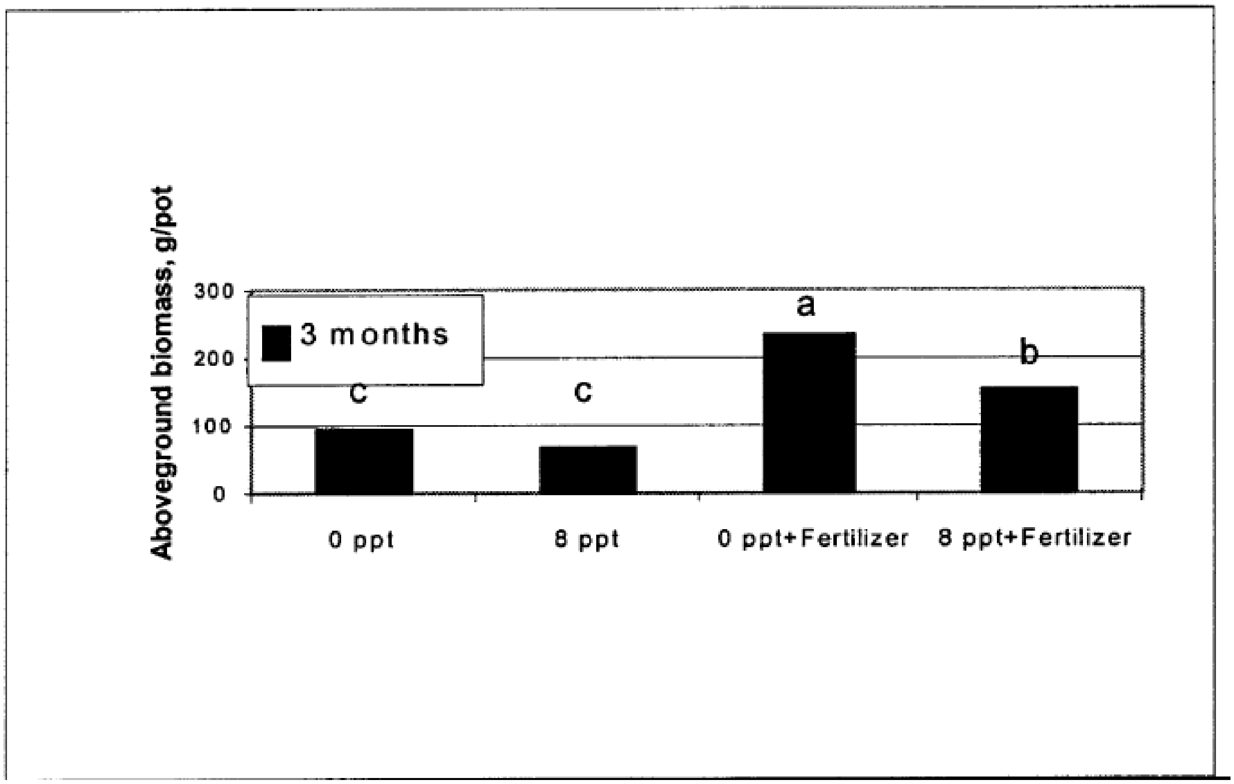


Figure 3-17. Effect of salinity level and nutrient addition on growth of saltmeadow cordgrass (from DeLaune *et al.* 2005)

3.4.3 Sediment

Sediment addition has been shown to increase plant growth. Sediment increased above-ground biomass and density of smooth cordgrass shoots when dredged material was added to salt marsh plots (DeLaune *et al.* 1990). Similarly, total vegetative cover, plant height, and plant biomass was higher at marshes that received dredged materials (Mendelssohn and Kuhn 2003).

Sediment addition may not have the same effect on floating marshes. Carpenter *et al.* (2007) and Carpenter (2005) examined effects of sediment treatments on freshwater thin-mat floating marsh sites (sites 1 and 2) dominated by Baldwin's spikerush *(Eleocharis baldwinii)*. Site 1 was located at Cypress Canal below Davis Pond and Site 2 was located at Turtle Bayou, in the northern Terrebonne Basin and is isolated from major flows from the Atchafalaya River. Aboveground biomass increased although not significantly, and belowground biomass was not significantly affected by the addition of sediment (Figure 3-18; Carpenter *et al.* 2007). Sediment treatments had no significant effect on belowground biomass (Figure 3-19; Carpenter *et al.* 2007).

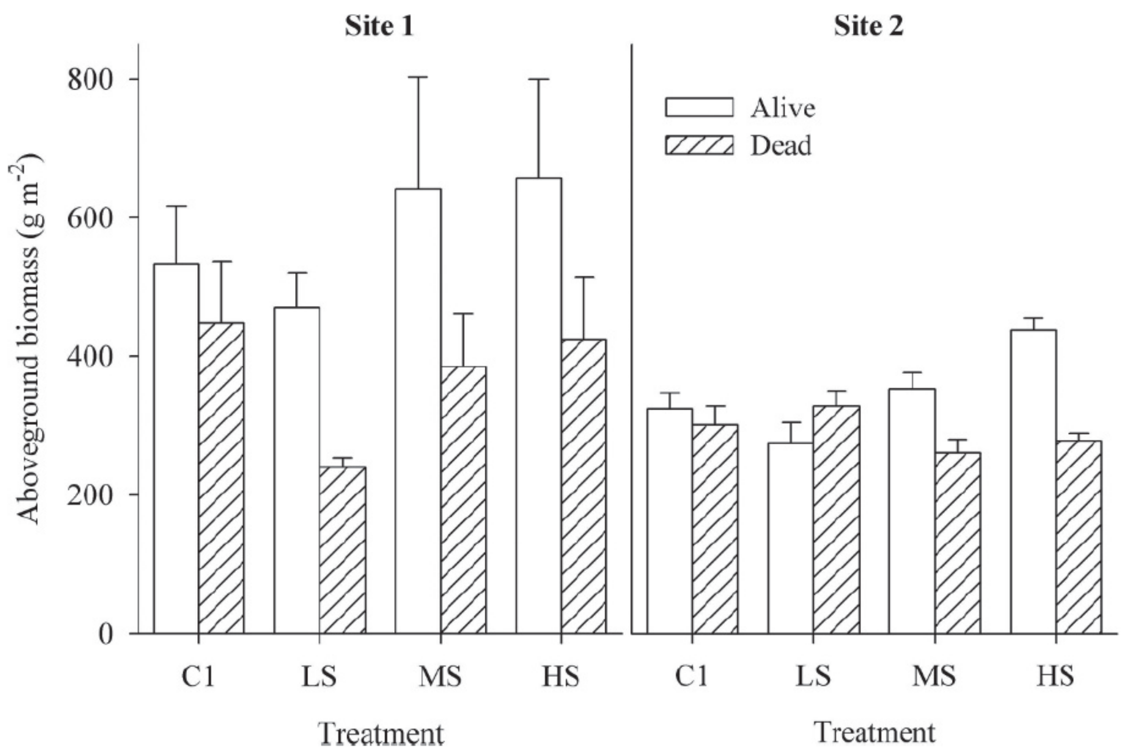


Figure 3-18. Site comparisons of live and dead aboveground biomass. Treatments were: control (C1), low sediment (LS), medium sediment (MS), and high sediment (HS) (from Carpenter *et al.* 2007)

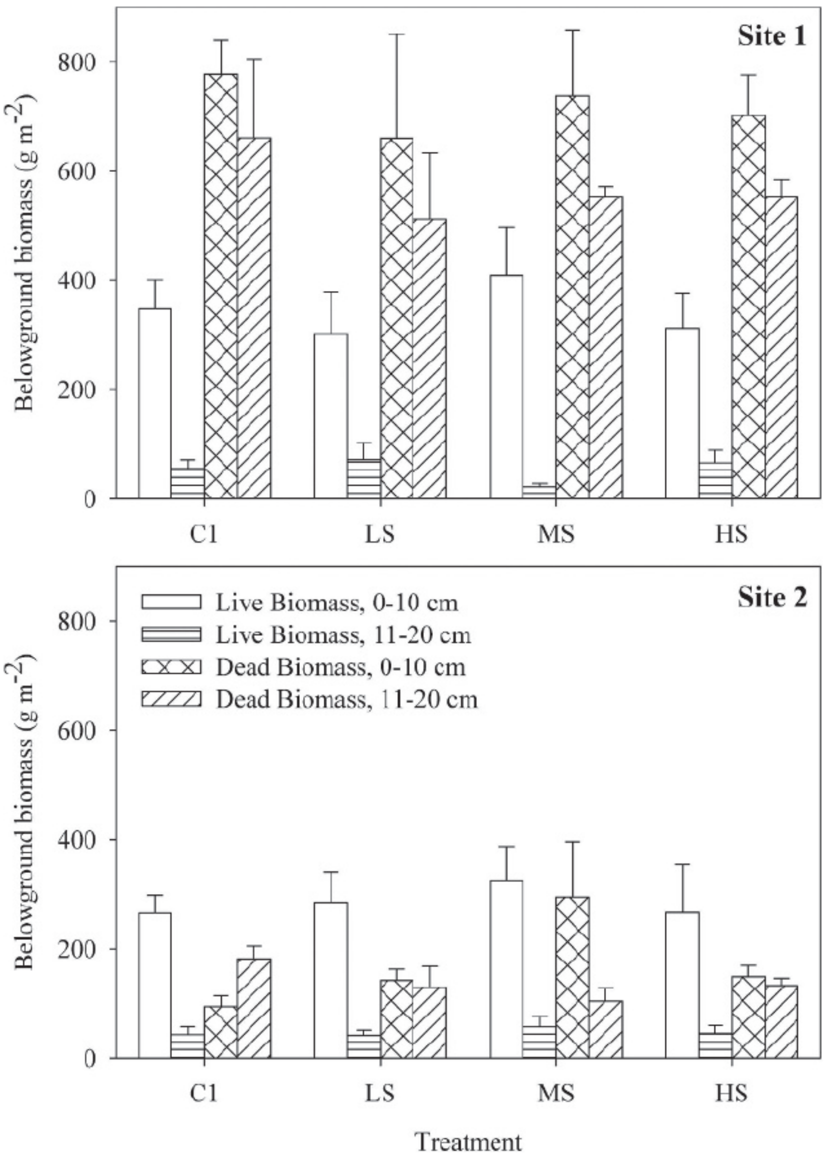


Figure 3-19. Live and dead belowground biomass as a function of site, treatment, and depth. Error bars represent one standard error. Treatments were: control (C1), low sediment (LS), medium sediment (MS), and high sediment (HS) (from Carpenter *et al.* 2007)

3.4.4 Soil Stability

Nutrient loading tends to increase soil metabolism and lower root and rhizome biomass; these responses can compromise soil strength (Turner 2010). Porewater and substrate quality of organic-rich maidencane freshwater marshes inundated by river water annually for more than 30 years had a more reduced soil environment, more decomposed organic substrate and accumulated more sulfur (Swarzenski *et al.* 2008). Marshes with more decomposed root mat are more susceptible to erosion during infrequent high energy events (such as hurricanes) and regular low-energy events, such as tides and the passage of weather fronts (Swarzenski *et al.* 2008).

Sediment input may be needed, along with freshwater and nutrients, to build a resilient marsh. During the 2005 hurricane season, the storm surge and wave field associated with Hurricanes Katrina and Rita eroded 527 km^2 of wetlands within the entire Louisiana coastal plain, including the Caernarvon and Wax Lake Delta areas (Howes *et al.* 2010). Low salinity wetlands (more organic) were eroded more than higher salinity wetlands (more mineral). A weak zone (shear strength 500–1450 Pa) was observed ~30 cm below the marsh surface in low salinity wetlands, coinciding with the base of rooting. High salinity wetlands had no such zone (shear strengths > 4,500 Pa) and contained deeper rooting (Howes *et al.* 2010). Storm waves during Hurricane Katrina produced shear stresses between 425–3,600 Pa, sufficient to cause widespread erosion of the low salinity wetlands. Vegetation in low salinity marshes is subject to shallower rooting and is susceptible to erosion during large magnitude storms (Howes *et al.* 2010).

Widespread increases in nutrient loadings may alter marsh ecosystem functions and compromise the long–term stability of coastal marshes by increasing belowground organic matter decomposition rates and reducing root production, resulting in a net decline in soil strength, making marshes more susceptible to hurricanes (Turner 2010). However, the lack of sediment may reduce plant productivity and the contribution of organic matter to soil formation (Twilley and Nyman 2002). Ground and aerial surveys of low salinity wetlands in Breton Sound following Hurricane Katrina revealed extensive deposits of *marshballs*, uprooted masses of marsh grass consisting of a rooting mat and bound sediment. Similar observations have been made elsewhere. Marshballs typically had a rooting depth of 20–30 cm and were neutrally buoyant. Devegetated peat surfaces in the nearby marsh surface marked the source regions of the rafted marshballs. Erosion occurred by scouring of the marsh surface, including the root mat, rather than by sediment resuspension as has been studied elsewhere (Howes *et al.* 2010). Marsh areas of a mile or more long were compressed like an accordion in upper Breton Sound basin during Hurricane Katrina (Barras and Johnston 2006). In contrast to the low salinity regions, the saline portions of the marsh were left largely intact (Howes *et al.* 2010).

Storm-induced tidal stress and lack of sediment events can decrease plant productivity and create a negative feedback loop (Nyman *et al.* 1993). Marshes that receive fresh water and mineral sediment (active marsh) contains twice as much mineral and organic matter than marshes that only receive reworked sediments and rainfall (inactive marsh). Active marsh had the highest accretion rates in the active delta zone (Nyman *et al.* 1990). Aboveground and belowground biomass production was higher and decomposition was slower at non-saline marsh sites where subsidence simulates sea level rise than at the less saline site. Lower vertical accretion occurs from this reduction in biomass; this will lead to conversion to open water in the next few decades (Nyman *et al.* 1995). Vegetative growth stimulated through flooding is more likely than sedimentation to be primary cause of adequate accretion (Nyman *et al.* 2006; CPRA 2010a).

3.4.5 Vegetative Biomass

Marsh productivity depends on the ability of the species present to deal with salt stress and flooding. For example, saltmeadow cordgrass production is more negatively affected by increased flooding depth than by changes in salinity below 6 psu. In contrast, maidencane productivity is stimulated by a certain degree of increased flooding. Increased salinity and flooding interact to affect the production of particular plant species. Individual plant species adapt differently to salt stress and flooding. Increased salinity and flooding cause dieback of bulltongue arrowhead, an oligohaline (<5 psu) marsh species. When flooding was reduced in the presence of increased salinity, plant dieback did not occur (Moerschbaecher 2008).

Fresh water has a positive effect on increasing growth of marsh plants and increasing biomass production in the sites nearest to freshwater input (DeLaune 2002). Added nutrients may stimulate marsh productivity (Day *et al.* 2003). High levels of biomass, particularly belowground, were found in the marshes of the upper Breton Sound basin affected by the Caernarvon diversion project (Moerschbaecher 2008). Biomass at all sites generally tended to be highest during the growing season (May to November) and lowest in the winter. Longer growing seasons combined with milder winter growing conditions in Louisiana contribute to less seasonality in above and belowground plant biomass peaks (Good *et al.* 1982; Moerschbaecher 2008). End of season peak live (EOSL) biomass was highly variable, but the highest values (2,000 g m^{-2}) were found within 20 km of the Caernarvon Diversion structure. Beyond 40 km from the diversion, values were lower than 2,000 g m^{-2} (Day *et al.* 2009). However, biomass did not decrease away from the diversion due to differences in the frequency and duration of flooding, or with the variability in species composition at the study sites (Figure 3-20; Moerschbaecher 2008).

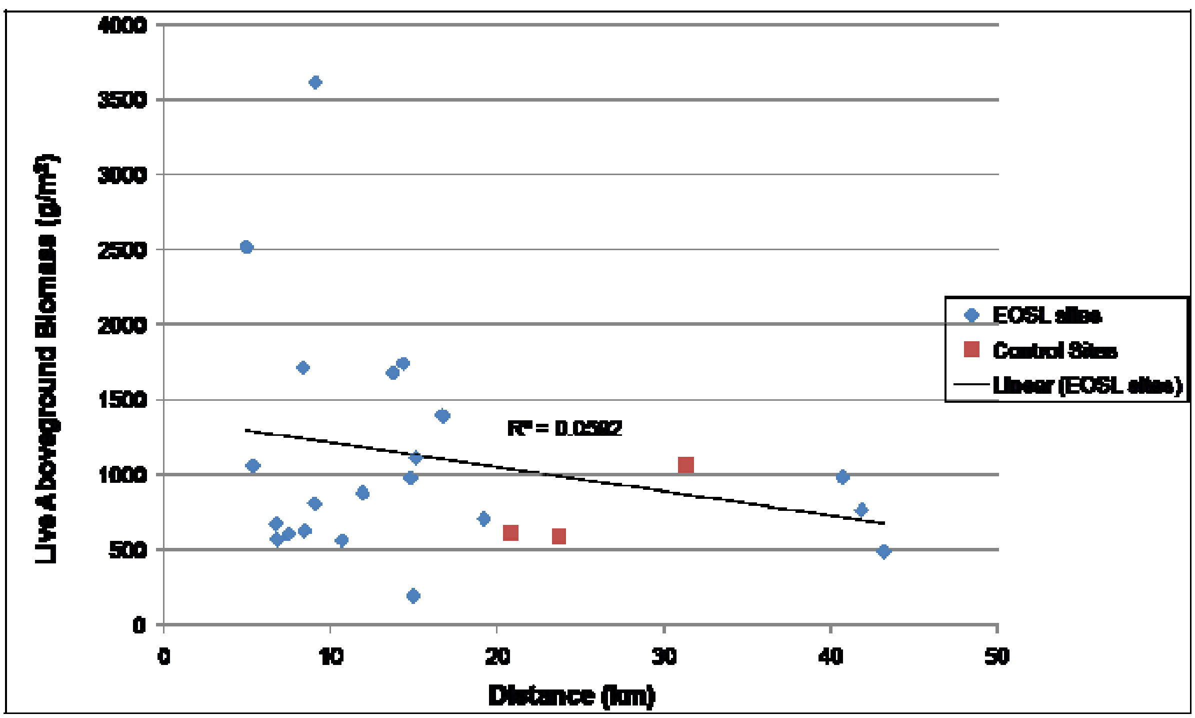


Figure 3-20. EOSL site live aboveground biomass in relation to distance from Caernarvon (from Moerschbaecher 2008)

3.4.5.1 Aboveground Biomass

Average aboveground biomass production was greater at sites near Caernarvon compared to sites in the lower basin. Aboveground biomass patterns were more variable according to growing season than belowground biomass (Moerschbaecher 2008). Biomass was generally higher during the growing season. Low growth rates as a result of cooler temperatures result in decreased aboveground biomass in winter (Figure 3-21). In contrast, nutrient rich river water from the Lower Atchafalaya River did not enhance end-of-year aboveground standing biomass in maidencane freshwater marshes compared to marshes unaffected by the diversion (Swarzenski *et al.* 2008).

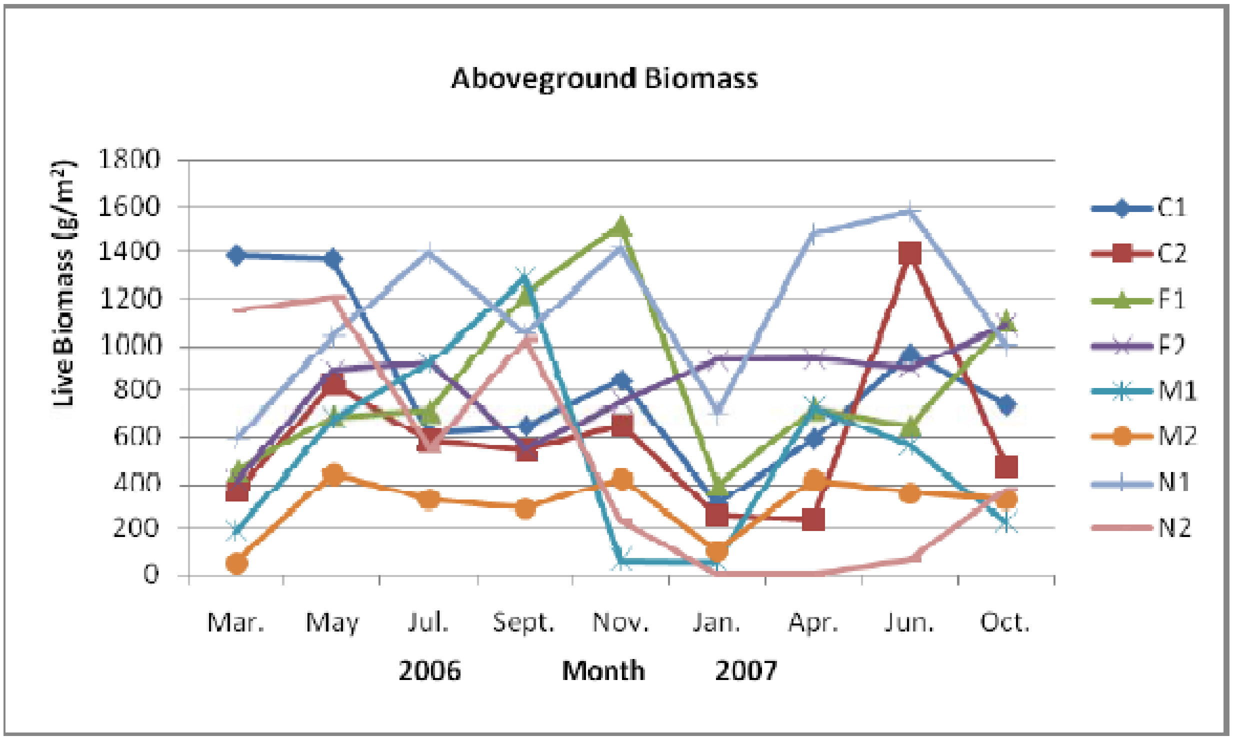


Figure 3-21. Mean aboveground biomass at eight study sites during March 2006 – Sept. 2007 (from Moerschbaecher 2008)

3.4.5.2 Belowground Biomass

Salt marshes are physiologically dry environments assumed to have high below ground biomass (Twilley and Nyman 2002). Belowground biomass may be inversely related to nutrient loading. Root and rhizome biomass declined with increased nutrient loading in many wetland areas (Holm 2006; Darby and Turner 2008; Langley *et al.* 2009). The constant inundation of subsiding marshes stresses the vegetation and eventually leads to vegetative death (aboveground biomass) followed rapidly by elevation loss due to the decomposition of root biomass (belowground biomass). The patterns of above and belowground biomass are a result of a combination of factors such as sediment availability, salinity variations, and nutrient fluctuations that affect marsh growth (Moerschbaecher 2008). The aboveground portion creates organic matter during photosynthesis and the belowground portion stabilizes the marsh soil. (Twilley and Nyman 2002). The root (belowground) to shoot (aboveground) ratio is the relative biomass of each compartment. High root:shoot ratios (>1) are indicative of unfavorable soil conditions and are evidence of excessive flooding. Sediment enrichment decreased root:shoot ratios; root:shoot ratios were highest without sediment enrichment (Twilley and Nyman 2002). Marsh plants in greenhouse studies appear to put more energy into root production under unfavorable soil conditions; unfavorable soil conditions may require more root surface to service each unit of above-ground biomass (Good *et al.* 1982).

In marshes affected by the Caernarvon diversion, biomass typically occurs in the upper 30 cm of the soil column, and the greatest amount of belowground biomass production generally occurs at the 0–20 cm depth range (Moerschbaecher 2008). Below ground biomass productions in the upper basin and in the lower basin were essentially the same with a slightly greater amount at the upper station nearest freshwater input (DeLaune 2002).

Belowground biomass peaked during April 2007 at all sites except the mid sites which peaked in June 2007 (Figure 3-22; Moerschbaecher 2008). The variation in belowground biomass throughout the year indicates that increased production begins during the winter months, peaks in the spring, and declines until the next winter (Moerschbaecher 2008). Similar trends in the growth patterns of belowground biomass, but with greater seasonality than Moerschbaecher found in 2008 were observed (Darby 2006). Apart from seasonality, it was found that there was a net increase in belowground biomass at all study sites from March 2006 to October 2007 (Moerschbaecher 2008). Day *et al.* (2009) also reported high belowground biomass in marshes affected by the Caernarvon diversion. The overall net increase in belowground growth at each site may be evidence of marsh recovery and increased marsh stability (Moerschbaecher 2008).

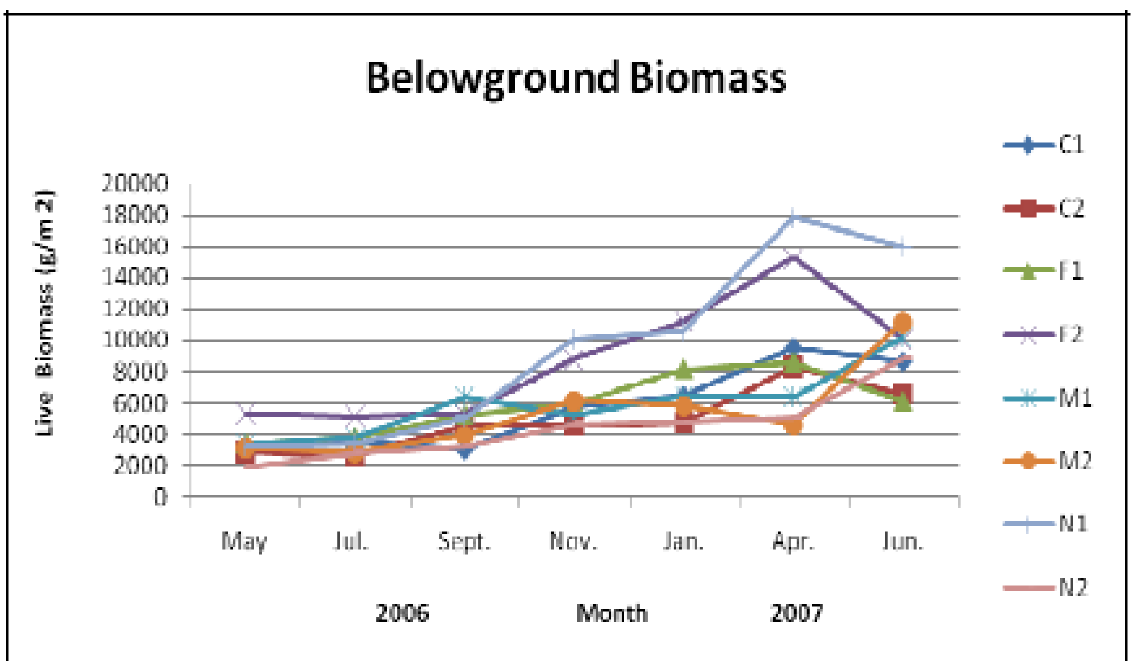


Figure 3-22. Mean belowground biomass at the eight study sites during May 2006-June 2007 (from Moerschbaecher 2008)

Variations in additional nutrient input levels did not appear to affect belowground biomass production (Moerschbaecher 2008). Below ground biomass production was reduced when nutrients, ranging from 80 to 900 g $N/m^2/yr$, were added to salt marsh plots (Darby and Turner 2008). Total nitrogen loading to upper Breton Sound is from 1.9 to 3.2 g $N/m^2/yr$ (Hyfield *et al.* 2008, Moerschbaecher 2008). Most other marsh fertilization studies and natural loadings are less than 200 g $N/m^2/yr$.

3.5 Lessons Learned

- Vegetation habitat in the Breton Sound Basin changed from 1978 to 2000 due to the operations of Caernarvon. Freshwater marsh was not observed in 1978; however, in 2000, 628 acres were documented. Since 1978, brackish and saline marsh decreased, and intermediate marsh increased by 10,582 acres.

- For Delta Wide Crevasses, lower plant diversity is observed in the late stages of succession as the most stable competitive species begin to dominate. Primary succession can be observed by combining the elevation and vegetation data; new plant growth follows land creation. In 1999, a non-diverse group of pioneer plants were observed. Post-construction of the crevasses (2002), a more diverse community of competitive species became dominant.

- Plant succession is dynamic at the Atchafalaya Delta and can be divided into three categories. Some species have increased over time and converged on certain elevational zones. Other species are relatively stable over time with elevational shifts attributable to local erosion or accretion. Some species are present over a wide range initially, eventually disappearing at low elevations.

- Freshwater releases through the Caernarvon Diversion and Davis Pond have increased the amount of submerged aquatic vegetation coverage.

- The phytoplankton community of the Breton Sound estuary appears to be moderated by temperature during high river input and nutrient availability during low river input. Cyanobacteria were highest during summer and fall when temperatures were high and flushing was low.

- Increased phytoplankton growth has been noted after Bonnet Carré Spillway openings. Phytoplankton composition changes after the 2008 Spillway opening were similar to those of the 1997 opening. Blue-green algae dominated the phytoplankton community in 2008, but were less severe than in 1997, when a large blue-green algae bloom resulted in lake-wide recreation health advisories.

- Ammonium concentrations were highest at sites near Caernarvon during months of high flow; however, concentrations at the far site were less variable. A spatial pattern was also observed within basins and within core samples. Porewater concentrations of ammonium increased with depth and ammonium concentrations were greater at the upstream and transition sites compared to the downstream site.

- Concentrations of phosphate (PO_4) during late spring and early summer were typically higher towards Caernarvon and at the marine end of the estuary. Total phosphorus was also higher during high discharge periods. Distinct zones of high phosphate concentrations were evident during high discharge periods in the winter.

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- Freshwater from Caernarvon may help to maintain low sulfide concentrations. Increased frequency and volume of riverine discharge could potentially decrease sulfide levels. Sulfide concentration was significantly correlated to belowground biomass. Sulfide concentrations during the growing season appeared to be correlated to lower biomass at the sites least affected by the diversion. Introductions of river water may be successful at decreasing chloride concentrations and increasing habitat space for organic rich, freshwater marshes.

- Average aboveground biomass production was greater at sites near Caernarvon compared to sites in the lower basin.

- In marshes affected by the Caernarvon diversion, biomass typically occurs in the upper 30 cm of the soil column, and the greatest amount of belowground biomass production generally occurs at the 0–20 cm depth range. Belowground biomass productions in the upper and lower basins were essentially the same with a slightly greater amount at the upper station nearest freshwater input.

3.6 Recommendations from the Literature

Recommendations from the literature follow:

- The variability in marsh elevation and local hydrology are significant factors effecting productivity which should be accounted for in future studies (Moerschbaecher *et al.* 2008).

- Ideally, efforts to mitigate coastal wetland loss should include measures that assure that adequate mineral sediment is supplied to salt marsh. Where this is not possible, increasing the freshwater supply (such as Mississippi River freshwater diversions) will reduce wetland loss where salinity increases, and elevated sulfide causes plant mortality, and the soil bulk density is too low to support growth of saline marsh plant species (DeLaune *et al.* 2001).

- Currently structural, hydrological, and even human constraints determine the placement of controlled river diversions along the Mississippi River. Soil type and the organic matter that gives the marsh soil its structure and resilience to perturbations have not been considered and should be (Swarzenski *et al.* 2008).

- Operating the diversion consistently in response to saltwater intrusion events may help to maintain marsh species composition along the estuarine gradient while increasing species survival and rates of production (Moerschbaecher 2008).

- Swarzenski *et al.* (2008) suggested that chronic riverine input led to deterioration of soils in highly organic freshwater marshes. This should be monitored in current and future diversions (Day *et al.* 2009).

- Whatever benefit results from increases in the inorganic sediment supply should be weighed against the impact of also adding nutrients that weaken the soils (Turner 2010).

- Greater flushing of parts of the estuary would be beneficial by reducing the potential for algal blooms. Diverting river water on higher river stages, and when southerly winds are present, may increase flushing and reduce phytoplankton abundance (Day *et al.* 2009).

- Implications for phytoplankton management include avoiding higher diversion discharges under high light and high temperature regimes, carrying out diversions in the winter and spring, and changing hydrology to reduce residence time (Day *et al.* 2009).

- The diversion can be managed to achieve a number of desired objectives including: (1) increasing the potential for nutrient uptake via plant growth and denitrification, (2) increased over marsh flow to enhance sediment capture efficiency, marsh productivity, and organic soil formation, and (3) decreased residence time. A decrease in residence time would be especially beneficial during late spring/early summer when phytoplankton blooms may occur. Thus it is possible that the diversion could be managed to minimize the potential for algal blooms (Hyfield *et al.* 2008).

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4.0 WILDLIFE

Changes in water quality, vegetation, and habitat caused by freshwater diversions can affect wildlife. Freshwater, intermediate, and low-salinity brackish marshes provide habitat and food for many wildlife species such as alligator, muskrat, nutria, wading birds, waterfowl and other wildlife species. Increased plant diversity and submerged aquatic vegetation have been observed in the outfall of freshwater diversions (LNDR 2003, 2005, 2006; OCPR 2010a, 2010b; USACE-LDWF 1998; and Villarubia 1999).

Evaluating the effects of freshwater diversions on wildlife populations can be complex. Other factors that control populations are independent of the diversion, including hunting, trapping and fur prices, predation, disease, food and habitat in other areas for migratory species, etc. The discharge and timing of the diversion must be accounted for as well. This section is divided into four subsections: alligator, muskrat, nutria, and birds.

4.1 Alligator

4.1.1 Caernarvon

Alligator population increases are associated with Caernarvon. However, the sampling designs and statistical evaluations appear to be insufficient to firmly conclude that freshwater diversions directly increase alligator populations. However, the data indicate that freshwater diversions likely improve alligator populations.

At Caernarvon, 36 alligator nests were observed pre-operation (1988-1990) and 54 nests post-operation (1991-1994) [from Geaghan 1995 as cited through Meffert and Good (1999); Figure 4-1]. However, these increases are unlikely solely attributable to Caernarvon, due to the absence of a control site (Meffert and Good 1999). The increasing trends were at least in part due to a return towards estuarine conditions more aptly suited for these wildlife resources.

Pre-operation nest density (acres per nest) did not significantly differ (P=0.1663) from post-operation density at Caernarvon (USACE-LDWF 1998). The highest pre-operation nest production was in 1998 (one nest per 298 acres); the highest post-operation density (one nest per 163 acres) was in 1993 (Figures 4-2 and 4-3). Annual variations of 25-50 percent are typical and variations in water level, salinity, and other environmental parameters can affect populations. LDWF increased the number of tags during the post-operation period and during the entire study period (1988-1995) the average size and size class frequency distribution of harvested alligators were consistent with statewide harvest statistics (USACE-LDWF 1998).

By 2002, alligator nests in the Caernarvon outfall area had increased by 243 percent (LDNR 2003). Between 2000 and 2003, alligator nests were documented for the first time in fresh marsh, and their numbers had significantly increased in intermediate marsh. Alligator nests had increased from 10 in 1990 to almost 100 by 2007 (CPRA 2010a; Figures 4-4 and 4-5).

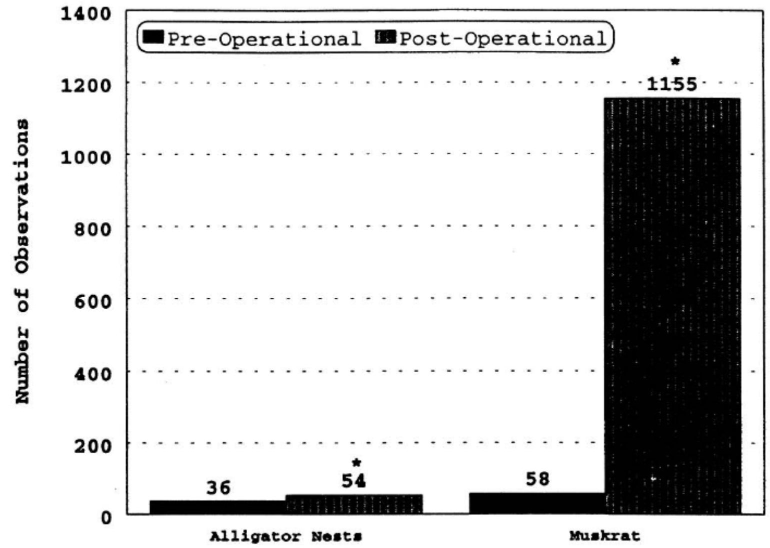

Figure 4-1. Observations of Alligator Nests and Muskrat at the Caernarvon Diversion Project Area (from Geaghan 1995 cited through Meffert and Good 1996)

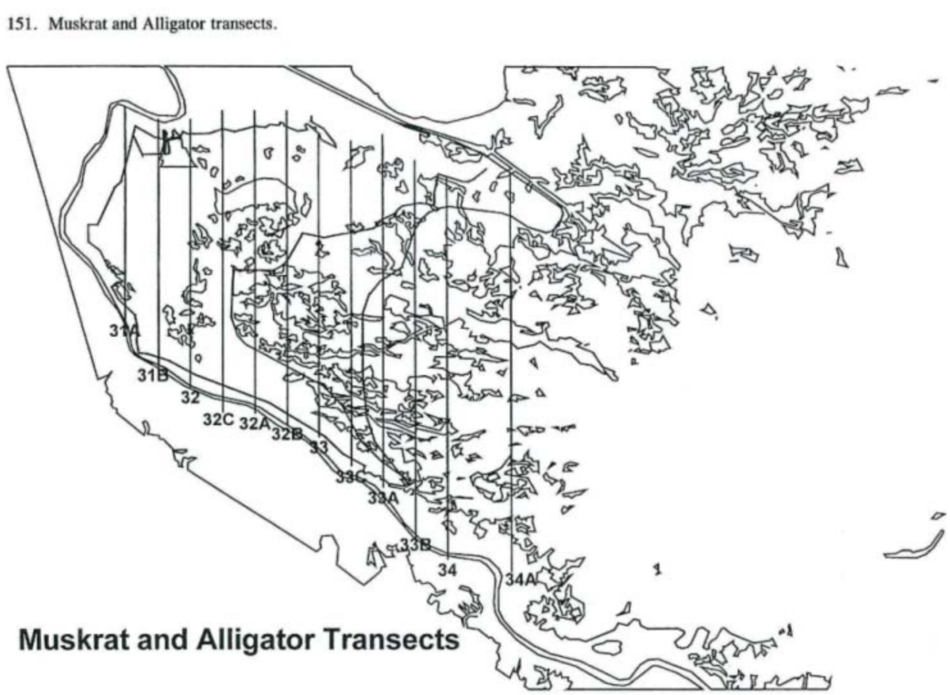

Figure 4-2. Muskrat and Alligator Transects for Caernarvon [from USACE-LDWF (1998)]

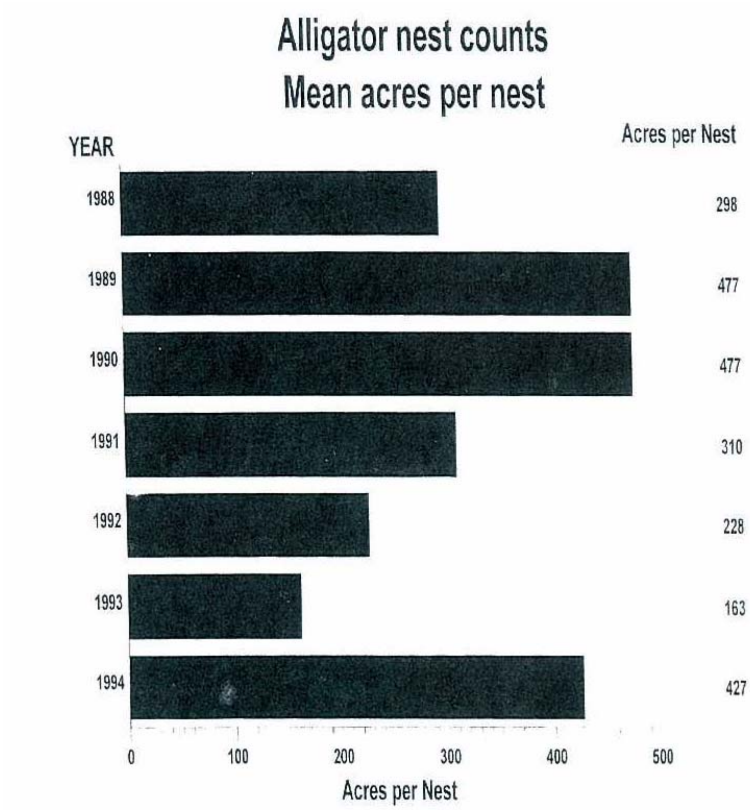

Figure 4-3. Alligator Nest Counts for Caernarvon [from USACE-LDWF (1998)]

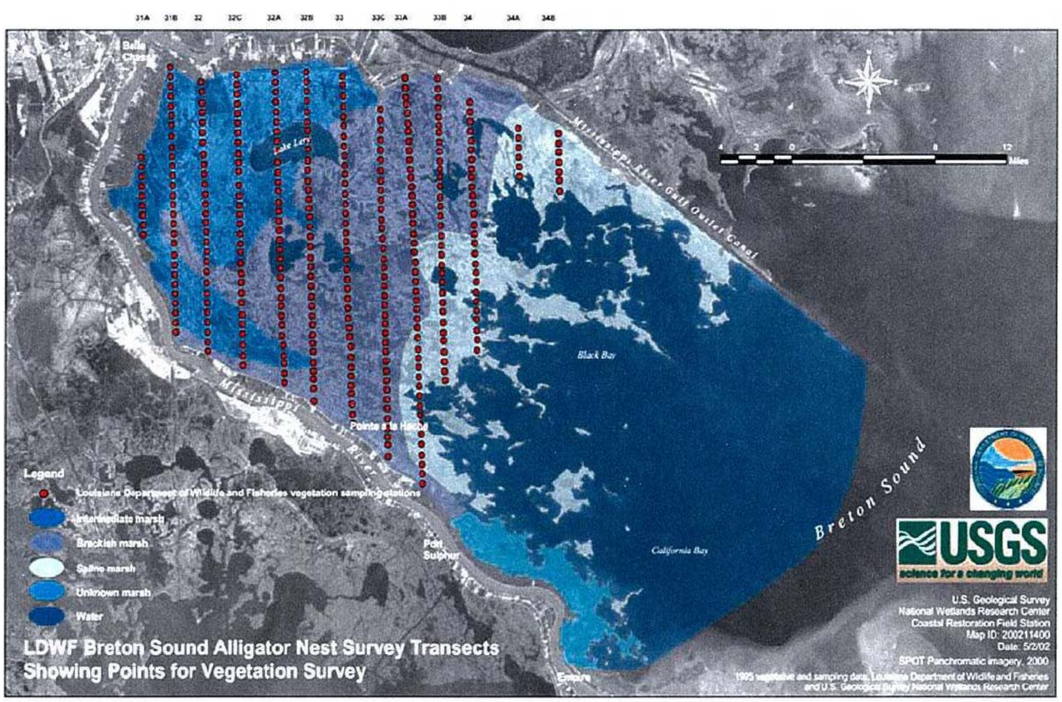

Figure 4-4. Location of Wildlife and Vegetation Transects at Caernarvon (USACE-LDWF 1998)

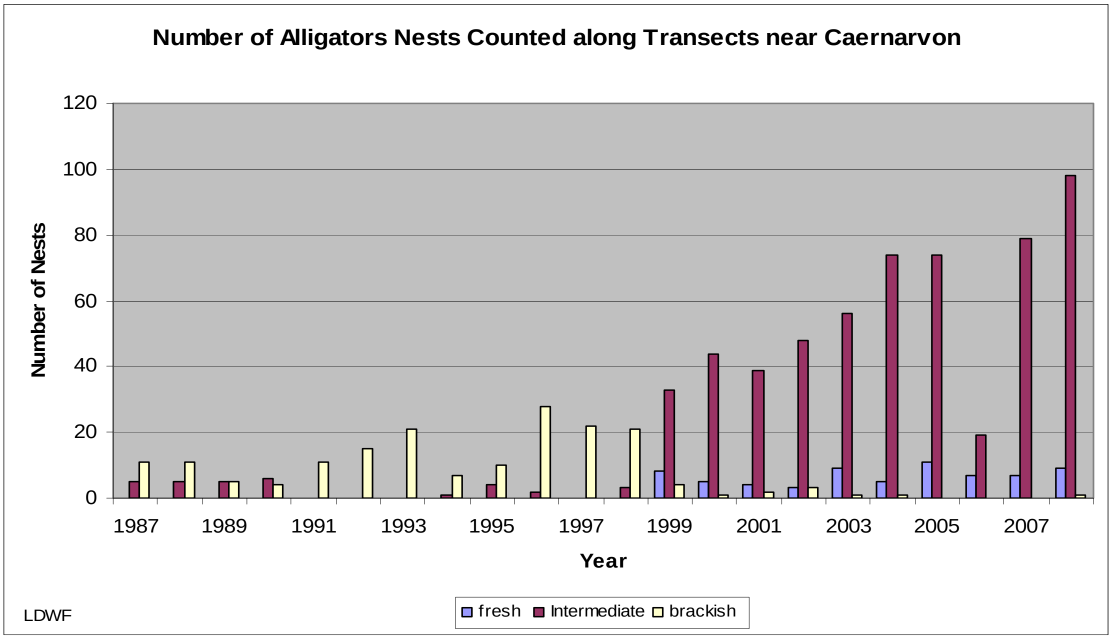

Figure 4-5. Number of Alligator Nests Counted Along Transects at Caernarvon (LDWF) (from CPRA 2010a)

Before 2000, alligator nests occurred mostly in brackish marsh (LDNR 2006). The occurrence of nests in intermediate marsh has increased in 1999 through 2005. Data collection began in 1987 and the first nest in freshwater was observed in 1999. This shift from brackish to more intermediate marsh is attributed to a shift in habitat and the fact that alligator nests are being found in more southerly areas. Landowners who participate in alligator and alligator egg harvests report an increase in the number of both harvests since the Caernarvon began operation.

4.1.2 Davis Pond

Alligator nests have increased 40 percent since Davis Pond began operation in 2005 (CPRA 2010b; Figure 4-6). Over 84 percent of the alligator nests were observed in fresh or intermediate marsh. The low counts in 2009 could be reflective of the 2008 hurricanes.

4.1.3 Atchafalaya Delta Wildlife Management Area

Alligator harvest has increased from 1987 to 2008 at the Atchafalaya Delta Wildlife Management Area (ADWMA) (Carloss and Warner-Finley 2009; Figure 4-7). Since alligator harvest is controlled by the number of tags issued by the Louisiana Department of Wildlife and Fisheries, this harvest increase was likely due to increased habitat, population, and an associated increase in tag issuance.

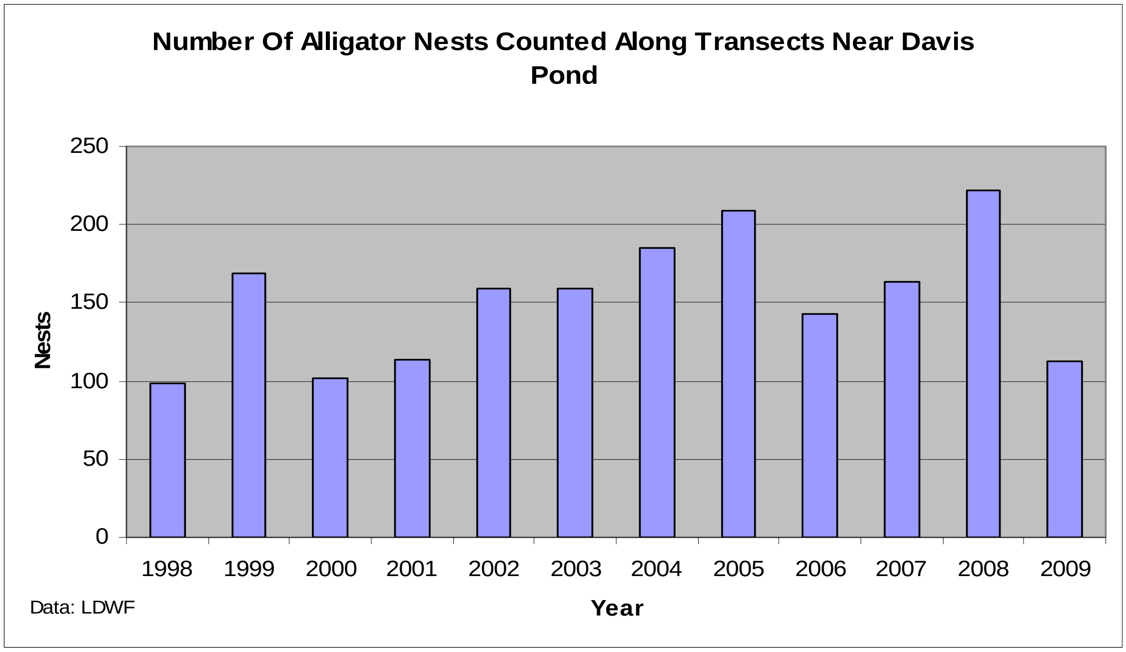

Figure 4-6. Number of Alligator Nests Counted Along Transects in Barataria Basin (from CPRA 2010b)

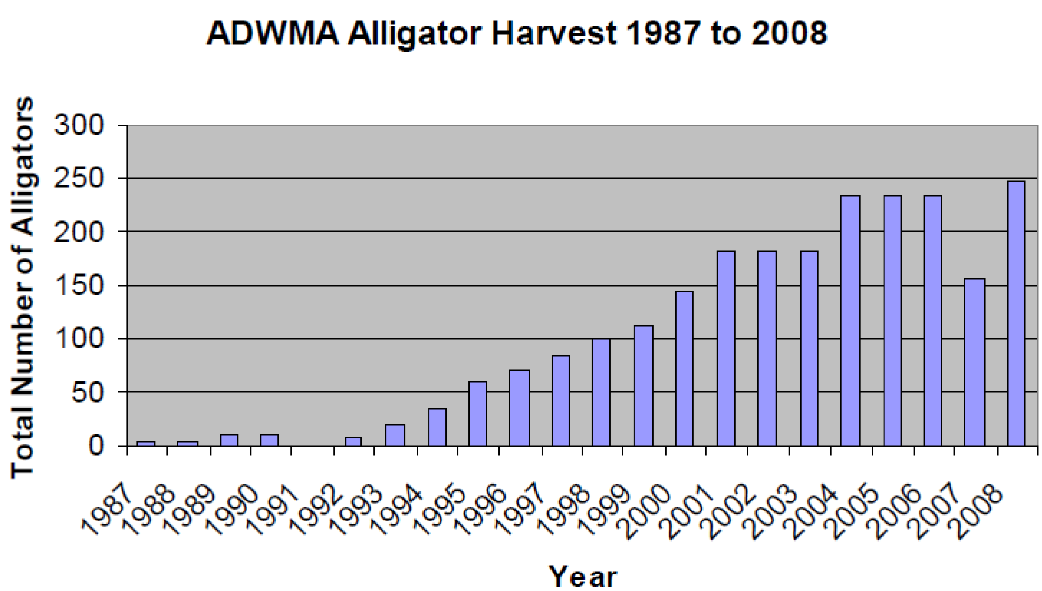

Figure 4-7. ADWMA Alligators Harvested (from Carloss and Warner-Findley 2009)

4.2 Muskrat

4.2.1 Caernarvon

Muskrats observed significantly increased ($P<0.05$) from 58 to 1,115 (Figure 4-1), from pre-operation (1988-1990) to post-operation (1991-1994) [Geaghan 1995 cited through Meffert and Good (1996)]. However, these increases are unlikely solely attributable to Caernarvon, due to the absence of a control site (Meffert and Good 1999). The increasing trends were at least in part due to a return towards estuarine conditions more aptly suited for these wildlife resources.

Muskrat populations increased significantly ($P=0.0007$) post-operation (USACE-LDWF 1998, Figures 4-8 and 4-9). Muskrat counts increased by almost 10 fold in 1991. In 1992, the populations again doubled. Populations decreased by 19 percent in 1993 and decreased an additional 29 percent in 1994. Chairmaker's bulrush *(Schoenoplectus americanus=Scirpus olneyi),* is the preferred food of salt marsh dwelling muskrats. This bulrush was only observed in a few sparse areas during the monitoring period and could be responsible for the decline of muskrat populations in the study area. Although muskrat populations increased dramatically post-operation, they remained low compared to other areas in Louisiana. Availability of preferred food sources and the cyclic nature of muskrat populations were determined to be the main factors involved in the increasing and/or decreasing muskrat populations (USACE-LDWF 1998).

4.2.2 1927 Flood

The great 1927 flood may have created new breeding habitat for muskrats due to the large freshwater input (Viosca 1927). After the flood of 1922, a severe drought occurred in 1924 and no muskrats were harvested on the coastal plain in 1924. The only muskrats harvested in Louisiana that year came from the break at the mouth of the Atchafalaya River and near the mouth of the Mississippi River where the crevasses had begun two years previously. During the 1927 flood, nearly 2,000 feet of levee was blown out and muskrat mortalities were high in the immediate area. A parallel was drawn between Louisiana and Maryland muskrat populations. In Maryland when an extreme southwest or southeast wind prevails for multiple days, extreme tides inundate the marsh and cause salt to settle in the marsh. This increase in marsh salinity is detrimental to the muskrat population. Muskrat populations in Louisiana utilize similar habitats. When freshwater is introduced to the marsh, new breeding grounds are created and utilized (Viosca 1927).

4.3 Nutria

4.3.1 Davis Pond

Yearly new marsh damage by herbivory decreased post-operation (CPRA 2010b; Figures 4-10 and 4-11). The total number of damaged acres in the Davis Pond area has been reduced to 38 acres. The LDWF Coastwide Nutria Control Program (CNCP) has removed almost 250,000 nutria from the Davis Pond project area and likely accounts for this decline in herbivory. The CNCP program began during the 2002-2003 winter season.

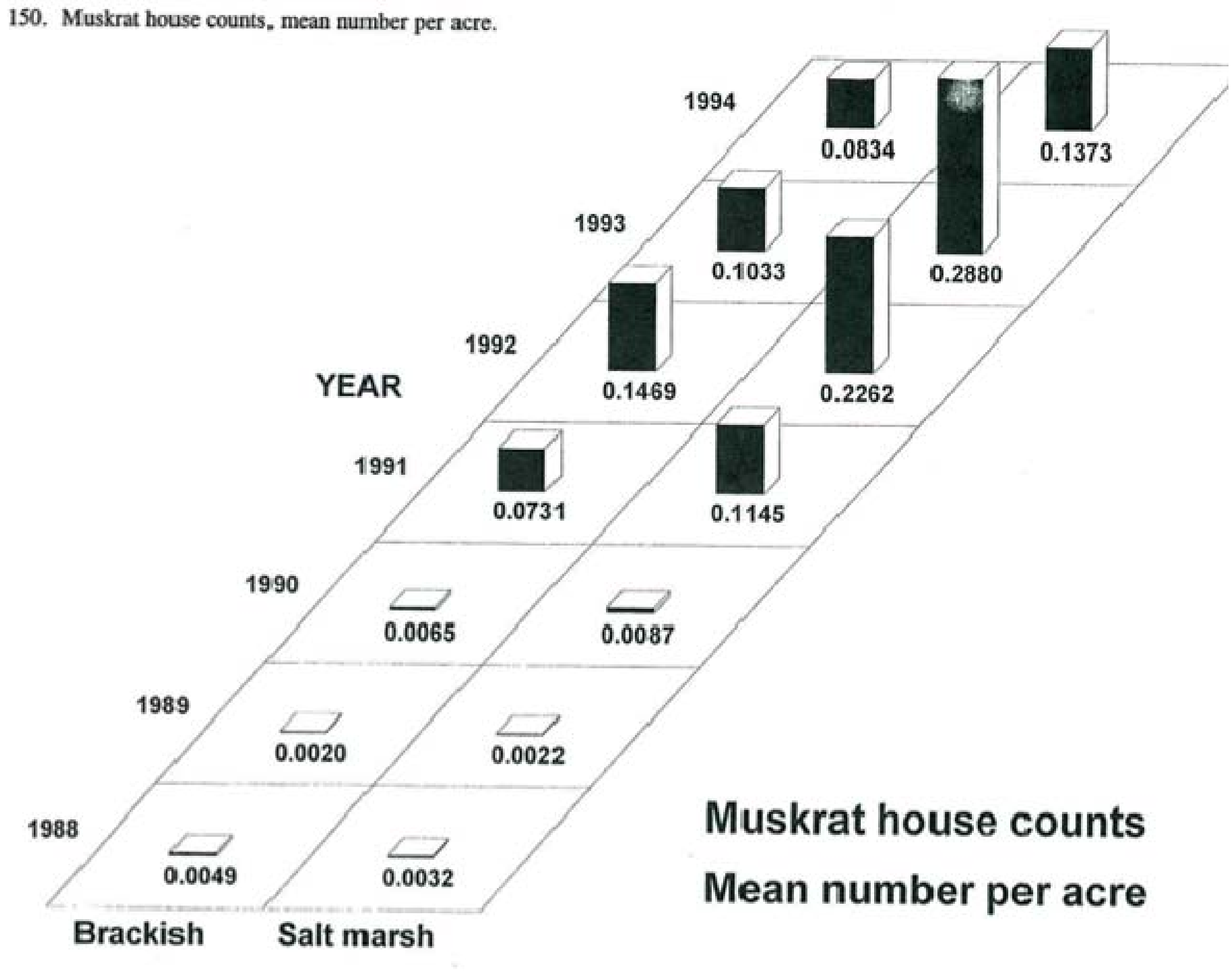

Figure 4-8. Muskrat House Counts, Mean Number per Acre (from USACE-LDWF 1998)

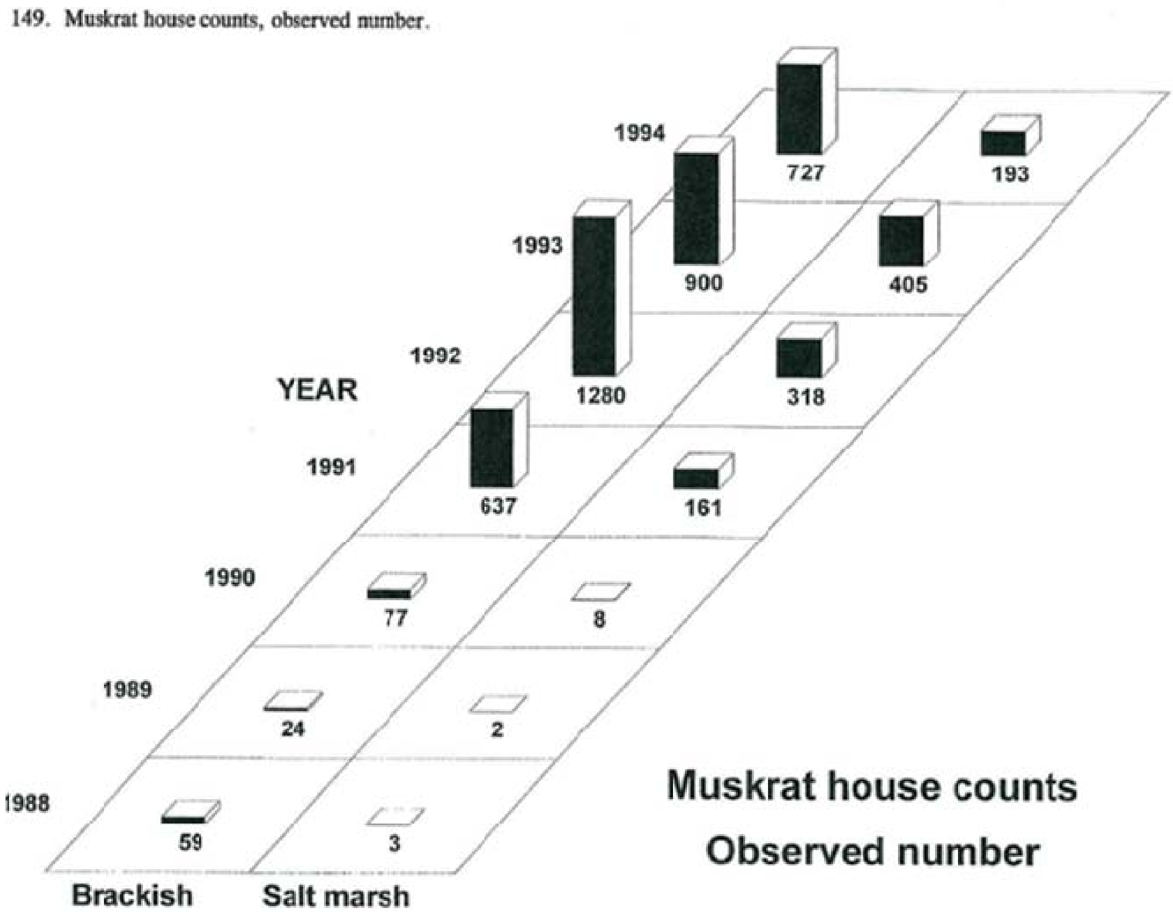

Figure 4-9. Muskrat House Counts, Observed Number for Caernarvon (from USACE-LDWF 1998)

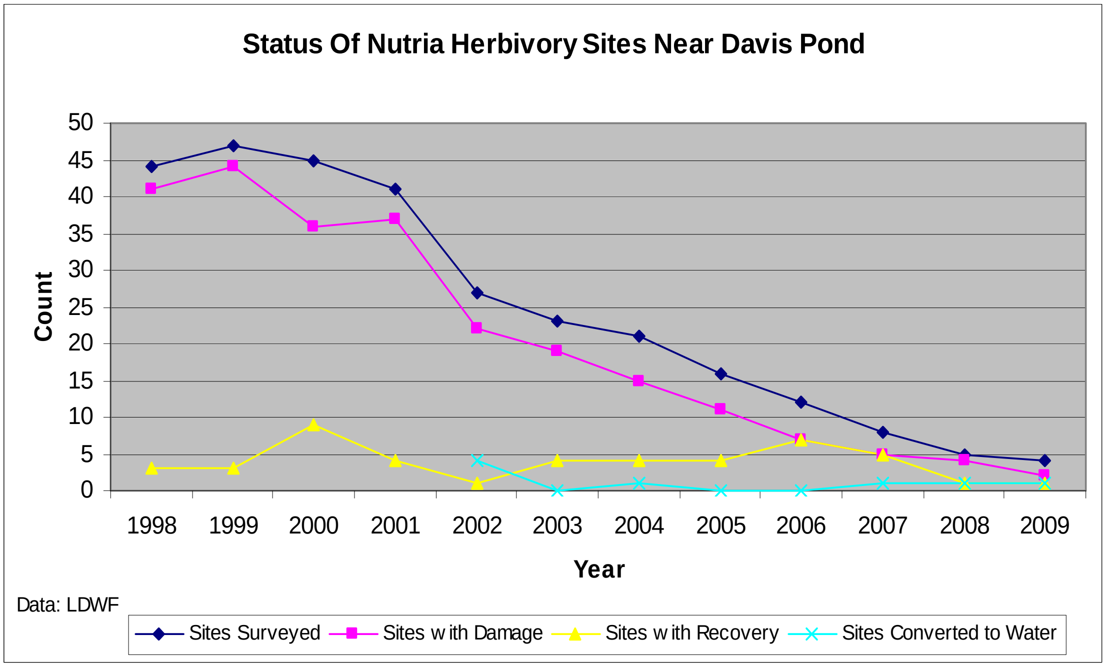

Figure 4-10. Status of nutria herbivory sites along transects in Barataria Basin (from CPRA 2010b)

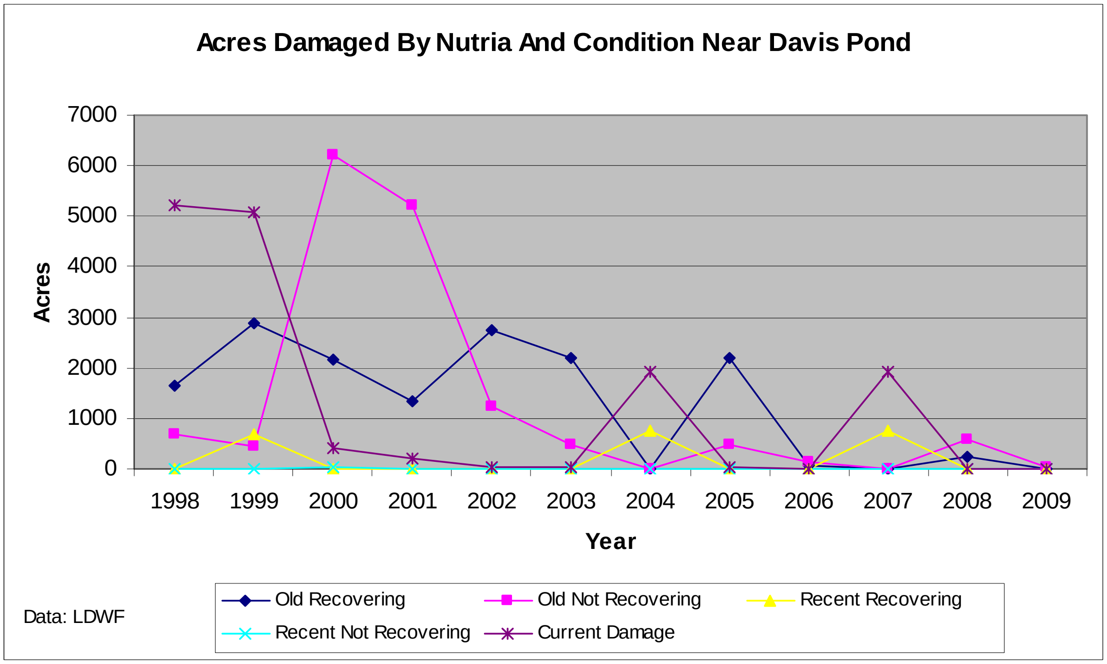

Figure 4-11. Acres Damaged by Nutria and Condition along Transects in Barataria Bay (from CPRA 2010b)

4.4 Birds

4.4.1 Caernarvon

Waterfowl populations near Caernarvon have increased post-operation (CPRA 2010a; Figures 4-12 and 4-13). The inter-annual variability of populations is high and ranges from 2,000 to 30,000 birds; therefore, it is difficult to attribute all this increase to Caernarvon. Approximately 77 percent of ducks observed pre-operation and 90 percent of the ducks observed post-operation were found in brackish and intermediate marsh (LDNR 2006). Waterfowl counts and populations are variable due to weather (both long-term and short-term), global population dynamics, hurricane damage to food sources, hunting pressure, hunting regulations, etc. Overall there seemed to be an increasing trend in waterfowl counts during post-operation.

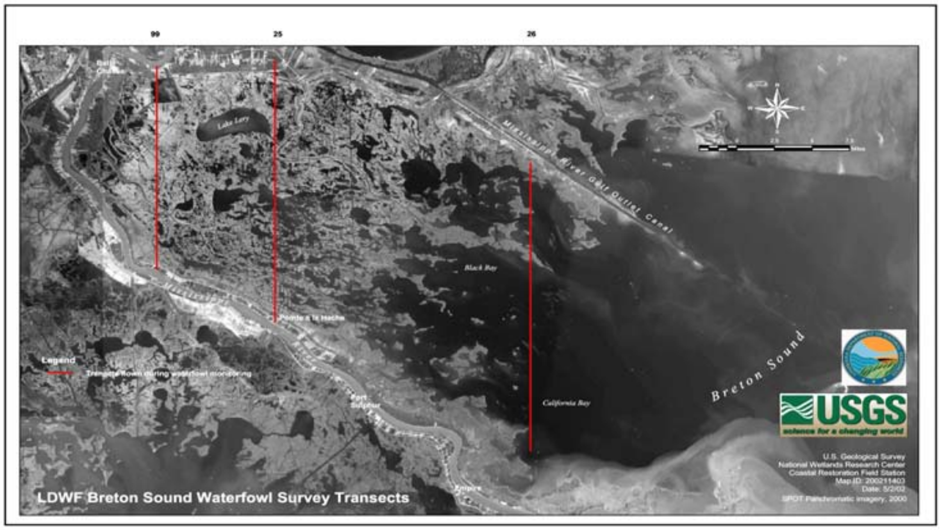

Figure 4-12. Location of Waterfowl Transects at Caernarvon (from CPRA 2010a)

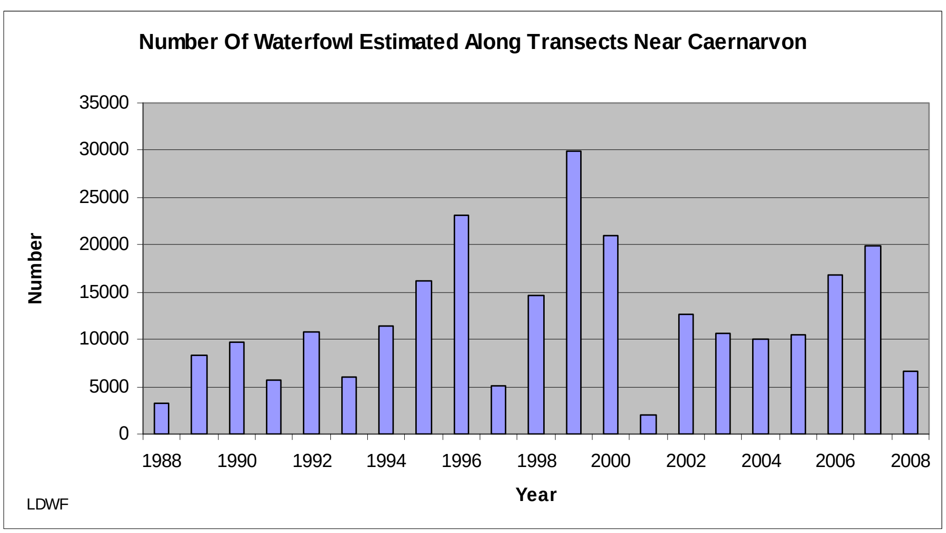

Figure 4-13. Number of Waterfowl Estimated Along Transects at Caernarvon (LDWF) (from CPRA 2010a)

4.4.2 Davis Pond

Waterfowl numbers are approximately 30 percent lower post-operation (CPRA 2010b; Figures 4-14 and 4-15). More than 87 percent of the waterfowl are recorded from fresh and intermediate marshes. Many other factors could confound the influence of Davis Pond on waterfowl numbers. Hunting seasons, weather, food availability, habitat in other areas of these migratory species, hurricanes, etc. can have large effects on the populations.

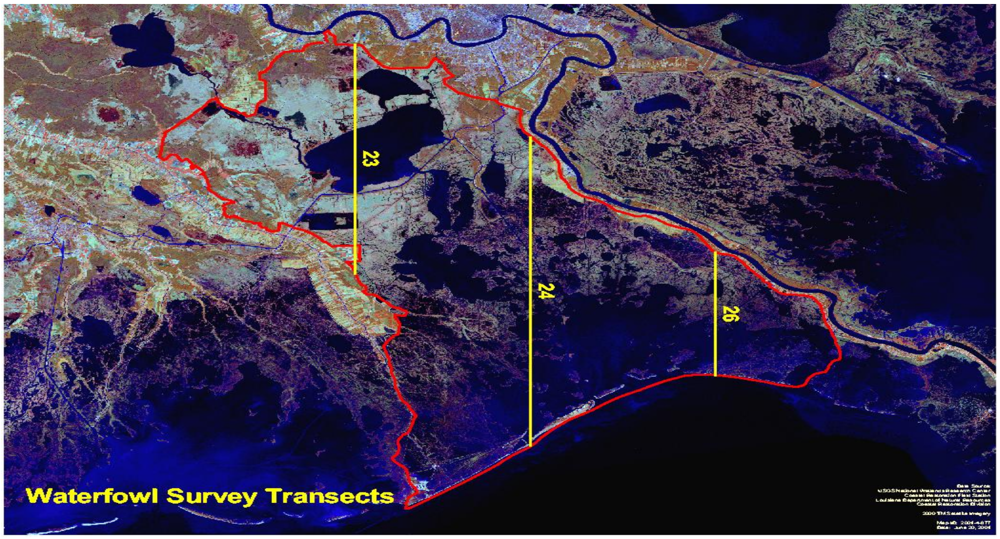

Figure 4-14. Location of Waterfowl Survey Transects in Barataria Basin (CPRA 2010b)

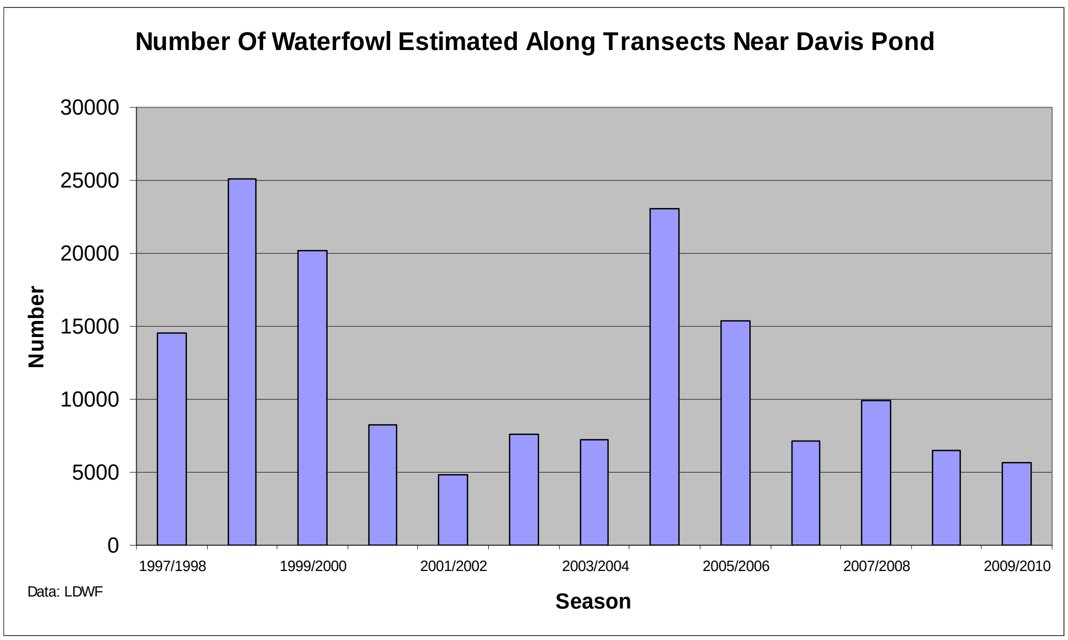

Figure 4-15. Number of Waterfowl Counted along Transects in Barataria Basin (from CPRA 2010b)

4.4.3 Atchafalaya Delta Wildlife Management Area

The marshes and associated habitat that were created in the otherwise open water demonstrates that a diversion of freshwater, sediments, and nutrients can create habitat for waterfowl, wading birds, and other wildlife. Waterfowl survey counts on December 15, 2010 documented approximately 40,000 ducks and 1,600 geese were using the Wax Lake Delta; while approximately 9,400 ducks were using the Atchafalaya Delta (Mr. Jerry Reynolds, personal communication, LDWF). Prior to the existence of the Atchafalaya Delta and Wax Lake Outlet, this area was a shallow bay, providing little wildlife habitat, especially for waterfowl and furbearers.

Wading bird surveys have shown a decrease in populations from 1983 to 2006 at the ADWMA [Carloss and Warner-Finley (2009), Figure 4-16]. This may be a reflection of the growth and maturing of the Wax Lake Delta. Waterfowl harvested per effort for the ADWMA from the 2000-2001 season increased over the 2007-2008 season; the Wax Lake Outlet (an artificial opening for flood control) Delta created in 1942 produced more ducks (Carloss and Warner-Finley, Figure 4-17). Many other factors can control these populations so firm conclusions are difficult to make.

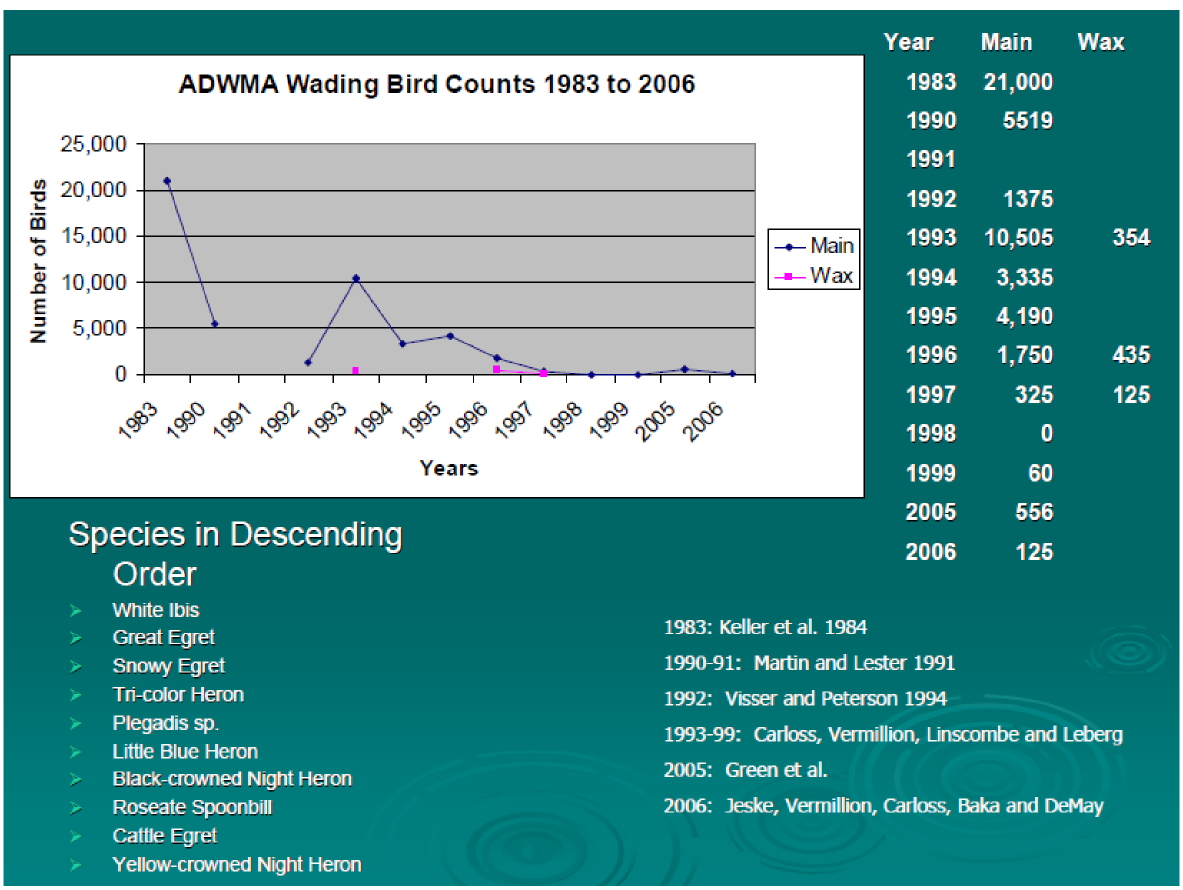

Figure 4-16. ADWMA Wading Bird Counts (1983-2006) [from Carloss and Warner-Finley (2009)]

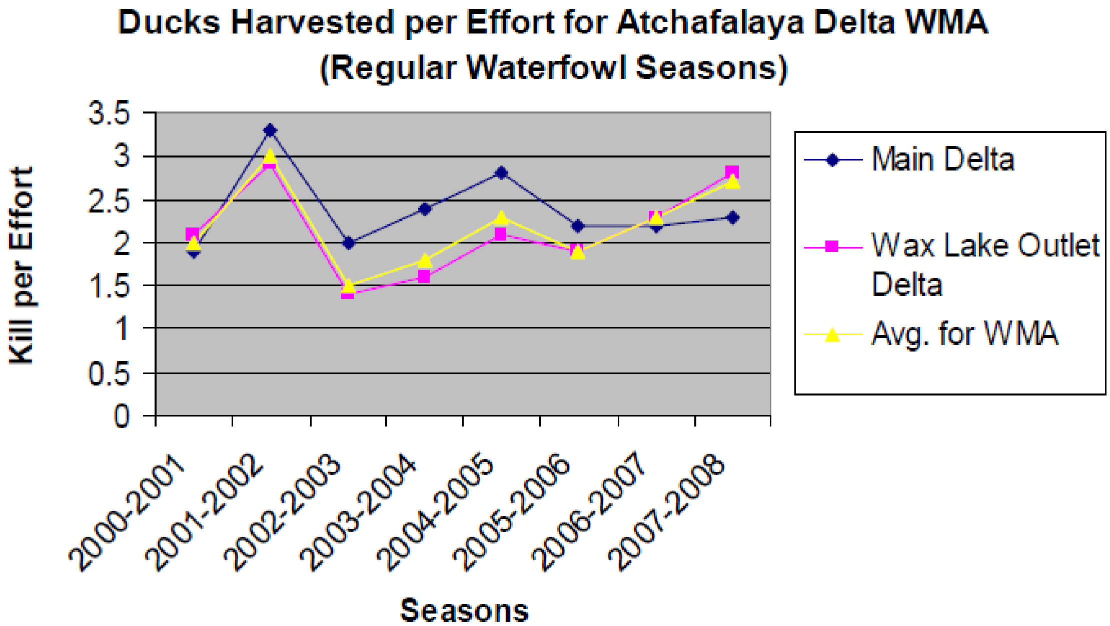

Figure 4-17. Ducks Harvested per Effort for ADWMA [from Carloss and Warner-Finley (2009)]

4.4.4 Delta National Wildlife Refuge

The land on which Delta National Wildlife Refuge (DNWR) is located was created when Cubit's Gap (an artificial crevasse) was dug in 1862. This diversion has created approximately 48,000 acres of prime waterfowl and wading bird habitat. DNWR is an important area for migratory birds and an average of 35,000 (peaks of 60-80,000) snow geese and 80-90,000 (peaks of 100-150,000) ducks have historically used the area during winter (Bohannan 2008). A recent bird count on January 3, 2011 indicated that approximately 107,000 ducks and 15,000 geese were on using the marshes of the DNWR (Mr. Jerry Reynolds, Personal Communication, LDWF). Likely, prior to the creation of Cubit's Gap and the creation of what is now DNWR, few waterfowl would have used this area.

4.5 Lessons Learned

Wildlife populations generally show increasing trends, especially for alligator, muskrat, and waterfowl. The best examples of diversions creating wildlife habitat are the Atchafalaya Delta, Wax Lake Outlet, and the Delta National Wildlife Refuge (Cubit's Gap). All of these diversions provided large volumes of sediments into the receiving areas.

The data suggest that alligator populations and nests increase with freshwater diversions and an increase in the aerial extent of freshwater and intermediate marsh habitats. This is consistent with the preferred alligator habitat (Chabreck 1988).

Information from Caernarvon and the 1927 flood event did indicate a likely relationship between diversions and increased populations of muskrat. The production of ideal salinity conditions and the increased growth of the desired food, *Schoenoplectus americanus*, are the most likely reasons for increased populations.

Not enough information is available to draw lessons learned for nutria. However, it would seem that nutria control may be critical to developing new marsh because this exotic mammal can decimate marsh vegetation.

Freshwater diversions create waterfowl habitat, such as the Wax Lake Outlet, Delta National Wildlife Refuge, and Atchafalaya Delta. Recent data suggest that increases in numbers of waterfowl and ducks harvested per effort. Data interpretation can be confounded by other factors, beyond the influence of the diversion, which can control waterfowl populations.

4.6 Recommendations

It is recommended that adequate data be collected in the pre- and post-operation phases of diversions to evaluate the actual affects of the diversions on wildlife. This may require data collection at appropriate stations and may require a long-term program to actually determine the trends and be able to evaluate the effects of the diversion. Other information should be collected and analyzed to filter out other parameters that can affect populations, such as harvests, regional and global population trends (waterfowl), weather patterns as they can affect data collection, and any other factor that can affect populations.

Sufficient data should be collected in a manner to enable the pre- and post-operation periods to be compared statistically. Although wildlife counts may appear higher post-operation, they may not be significantly higher. And although counts may be significantly higher or lower post-operation, the differences observed may not be due to the operation of the diversion.

Likely there are various sources of data that have been collected by various agencies that could be analyzed to evaluate the wildlife value of existing diversions, such as wildlife counts by the LDWF and the U.S. Fish and Wildlife Service.

4.7 References

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5.0 FISHERIES

River diversions have the potential to affect fisheries and aquatic organisms. Some potential effects of diversions on nekton that have been suggested include: relocate estuarine resident and transient fish, affect abundances; expand habitat available for freshwater fish; increase SAV coverage; redistribute endangered species; introduce invasive species; affect macrofaunal invertebrates; potential eutrophication and subsequent fish kills; and changes in the food web. Salinity, water temperature, and diversion flow rates have been correlated to fish community structure (Alford 2010).

5.1 Environmental Factors

5.1.1 Salinity

River diversions lower salinities in the receiving waters and generally redistribute isohalines towards the Gulf of Mexico. Salinity is the primary factor in determining the distribution and abundance of many estuarine organisms (Gunter 1961; Gunter *et al.* 1974; Chatry and Chew 1985). In general, the number of species declines as salinity declines (Gunter 1961). Most estuarine species are euryhaline and can tolerate full sea water for a period time. Estuarine-dependent marine species share similar life history characteristics. The adults spawn offshore and then the young (larvae, postlarvae, and juveniles) migrate into the estuaries where they grow in low-salinity waters. After a period of time, these species move offshore; larger adults of many species are only found in the ocean (Gunter 1961). Some estuarine species are residents and spend their entire life cycle in the estuary. Individuals of many species immigrate into, and emigrate out of, the estuary during specific times of the year (Figure 5-1; Rogers and Herke 1985). At any given time of the year, several species are

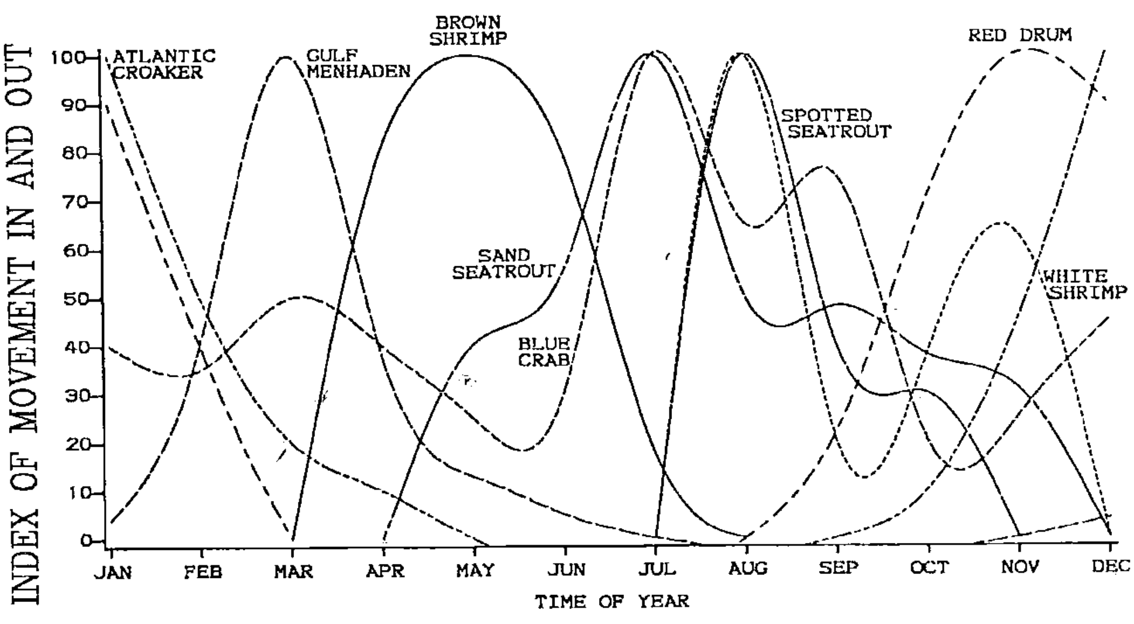


Figure 5-1. Index of movement in and out of the estuary for eight estuarine species (from Rogers and Herke 1985)

moving in and out of the estuary. Logically, diversions would likely have greater effects on those species whose greatest movements are occurring during the time of the high discharge.

The most abundant species collected in coastal areas have a wide tolerance to changes in salinity. Christensen *et al.* (1997) developed an index to evaluate how sensitive common Gulf of Mexico organisms were to changes in salinity. Adult bay anchovy, grass shrimp, blue crab, and silversides were classified with low sensitivity; Atlantic croaker, sand seatrout, and spot were classified with moderate sensitivity. Juveniles of many species tend to have higher tolerances to salinity changes than adults. In Louisiana, these include juvenile Gulf menhaden and brown shrimp with low sensitivity and juvenile white shrimp and hardhead catfish with moderate sensitivity.

The salinity in the Caernarvon outfall area post-operation was significantly lower than before the opening (USACE-LDWF 1998), except in the lower estuary (Lane *et al.* 1999). Changes in the salinities in response to freshwater input from Caernarvon are more apparent at locations nearest the structure (USACE-LDWF 1998; Figures 5-2 and 5-3).

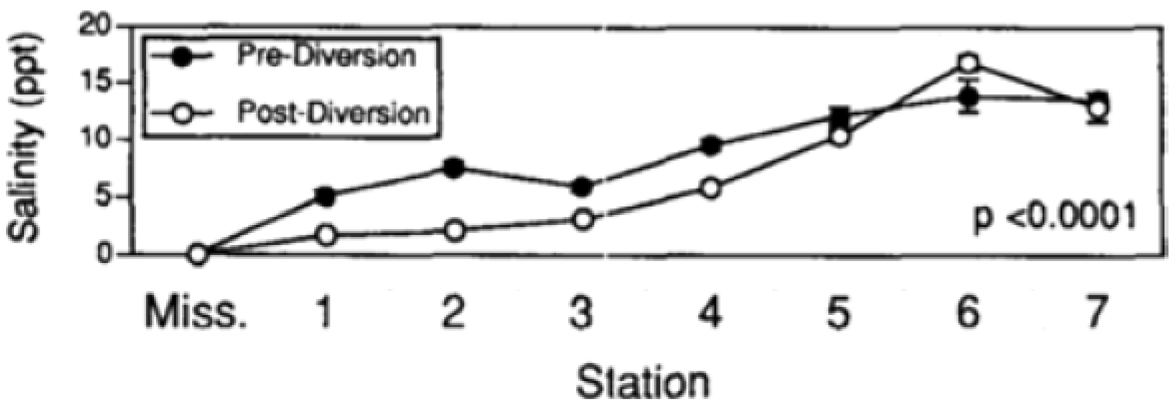


Figure 5-2. Caernarvon pre- and post-operation annual means for salinity. Significant results from the BACI analysis are indicated (from Lane *et al.* 1999)

5.1.2 Water Temperature

The Mississippi River water diverted through diversions is colder than the receiving waters. The Caernarvon Diversion water was always cooler than the estuarine waters, but generally equilibrated to the rest of the estuary within several kilometers. During large discharges cooler water from Caernarvon can circulate through the entire estuary (Lane 2003). The water in Lake Pontchartrain near the Bonnet Carré Spillway stratified during at least one spillway opening due to temperature driven density gradients (USGS 1996; Lane 2003).

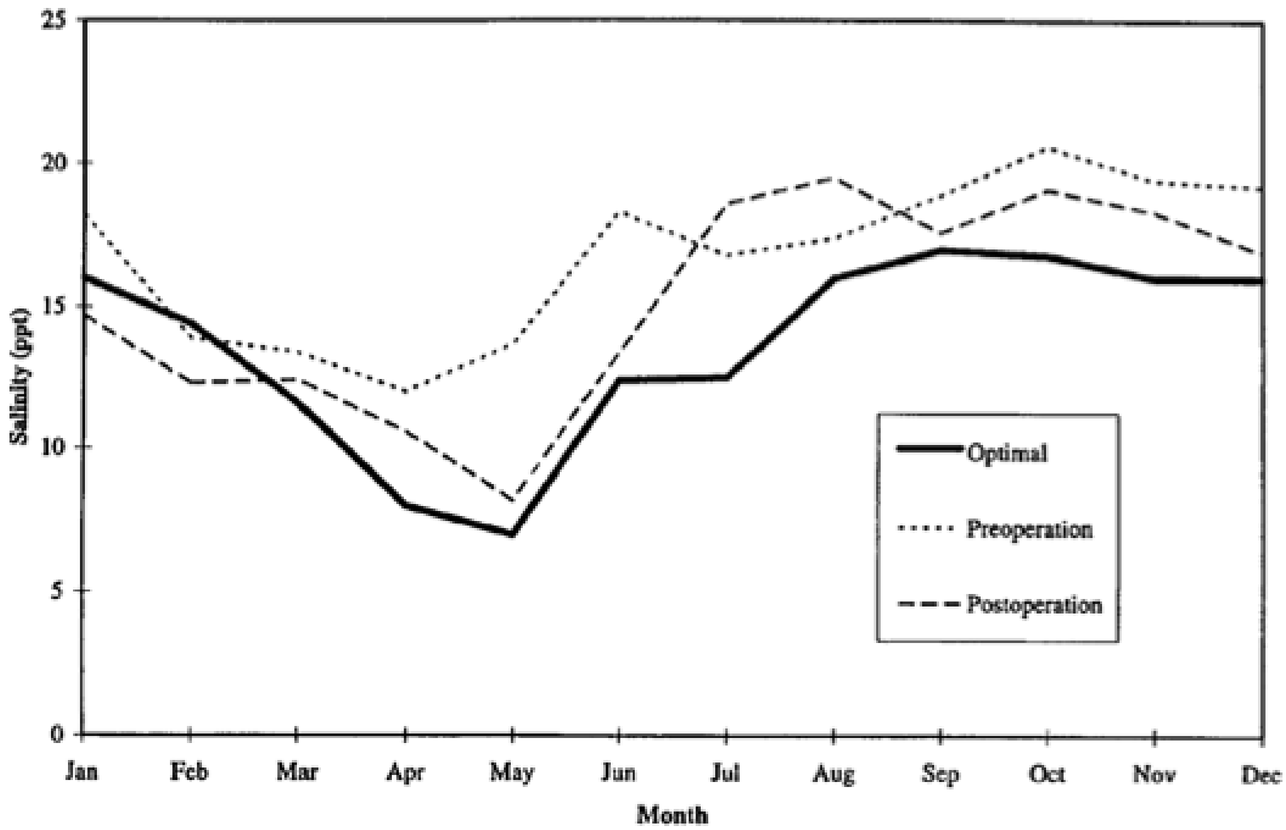


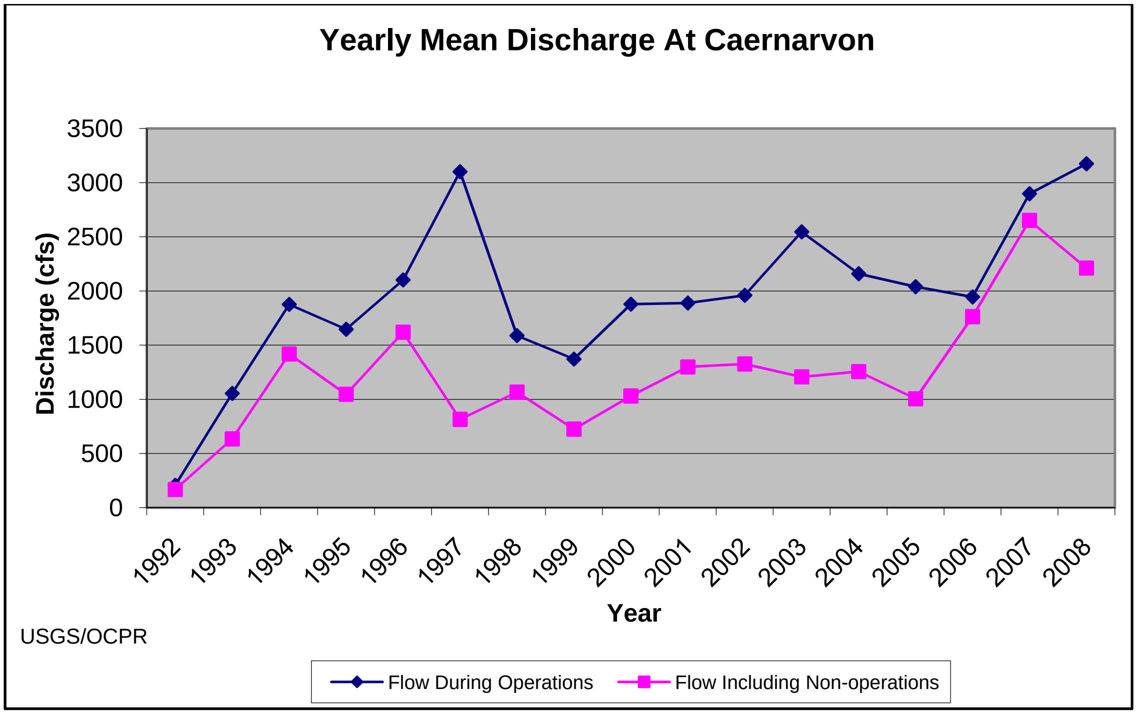
Figure 5-3. Combined monthly average salinity from grids 48, 49, 55, 56, and 57 near Caernarvon during the pre-and post-operation periods versus the optimal salinity regime for seed oyster production (from USACE-LDWF 1998)

5.1.3 Discharge

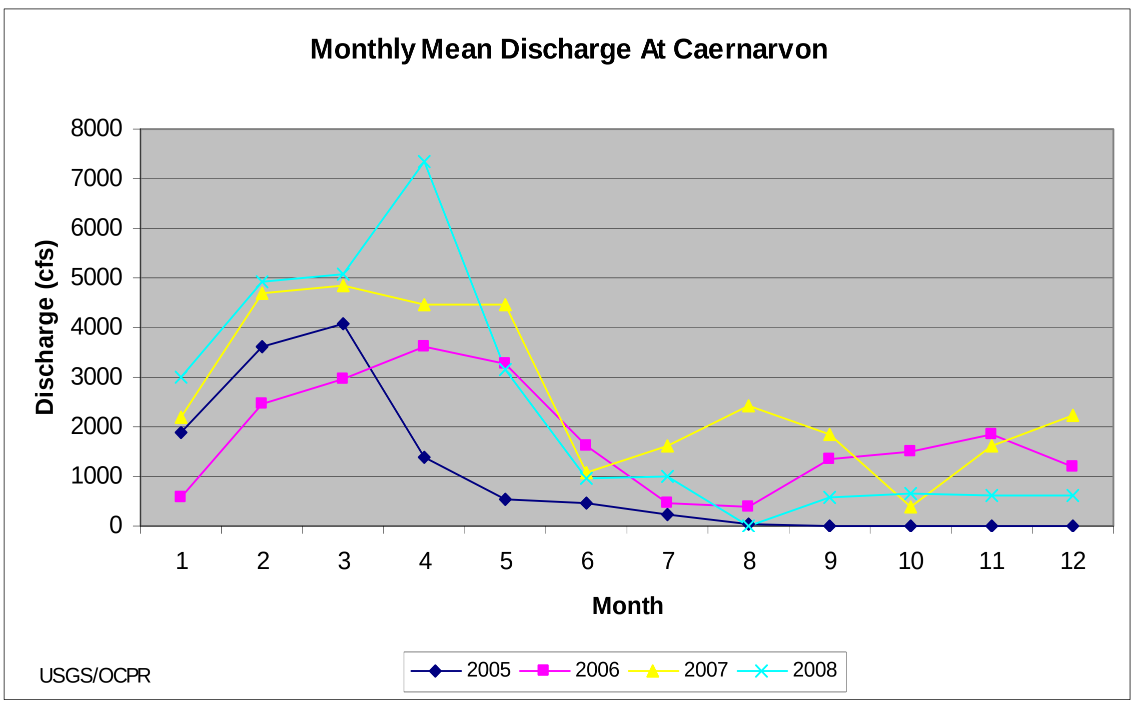
Discharges from diversions can vary. The yearly mean discharge at Caernarvon has varied since the diversion began operations in 1991 (Figure 5-4). The peak discharge occurred in 1997 and 2008 (Figure 5-4); discharges have been generally highest from February through May (Figure 5-4).

The Davis Pond diversion began limited operations in July 2002 and was closed more than 50 percent of the time in 2003-2004 due to issues with ponding. During October 2004-September 2004, the diversion was open about 40 percent of the time and discharged approximately 1,300 cfs when operated. Peak discharges at Davis Pond occurred in 2008 and 2009 (Figure 5-5).

Seven diversions and siphons and one navigation lock were opened from May to August, 2010 to move water out of the Mississippi River and into coastal wetlands because of the Mississippi Canyon 252 (Deepwater Horizon) oil spill (Table 5-1). The total measurable flow from these diversions was 29,550 cfs (LDWF 2010).



Yearly Mean Discharge



Monthly Mean Discharge

Figure 5-4. Yearly and Monthly Mean Discharge at Caernarvon (from CPRA 2010a)

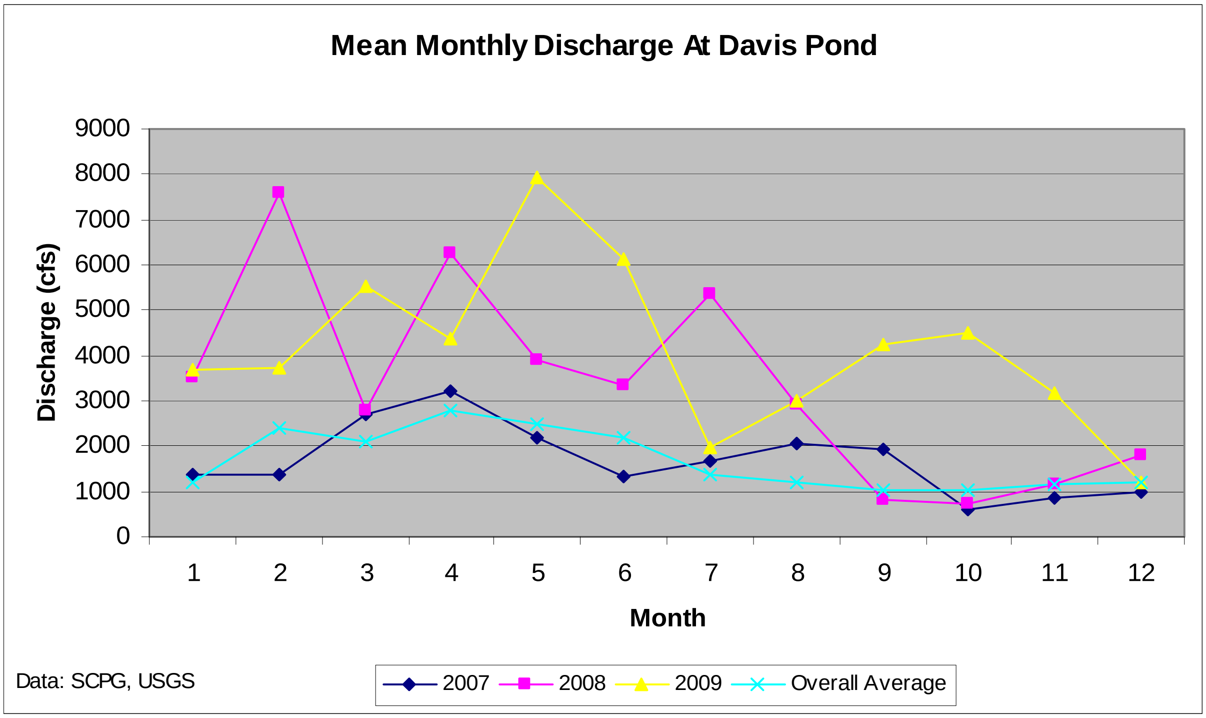


Figure 5-5. Monthly Mean Discharge at Davis Pond (from CPRA 2010b).

Table 5-1. Diversions Opened for the Oil Spill from May to August, 2010

Diversion	Capacity	cfs
Bayou Lamoque	12,000	7,500
Davis Pond	10,650	10,650
Caernarvon	8,800	8,000
Naomi Siphon	1,500	1,500
West Pointe a la Hache Siphon	1,500	1,500
Violet Siphon	200	200
White's Ditch Siphon	200	200

Source: Adapted from LDWF 2010.

The Bonnet Carré Spillway is opened to reduce the risk of flooding downstream. This spillway is opened such that the Mississippi River discharge is kept below 1.25 M cfs at New Orleans. This essentially keeps the stage at the Carrolton gage in New Orleans from exceeding 20 feet mean sea level (MSL). The spillway has been opened nine times during high water events since construction: 1937, 1945, 1950, 1973, 1975, 1979, 1983, 1997, and 2008 (Table 5-2).

Table 5.2. Historic Bonnet Carré Spillway Opening Data

Year	Date Opened	Date Closed	Number of Days Opened	Max. Number Bays Open	Maximum Flow (cfs)
1937	Jan. 30	Mar. 7	37	285	211,000
1945	Mar. 23	May 18	57	All 350	318,000
1950	Feb. 10	Mar. 19	38	All 350	223,000
1973	Apr. 8	Jun. 21	75	All 350	195,000
1975	Apr. 14	Apr. 26	13	225	110,000
1979	Apr. 18	May 21	34	All 350	191,000
1983	May 20	Jun. 23	35	All 350	268,000
1997	Mar. 17	Apr. 18	33	298	243,000
2008	Apr. 11	May 8	28	160	160,000

Source: USACE data.

5.2 Nekton Distribution

Diversions may relocate estuarine resident and transient fish farther away; this may affect transient species migrating at the time of the opening. The movement and abundance of larval, post-larval, juvenile, and adult organisms may be affected. Reduced salinities and growth of submerged aquatic vegetation may affect abundances.

Statistics Analysis - Analyses of Variance (ANOVA) tests were used to assess the fishery data evaluated in the USACE-LDWF (1998) report to test whether the effect of the Caernarvon operation was significant. Because the data were not collected in a true control area (a similar area unaffected by Caernarvon) a BACI-type (Before-After-Control-Impact) model was used. An alpha level of 0.05 was used to assess whether differences were significant (USACE-LDWF 1998).

Although catches may have increased or decreased significantly between the pre- and post-operation periods, these changes may have been caused by other factors. To test for this, a significant change in catch can only be attributed to the effect of the diversion operation if the pattern of catches among the different stations changed significantly post-operation. This is represented in the ANOVA test by the *station*operation* interaction term; the operation would be pre- and post-operation. For example, if the catch of a certain species significantly increased ($P<0.05$) post-operation and the *station*operation* interaction term was significant ($P<0.05$), then we can conclude that this increase is likely due to the operation of the diversion. However, if the *station*operation* interaction term was not significant, then we can still conclude that the catches were increased, but cannot attribute this increase to the diversion (USACE-LDWF 1998).

Nekton Sampling - Data for USACE- LDWF (1998), CPRA 2010a, CPRA 2010a, and portions of data for de Mutsert (2010) were collected by the LDWF. Since all nekton sampling gears are biased for certain species and certain sizes, a wide range of sampling gear was used by LDWF. LDWF used trawls (6-ft and 16-ft), gill nets, seines, and trammel nets for nekton; and meter square sampling for oysters. Rozas et al. (2005) and Piazza and La Peyre (2007) used a 1-m^2 drop sampler. LDWF (2002) presents a detailed description of their sampling techniques and are summarized below.

Trawl - Ten-minute trawl tows were taken using a 16-foot (ft) flat otter trawl with ¾-inch (in.) bar mesh in the body and ¼-inch bar mesh in the tail (codend). The 6-foot trawl was a balloon had ⅜-inch bar mesh in the body and ¼-inch bar mesh in the tail. Trawls were towed at a constant speed in a weaving or circular pattern to allow the prop wash to pass on either side of the trawl. All organisms were placed in plastic bags, labeled, and transported to the laboratory. Organisms were identified to species, when possible, counted, and up to 50 of each species in each sample were measured in 5 millimeter (mm) intervals.

Gill Net - An experimental 8-ft by 750-ft gill net consisting of a sequence of five 150-foot panels was used; each panel contained a progressively larger mesh size: 1-, 1.25-, 1.5-, 1.75-, and 2-inch bar mono mesh. Fish were forced into the net by running the net skiff around the inside and outside of the net at least two or three times in gradually tightening circles. All organisms were removed from the net and placed in baskets corresponding to each mesh panel of the net. Up to 30 individuals of certain species were individually measured (total length in mm); the remaining individuals of these species were counted.

Seine - A 50' nylon bag seine with ¼ inch delta mesh was used to sample. All organisms collected were identified to species and counted. Up to 30 randomly selected individuals of certain species were measured to the nearest millimeter.

Trammel Net - The trammel nets are 750 feet in length and 6 feet in depth, consists of three walls, and are constructed of treated nylon. The inner wall has 1 5/8-in. bar mesh, and the two outer walls have 6-in. bar mesh. The float and weight are thrown out adjacent to or on a shoreline or reef, and the net slowly deployed while at idle speed. Net configuration or distance from shoreline or reef varies because of water depth, presence of obstructions, or physical space limitations; therefore, the net may be set parallel to the reef or shoreline or in a half-moon shape. Enough room is left on one side of the net to allow the net skiff to enter and then maneuver within the net. Fish are forced to strike the net by running the net skiff around both the inside and outside of the net at least two or three times in gradually tightening circles. The net is then retrieved from the down-wind or down-current end.

Square Meter (Oysters) - A one-meter square frame was used by LDWF on the public seed grounds, seed reservations, and tonging areas to examine oyster density and availability (i.e., seed and sack oysters) per unit area and to provide ancillary data on oyster recruitment, hooked mussel *(Ischadium recurvum)* density, mortality, and predators. The square-meter frame was randomly thrown onto an oyster reef. A SCUBA diver removed all oysters, associated macroscopic organisms, and loose surface shell within the frames. All oysters and shells from recently dead oysters larger than 25 mm were counted and measured in 5-mm intervals. Shells from dead oysters were classified as *box* (both valves attached) or *valve* (one valve). Oyster size was determined by measuring the *straight-line* distance from the hinge to the apex of the shell. Live gastropod, crab, and mussel predators were counted. Cultch type and reef condition were noted. A minimum of two replicate samples were taken at each station.

Drop Sampler (Nekton) – The drop sampler was 1.14 m-diameter cylinder that was dropped from a boom attached to a shallow-draft boat [Rozas et al. (2005); Piazza and La Peyre (2007)]. The boat was allowed to drift until the sampler was over the sample station. The cylinder was rapidly released from the boom and entrapped organisms within a 1.0-m^2 sample area. Nekton and SAV samples were then collected.

5.2.1 Caernarvon

The effects of Caernarvon on fisheries reflects fish species motility, variations in diversion flow patterns, and biotic and abiotic factors related to the diversion, including food availability and salinity (CPRA 2010a).

The abundance of species collected in trawl samples changed since the opening of Caernarvon in 1991. The percent change in abundance of selected finfish and shellfish species in 6-ft trawl samples near Caernarvon between the pre- (1988-1990) and post-operation (1991-1994) periods is presented in Figure 5-6. Of the species examined, the

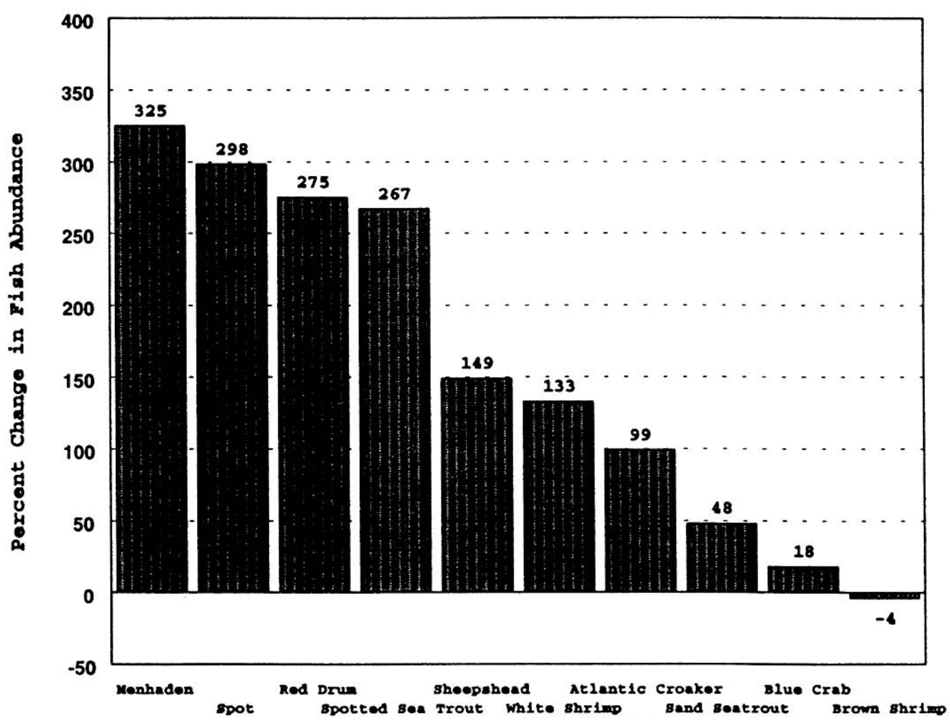


Figure 5-6. Percent change in selected finfish and shellfish species at the Caernarvon area. Change is between pre- (1988-90) and post-operation (1991-94) periods. Abundance was based on 6-ft trawl sampling by LDWF. (from Geaghan 1995 as cited in Meffert and Good 1996)

abundance of menhaden, spot, red drum, and spotted seatrout changed the most between pre- and post-operation. The abundance of blue crab increased slightly (18 percent) and the abundance of brown shrimp decreased slightly (-4 percent) post-operation (from Geaghan 1995, as cited in Meffert and Good 1996). Brown shrimp migrate during the time when the diversion would have the greatest discharge.

After the opening of Caernarvon in 1991, the nekton community, species biomass, and abundance distributions seined near Caernarvon changed (de Mutsert 2010). Estuarine nekton seined monthly from 1986 to 2007 near the Caernarvon Diversion by the LDWF were examined using a BACI (Before-After- Control-Impact) design. The Caernarvon impact area had significantly higher total nekton abundance than the control area ($t = -4.54$, $p = 0.0003$); however, the total biomass of nekton in the control and impact areas did not significantly differ post-operation. The number of species in the impact area seine samples did not change post-operation; however, the number of species in the control area samples significantly decreased ($t = -5.74$, $p < 0.0001$). The mean weight did not significantly differ between the control and impact areas before the diversion operation (de Mutsert 2010). The mean weight of individuals in the impact area samples was significantly lower than those from the control area ($t = 2.94$, $p = 0.006$) (de Mutsert 2010).

Salinity was identified as the primary environmental variable separating species biomass distributions among study sites near Caernarvon due to freshwater inflow, although seasonal variation had the greatest effect on species biomass distributions. The increase in nekton species richness, abundance and the proportion of smaller individuals suggested the nursery function of the Caernarvon area increased post-operation (de Mutsert 2010).

Increased nekton density and biomass in 1-m^2 drop samples taken on flooded marsh sites and along the vegetated shoreline were observed when freshwater inflows were pulsed from Caernarvon (Rozas *et al.* 2005). Communities in the two areas were similar and consisted primarily of marsh resident species (Rozas *et al.* 2005; Piazza and La Peyre 2007). Nekton density and biomass was significantly higher at flooded marsh sites near Caernarvon than the reference marsh sites (Figures 5-7 and 5-8). Inflow marsh sites had significantly deeper water and were flooded more than twice as long as reference marshes not affected by the diversion (Piazza and La Peyre 2007). The Caernarvon area had increased coverage of SAV (Rozas *et al.* 2005). Nekton communities were similar and were dominated by marsh resident species. Differences in density and biomass were attributed primarily to differences in water depth and duration of flooding (Piazza and La Peyre 2007) and increased SAV coverage (Rozas *et al.* 2005). These changes in the water regime and increased SAV were directly attributed to the pulsed inflow.

5.2.2 Davis Pond

No obvious trends were observed in sampling downstream of the Davis Pond Structure from October 2003 through September 2004 (LDNR 2005). Shrimp catches were generally higher post-operation but it followed the pattern of state catch during this time period. It is unlikely at this time that operation of Davis Pond, due to low discharge levels, is having any substantial effect on fish populations. It may take several years of higher operational levels at Davis Pond before biota respond to environmental changes.

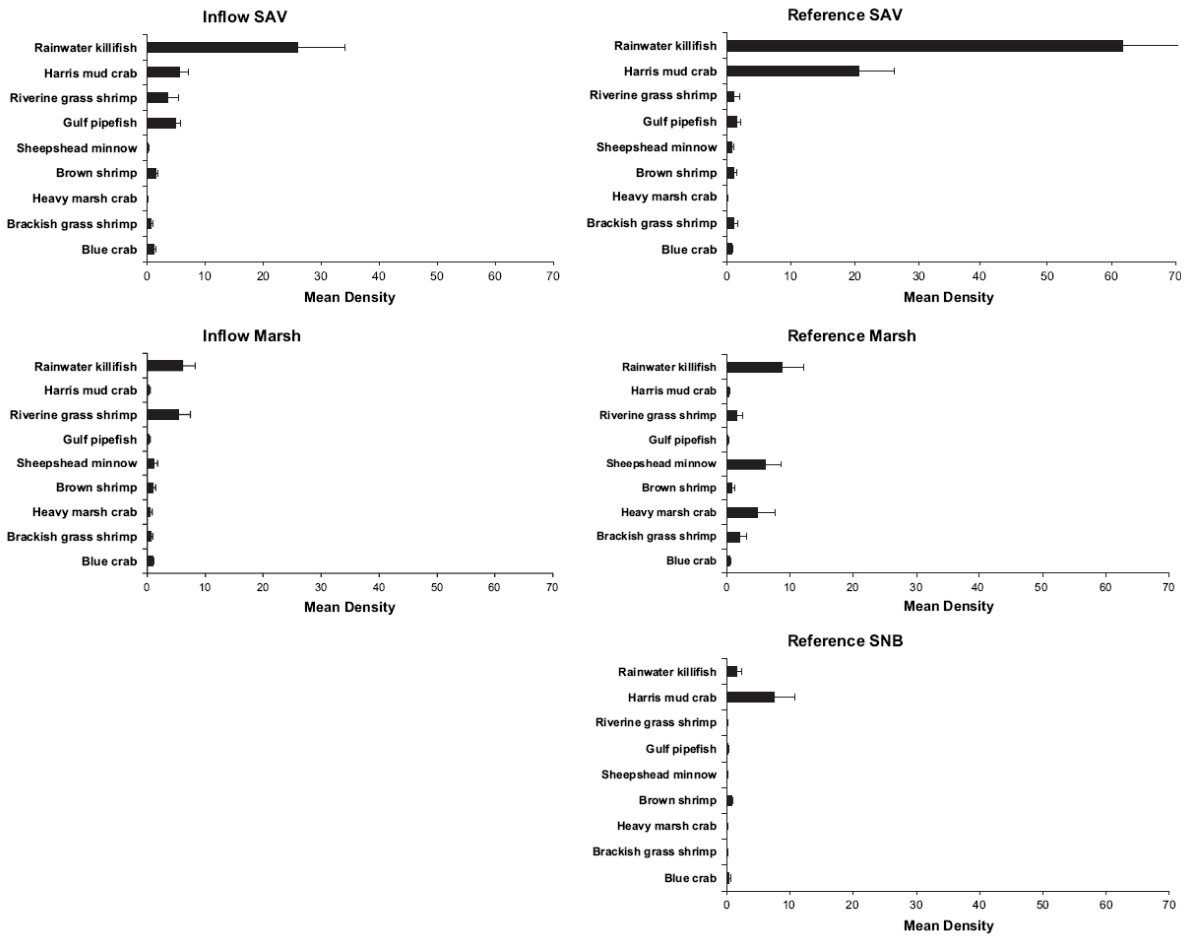


Figure 5-7. Distributions among habitat tpes (SAV and SNB subtidal nonvegetated bottom sites) of abundant nekton during May near Caernarvon. Error bars = 1 SE. (from Rozas *et al.* 2005)

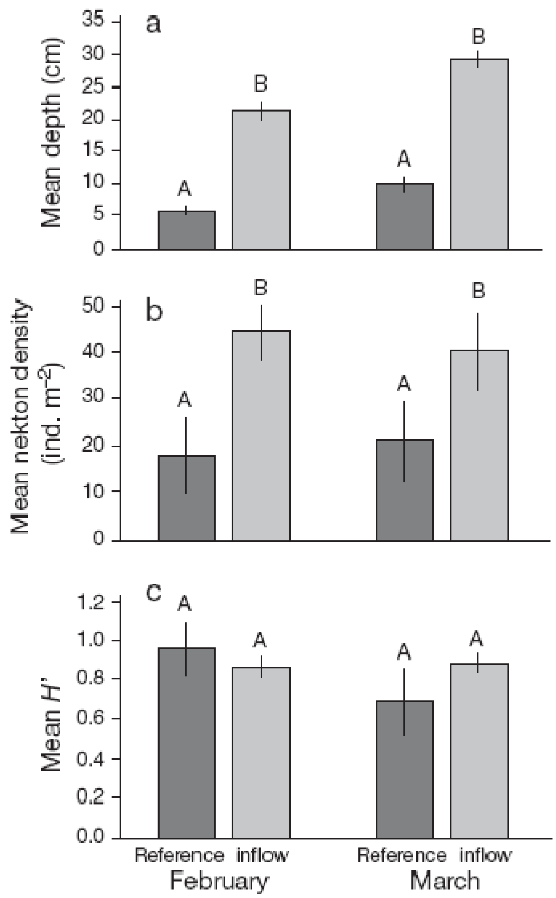
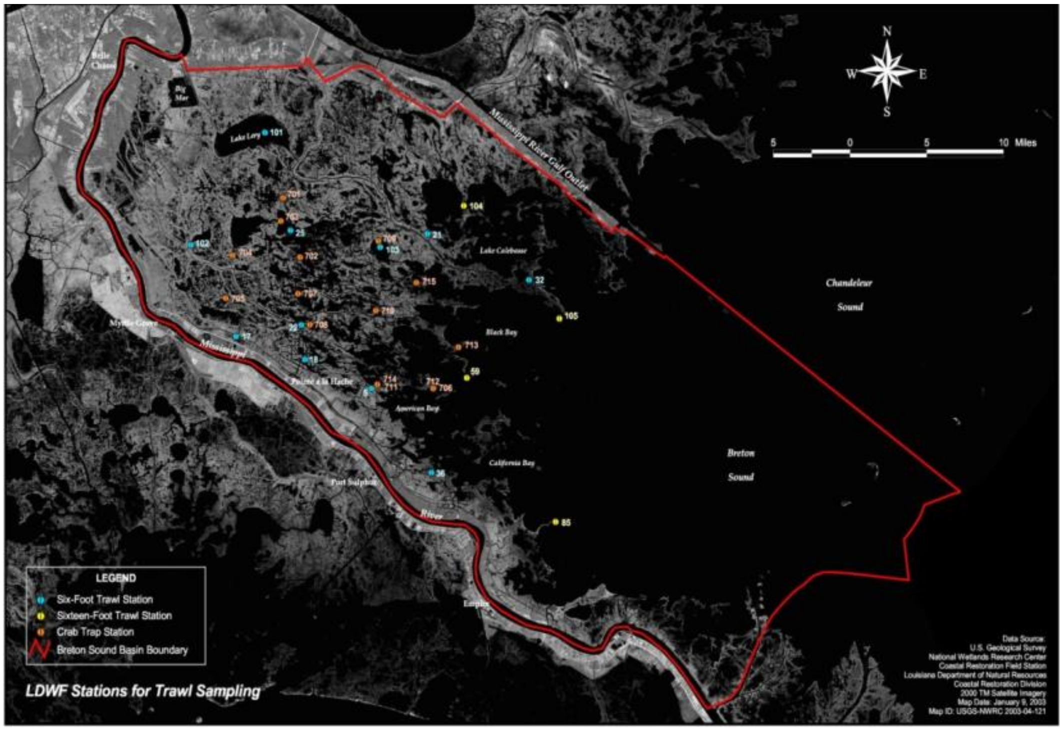


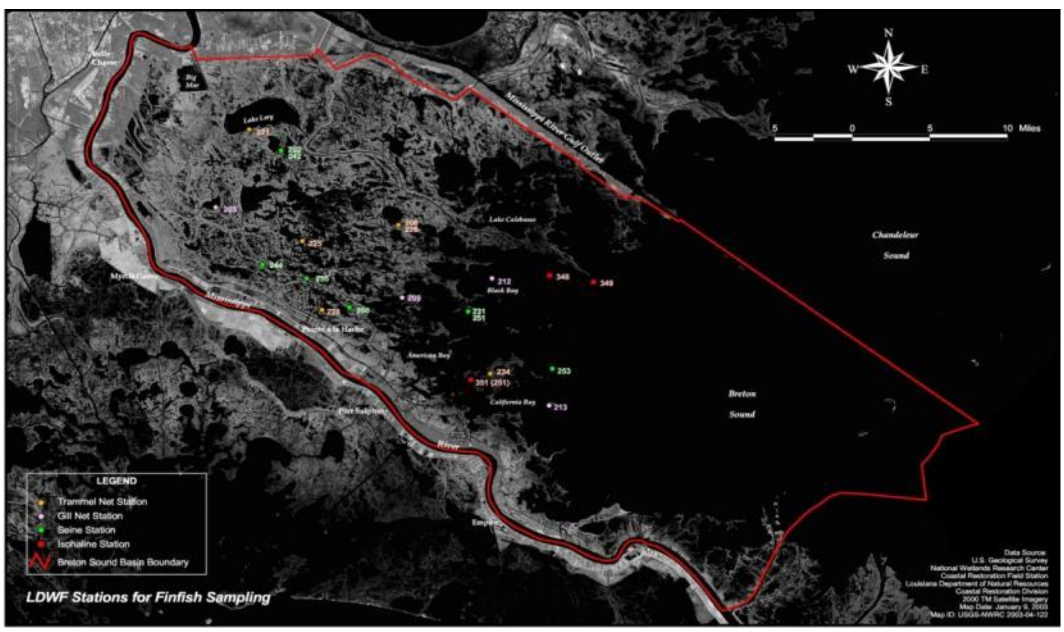
Figure 5-8. Water Depth (cm), nekton density (individuals per m^2), and Shannon-Weiner diversity (H') at flooded marsh sampling sites during Caernarvon high-pulse flow events in 2005 (mean±SE); reference (dark gray) and inflow (light gray). Significant statistical differences within and between pulse events are denoted by capital letters. Mean biomass (g/m^2) and mean Shannon-Wiener evenness followed the same pattern as density and diversity, respectively. (from Piazza and La Peyre 2007)

5.2.3 Sampling Station Locations

The locations of stations sampled in the various reports presented in the following discussion are presented below. LDWF 6-ft and 16-ft trawl stations in the Caernarvon outfall area that are reported in CPRA (2010a) are presented in Figure 5-9.



Trawl



Trammel, Seine, and Gill net

Figure 5-9. Location of LDWF trawl, trammel, seine, and gill net stations near Caernarvon (from CPRA 2010a)

The location of trammel, seine, and gill net stations near Caernarvon reported in CPRA (2010a) are presented in Figure 5-9. The locations of LDWF 6-ft (Figure 5-10) and 16-ft trawl stations (Figure 5-11) in the Davis Pond outfall reported in CPRA (2010b) are presented below. The location of trammel, seine, and gill net stations near Davis Pond reported in CPRA (2010b) are presented in Figure 5-12. The locations of stations in the de Mutsert (2010) (Figure 5-13), Piazza and La Peyre (2007) (Figure 5-14), and Rozas *et al.* (2005) (Figure 5-15) are also presented.

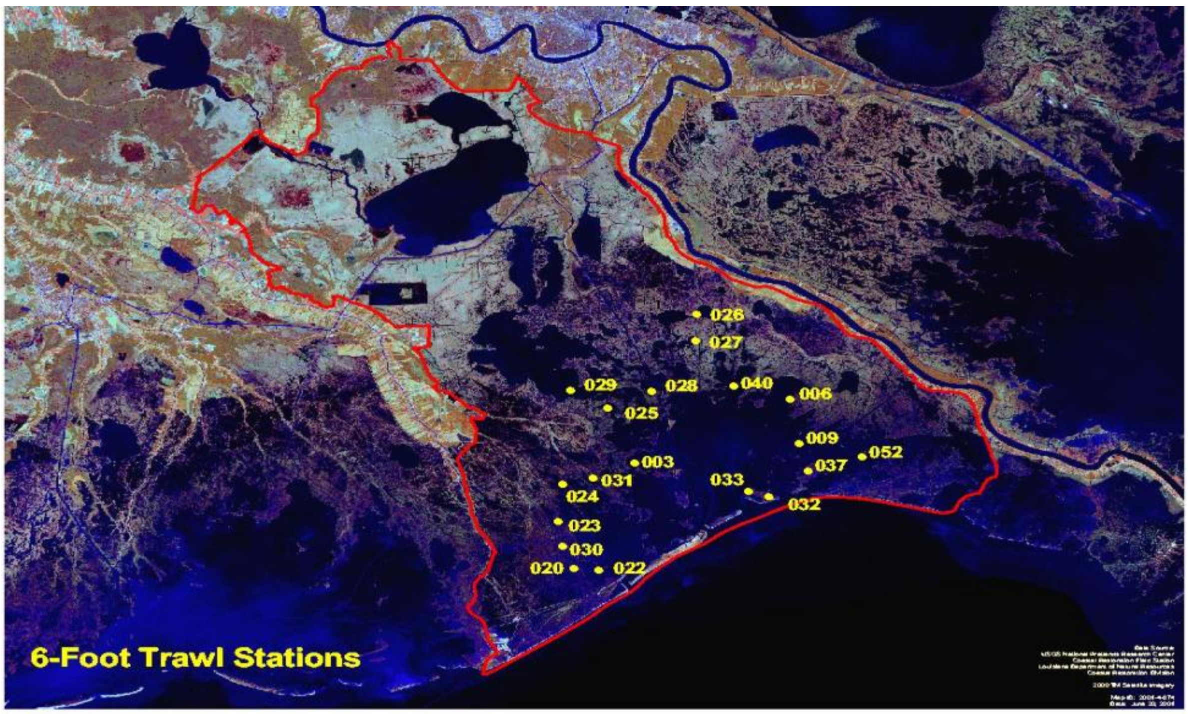


Figure 5-10. Location of LDWF 6-foot trawl stations in Barataria Basin near Davis Pond (CPRA 2010b)

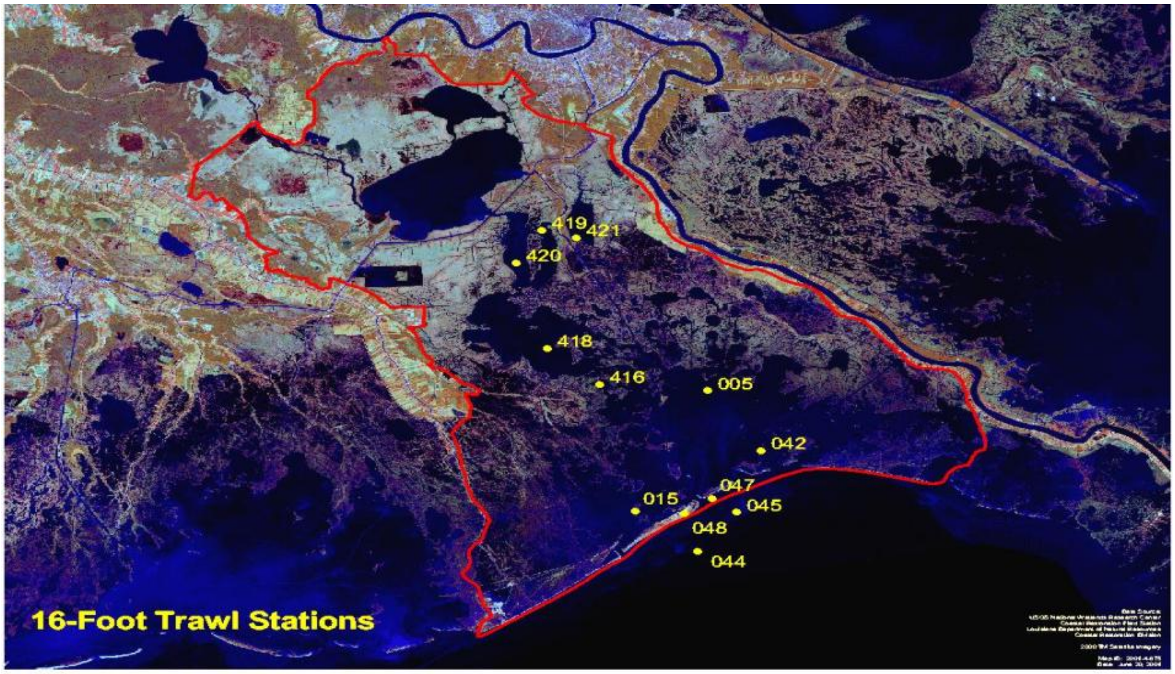


Figure 5-11. Location of LDWF 16-foot trawl stations in Barataria Basin near Davis Pond (from CPRA 2010b)

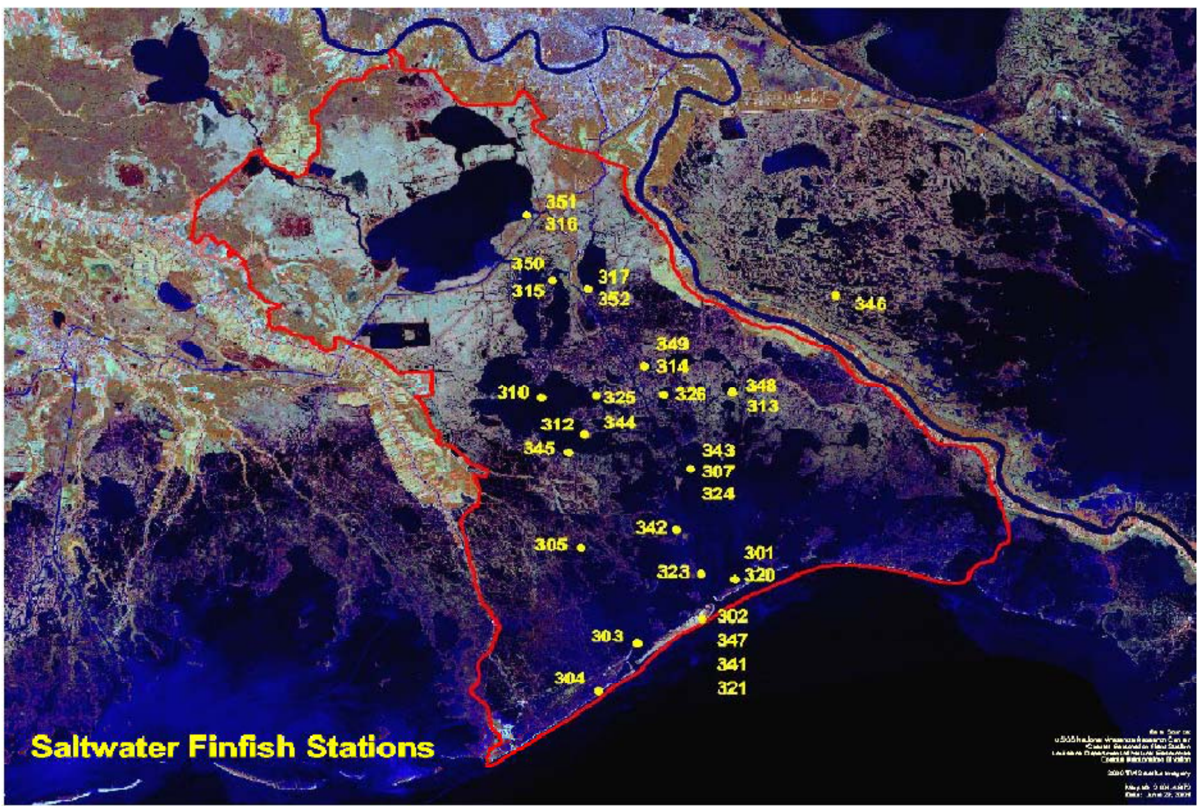


Figure 5-12. Location of seine and gill net stations in Barataria Basin near Davis Pond (LDWF) (from CPRA 2010b)

Figure 5-13. Location of monthly nekton collections and salinity measurements reported in the de Mutsert (2010) study. The Caernarvon freshwater discharge is shown with an arrow. Impact sites (circles) and control area sites (squares) are separated by an elevated road (white line) and Bayou Terre aux Boeufes (dashed line)

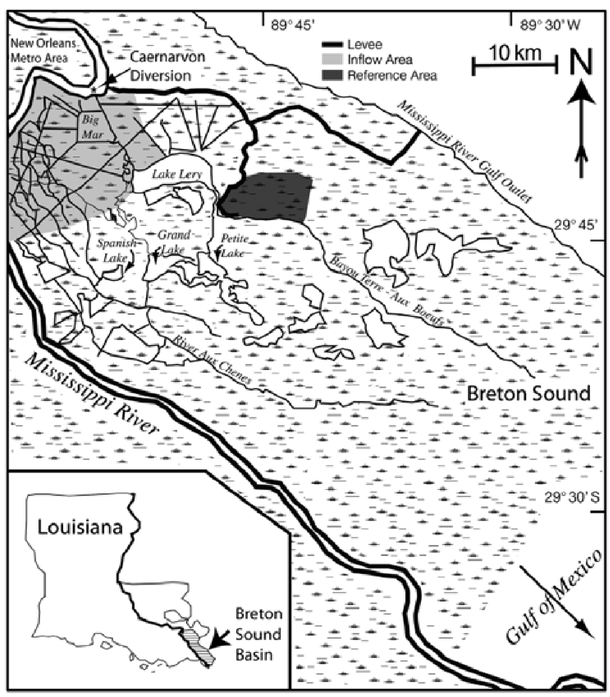


Figure 5-14. Locations of the Inflow (light gray) and Reference (dark gray)Areas used in the Piazza and La Peyre (2007) study

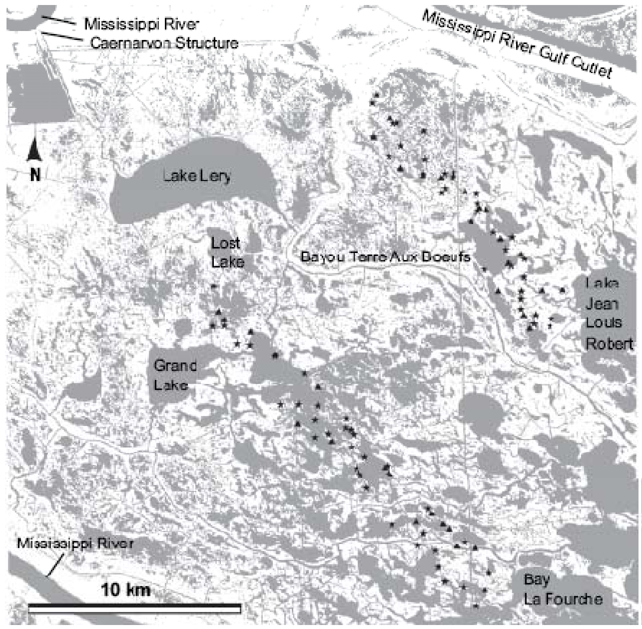


Figure 5-15. Study area of Rozas *et al.* (2005) showing the two transects and 100 sample sites near the Caernarvon Diversion. The inflow and reference areas are located south and north, respectively of Bayou Aux Boeufs. Marsh sample sites (triangles) and water (SAV and nonvegetated bottom) sites (stars) are marked.

5.2.4 Bonnet Carré

The Bonnet Carré Spillway was designed for flood control, but it is a river diversion and could have some of the effects of diversions designed for other purposes. Openings of the spillway have varied from 13 to 75 days in length and from 160 to 350 (all) gates; the height of the river also affects the discharge (Table 5-2). Larger and longer spillway openings (such as 1945 and 1973) may affect nekton more than smaller, shorter openings (such as 1975, 1979, and 2008).

The 2008 opening had little overall effect on the distribution of fishes and aquatic organisms, with the majority of the species that were statistically significant, were significantly higher during the opening when compared to the non-opening years (Table 5-3; GEC 2009). Trawl catches of bay anchovy, blue crab, and brown shrimp in Lake Pontchartrain and bay anchovy, Atlantic croaker, northern white shrimp, and sand seatrout in Lake Borgne were higher in 2008 than in the other years tested. Trawl catches of Gulf menhaden in Lake Pontchartrain; and blue crab, Gulf menhaden, hardhead catfish, and northern brown shrimp in Lake Borgne were not significantly different. The only species with significantly lower catches in 2008 after the Spillway opening were Atlantic croaker and sand seatrout in Lake Pontchartrain and spot in Lake Borgne. Gill net catches of Gulf menhaden and hardhead catfish, and seine catches of bay anchovy, Gulf menhaden, and inland silversides were not significantly different among the years tested. Catches of some of the less abundant species may have been lower in 2008 after the Spillway opening, but these species were collected in insufficient numbers to analyze (GEC 2009).

Table 5-3. Summary table of Analyses of Variance for selected species for the 2008 opening of the Bonnet Carré (GEC 2009)

Gear	Stations	Species	year	month	year*month	2008 different	reason for 2008 difference
Trawl	Lake Pontchartrain	bay anchovy	p<0.01	p<0.01	p<0.05	p<0.01	higher CPUE June 2008
		Atlantic croaker	p<0.01	p<0.01	p<0.01	p<0.01	higher CPUE June 2007; July/Oct. 2001
		Gulf menhaden	NS	p<0.01	NS	NS	
		sand seatrout	p<0.01	p<0.05	p<0.01	p<0.01	higher CPUE June 2007
		blue crab	p<0.01	NS	NS	p<0.01	higher CPUE May 2008
		northern brown shrimp	p<0.01	p<0.01	p<0.01	p<0.01	higher CPUE May 2001; June 2008
Trawl	Lake Borgne and south of Mississippi Sound	bay anchovy	p<0.01	p<0.05	NS	p<0.01	higher CPUE Oct. Nov. 2008
		Atlantic croaker	p<0.01	p<0.01	p<0.01	p<0.01	higher CPUE July - Sept. 2008
		blue crab	NS	p<0.01	NS	NS	
		Gulf menhaden	NS	p<0.01	NS	NS	
		hardhead catfish	NS	p<0.01	NS	NS	
		northern brown shrimp	p<0.01	p<0.01	NS	NS	
		northern white shrimp	p<0.01	p<0.01	NS	p<0.01	higher CPUE Sept. Oct. 2008
		sand seatrout	p<0.01	p<0.01	NS	p<0.01	higher CPUE June 2008
		spot	p<0.01	p<0.01	p<0.01	p<0.01	higher CPUE May 2000, 2001, 2002
Gill net	Lake Pontchartrain	Gulf menhaden	NS	p<0.05	NS	NS	
		hardhead catfish	NS	NS	NS	NS	
Seine	Lake Pontchartrain	bay anchovy	NS	p<0.05	NS	NS	
		Gulf menhaden	NS	p<0.01	NS	NS	
		inland silverside	NS	p<0.01	NS	NS	

Many factors can affect populations of fish and other aquatic organisms, including yearly variability in spawning and migration patterns; other environmental factors such as high freshwater inflow from streams and rivers, storms, rainfall, drought; and effects of fishing, such as shrimping, crabbing, change in predator populations, etc. Even if catches of a particular species are lower during a particular year after a Spillway opening, it is difficult to isolate one particular cause. A number of factors could be responsible, and demonstration of a cause and effect is difficult. Trawl catches of most species are often variable from year to year.

The time of year the Spillway is open may affect marine transient species differently depending on migration patterns. The Spillway is typically opened in April and May due to high Mississippi River levels, although it has been opened as early as January and as late as June. The species that are migrating into the estuary during that time and may be more susceptible to the effects of Spillway openings include Gulf menhaden, northern brown shrimp, and sand seatrout.

5.3 Individual Species – Caernarvon and Davis Pond

Effects of the Caernarvon and Davis Pond diversions on individual species are discussed in the following sections.

5.3.1 Spotted Seatrout

5.3.1.1 Caernarvon

Catches of spotted seatrout (*Cynoscion nebulosus)* post-operation were higher in trawls and trammel nets and slightly lower in seines and gill nets (USACE-LDWF 1998). Only 211 spotted seatrout were collected in gill nets, seines, trammel nets, and trawls near Caernarvon over the 7-year period. Trawl catches increased by 267 percent (6-ft trawls) and 79 percent (16-ft trawls) post-operation.

Seine catches of primarily small juvenile trout decreased by 33 percent in the post-operation. Catches were the greatest at stations located an intermediate distance from the diversion. Gill net catch decreased by 22 percent post-operation. The overall catch of spotted seatrout in trawls near Caernarvon was 33 percent higher during the post-operation period (above and below the 5 ppt isohaline). The seine catch was 20 percent higher during the post-operation period and catch was higher post-operation (above and below the 5 ppt isohaline) (CPRA 2010a). No statistical significance was given in the CPRA (2010a) report. Spotted seatrout CPUE is presented in Figures 5-16 to 5-18.

Trammel net catch increased significantly ($P<0.05$) by 536 percent post-operation; however, the increase could not be attributed to the diversion because the *station*operation* interaction was insignificant. No clear relationship between catch and salinity was found (USACE -LDWF 1998).

The biomass of spotted seatrout was not affected relative to the control area after the opening of Caernarvon (de Mutsert 2010) (Figure 5-19).

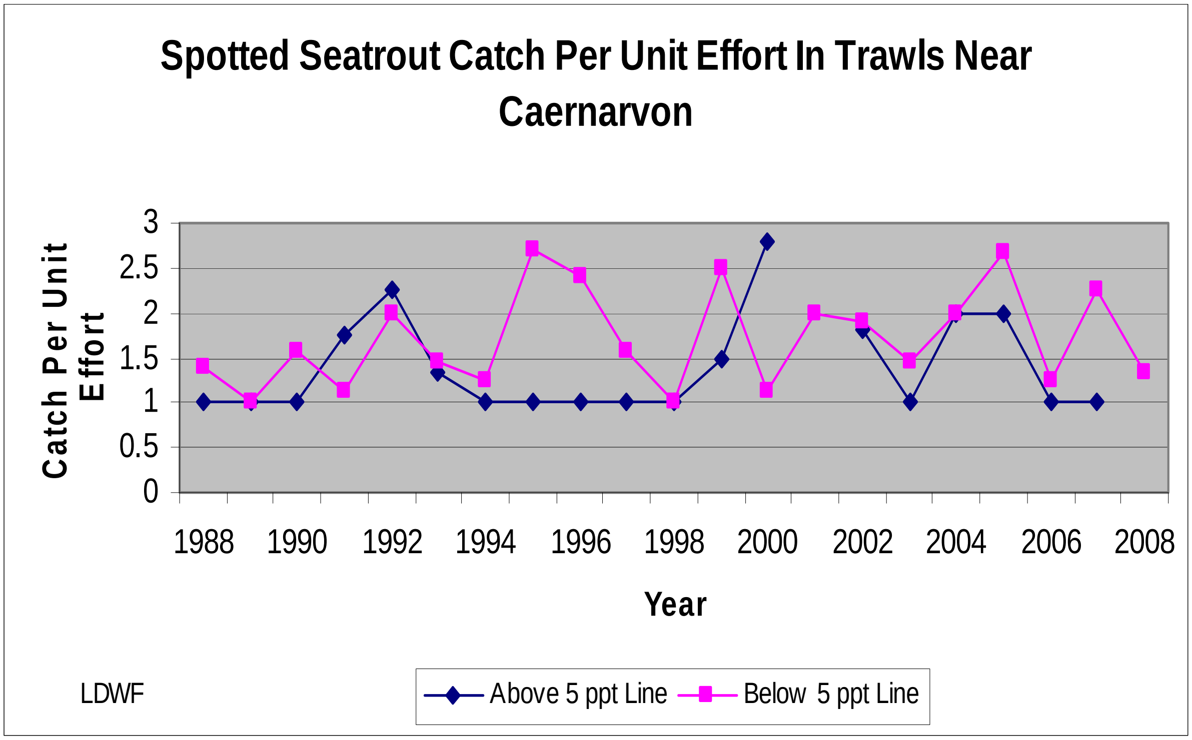


Figure 5-16. Spotted seatrout CPUE in trawls near Caernarvon (LDWF) from CPRA 2010a)

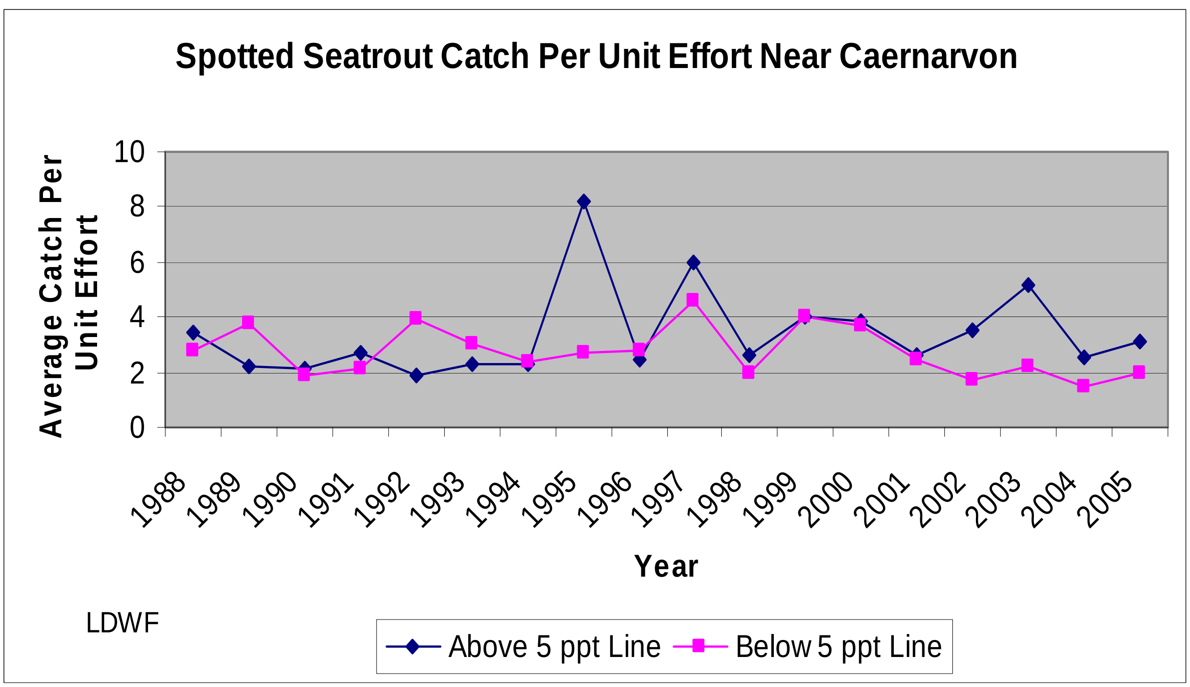


Figure 5-17. Spotted seatrout CPUE in seines near Caernarvon (LDWF) (from CPRA 2010a)

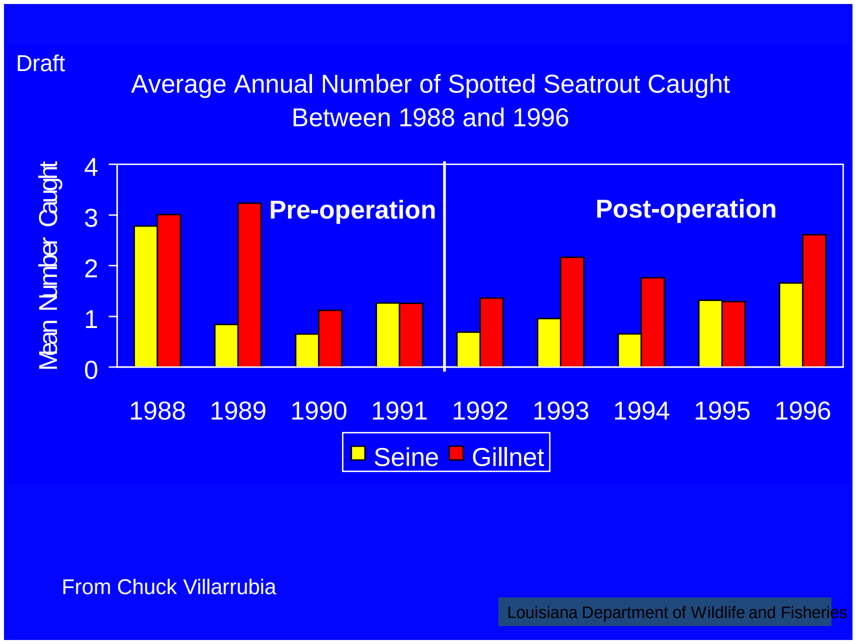


Figure 5-18. Mean number of spotted seatrout caught in seines and gill nets between 1988 and 1996 near Caernarvon pre- and post-operation (from C. Villarrubia, personal communication)

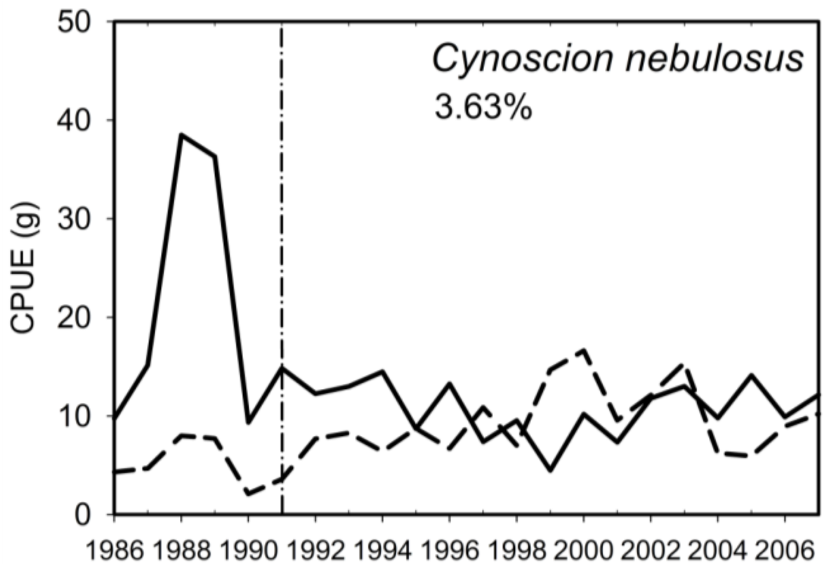


Figure 5-19. Spotted seatrout yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010).

5.3.1.2 Davis Pond

Spotted seatrout near Davis Pond were caught in trawls more consistently below the 5 ppt isohaline (CPRA 2010b). The increased catch during 2000 and 2001 may have been due to drought conditions. Approximately 25 percent fewer spotted seatrout were caught during the post-operation period.

Spotted seatrout were caught in seine samples in fairly equal numbers between pre- and post-operation periods and more frequently below the 5 ppt isohaline (CPRA 2010b). No statistical significance was given in the CPRA (2010b) report. Spotted seatrout CPUE is presented in Figures 5-20 and 5-21.

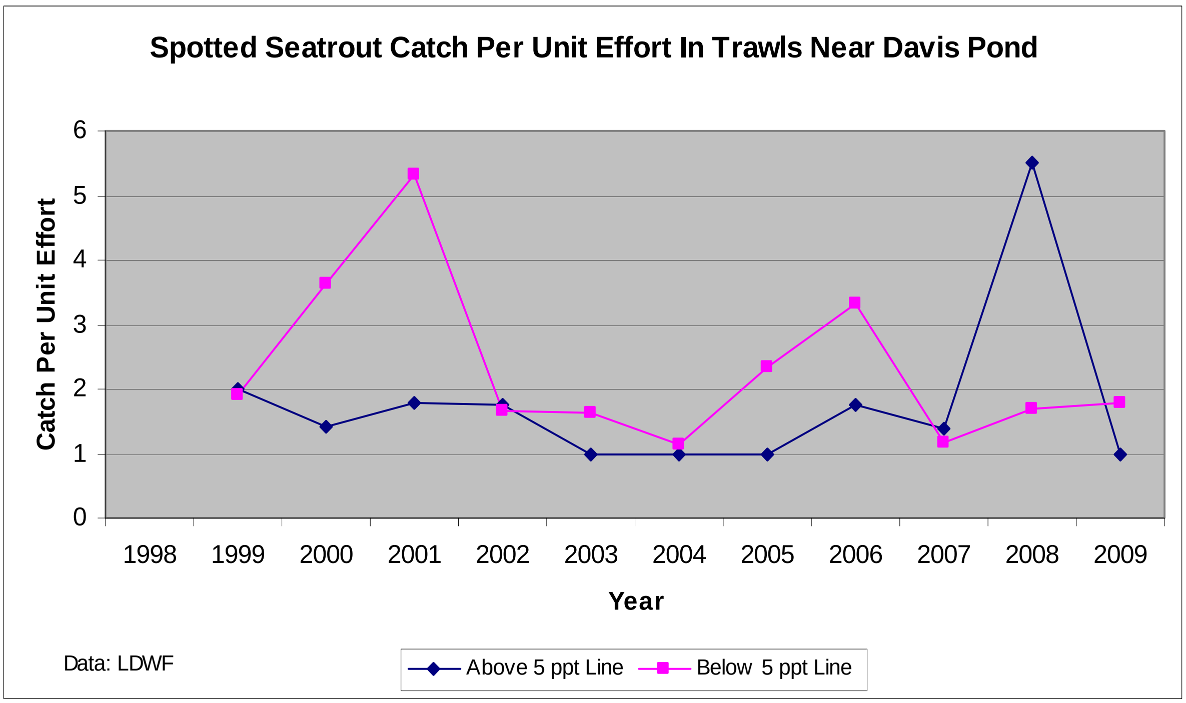


Figure 5-20. Spotted seatrout CPUE in trawl samples in Barataria Basin near Davis Pond (LDWF) (from CPRA 2010b)

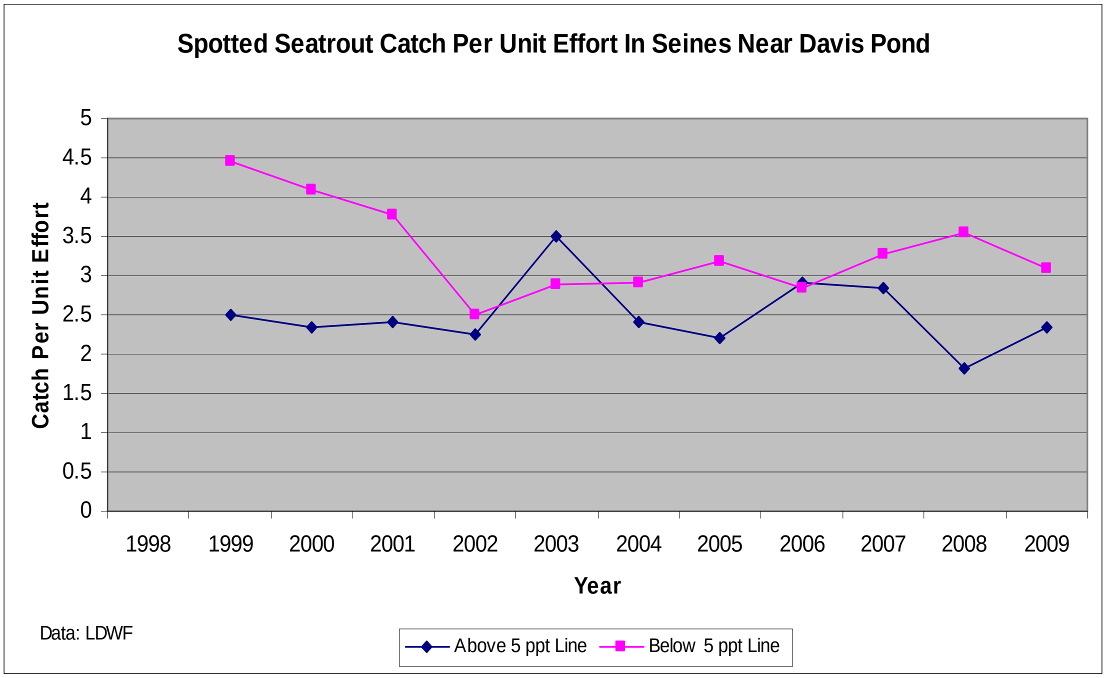


Figure 5-21. Spotted seatrout CPUE in seine samples in Barataria Basin near Davis Pond (LDWF) (from CPRA 2010b)

5.3.2 Red Drum

5.3.2.1 Caernarvon

Red drum *(Scieanops ocellatus)* were generally more abundant in the post-operation period and were caught in the greatest numbers in trammel nets, gill nets, and seines. Seine catch increased slightly (11 percent) in the post-operation (USACE-LDWF 1998). Gill net catch of red drum increased significantly (359) in the post-operation period ($P<0.05$). The catch of red drum in trammel nets increased by 1,297 percent post-operation. No clear trends between CPUE and salinities were observed and red drum were caught in large numbers at stations near the structure with salinities less than 1 ppt (USACE-LDWF 1998).

The red drum catch in the seine data was 29 percent higher during the post-operational period and were caught below and above the 5 ppt isohaline. The red drum catch was relatively consistent across post-operation years; peak catches occurred in 1994 and 2003. Peak catches occurred above the 5 ppt isohaline and the catch above this line doubled in the post-operation period. Trawl data catch was light for both periods (CPRA 2010a). No statistical significance was given in the CPRA (2010a) report. Red drum CPUE pre- and post-operation of Caernarvon in seines (Figure 5-22) and seines and gill nets (Figure 5-23) are presented below.
Red drum biomass was significantly higher post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010). Red drum yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF) is presented in Figure 5-24.

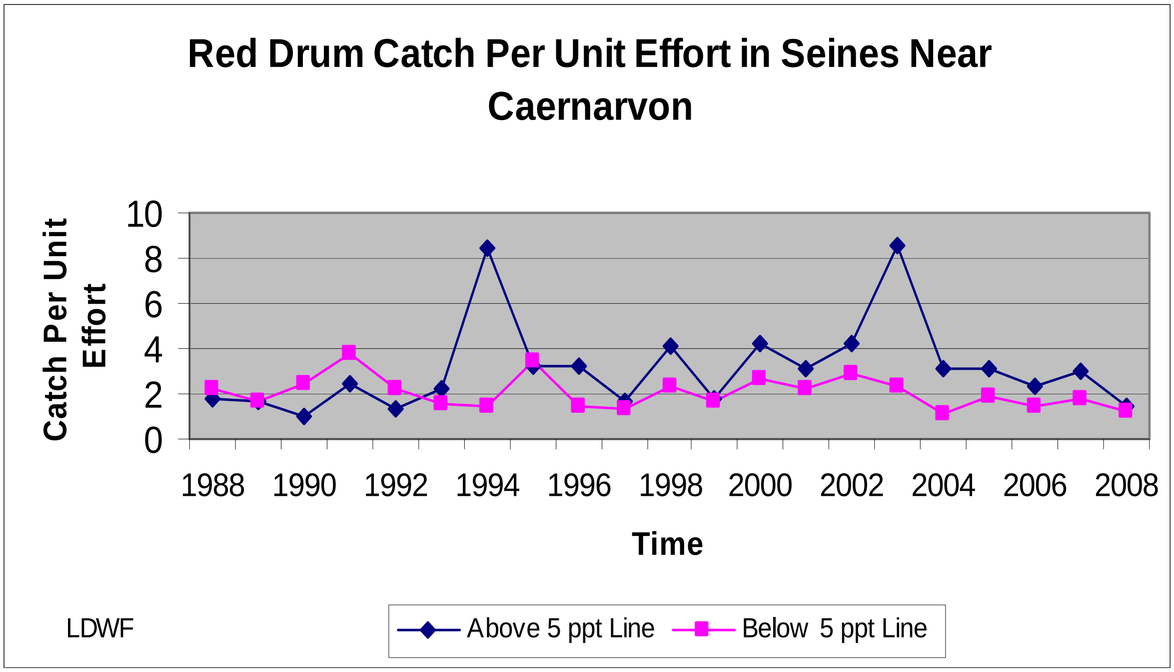


Figure 5-22. Red drum CPUE in seines near Caernarvon (LDWF) (from CPRA 2010a)

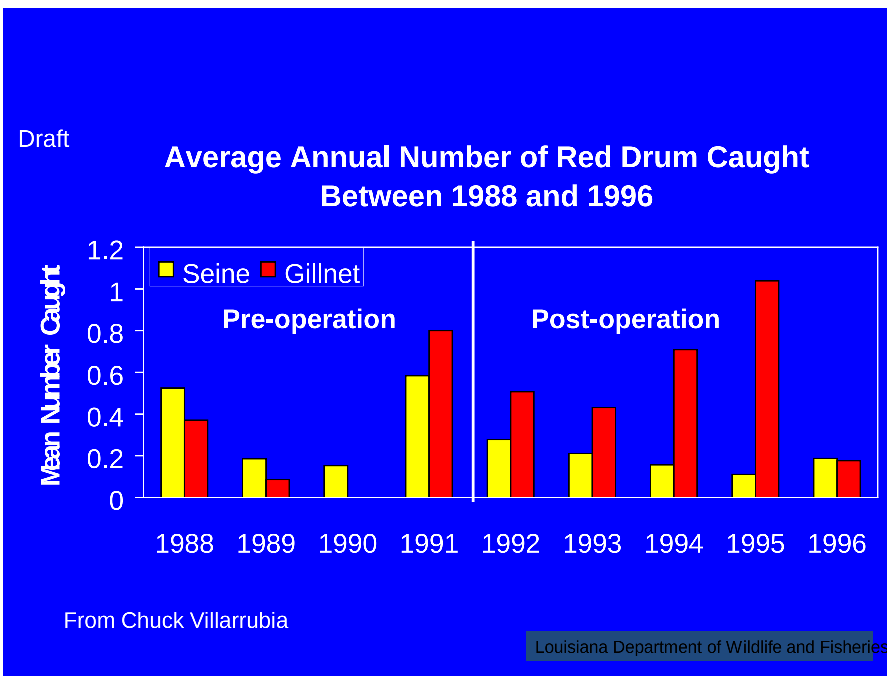


Figure 5-23. Mean number of red drum caught in seines and Gill nets between 1988 and 1996 near Caernarvon pre- and post-operation (1991) (from C. Villarrubia, personal communication).

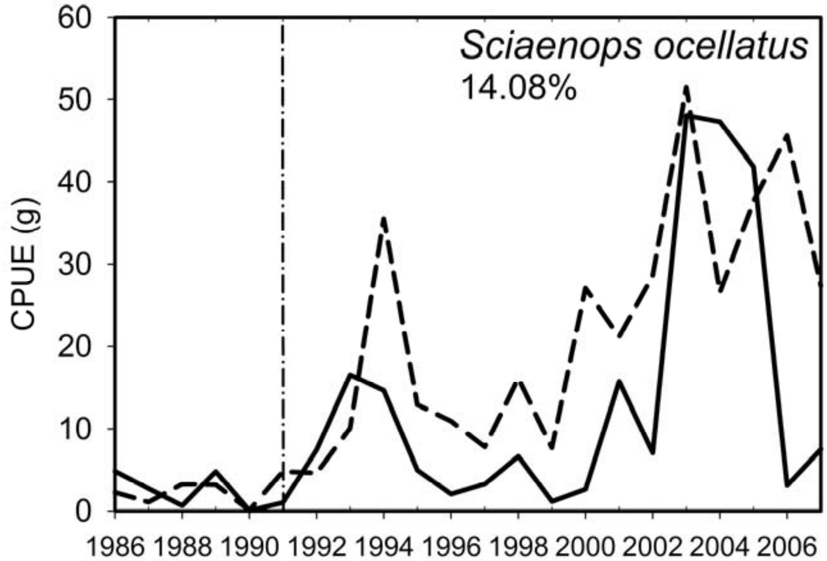


Figure 5-24. Red drum yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010).

5.3.2.2 Davis Pond

Red drum in trawl samples were more abundant in the post-operation period below the 5 ppt line; however, this was primarily due to one high catch in 2005 (Figure 5-25). About 47 percent fewer red drum were caught in seines in the post-operation period primarily due to high catches during drought years (1999 and 2000).

Seine catches of red drum were relatively equal above and below 5 ppt isohaline, except for a five to seven fold increase in CPUE below the 5 ppt line in late 1999 and early 2000 (Figure 5-26). High catches also occurred in 2006 above the 5 ppt line. No statistical significance was given in the CPRA (2010b) report.

5.3.3 Black Drum

Black drum *(Pogonias cromis)* catch rates increased during the post-operation period in gill nets and trammel nets, and CPUE was higher at stations nearest the diversion. The catch in gill nets increased by 65 percent in the post-operation period. Black drum were infrequently caught in trammel nets during the pre-operation period and catches significantly increased ($P<0.05$) by 177 percent post-operation. However, the *station*operation* interation term was not significant, so this increase was not attributable to the diversion (USACE-LDWF 1998).

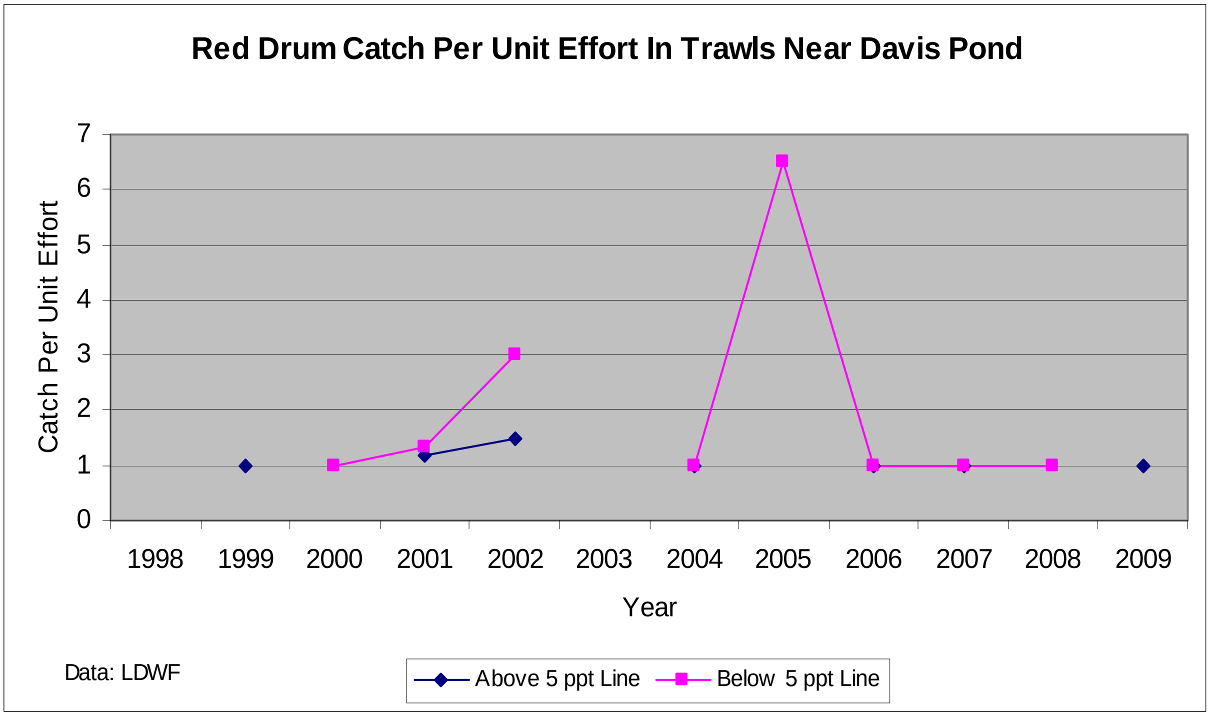


Figure 5-25. Red drum CPUE in trawl samples in Barataria Basin near Davis Pond (LDWF) (CPRA 2010b)

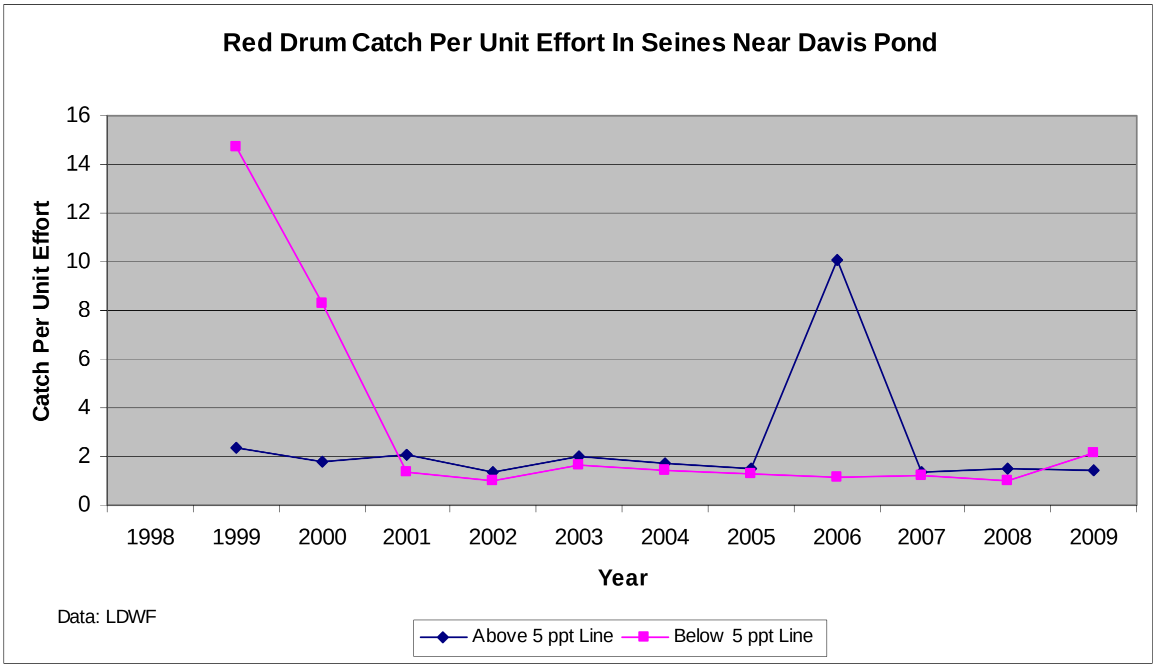


Figure 5-26. Red drum CPUE in seine samples in Barataria Basin near Davis Pond (LDWF) (from CPRA 2010b).

5.3.4 Atlantic Croaker

Atlantic croaker *(Micropogonias undulatus)* catch in seines increased slightly (10 percent) post-operation, but the pattern of catch among stations did not change in the post-operation period, and the change observed did not appear to reflect a structure impact (USACE-LDWF 1998). Catch increased in 6-ft and 16-ft trawls by about 100 percent. The increase in the 16-ft trawls was significant (P<0.05), but this was not attributable to the structure (the *station*operation* interaction term was insignificant). No clear trend related catch to salinity. Steep declines in catch may have reflected removal of juvenile croaker as bycatch in shrimp trawls, or may have reflected a seasonal migration of croaker.

Croaker catch in gill nets decreased slightly post-operation (-2.8 percent); these larger fish may have shifted away from the structure (USACE-LDWF 1998).

Atlantic croaker biomass was significantly higher post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010) (Figure 5-27).

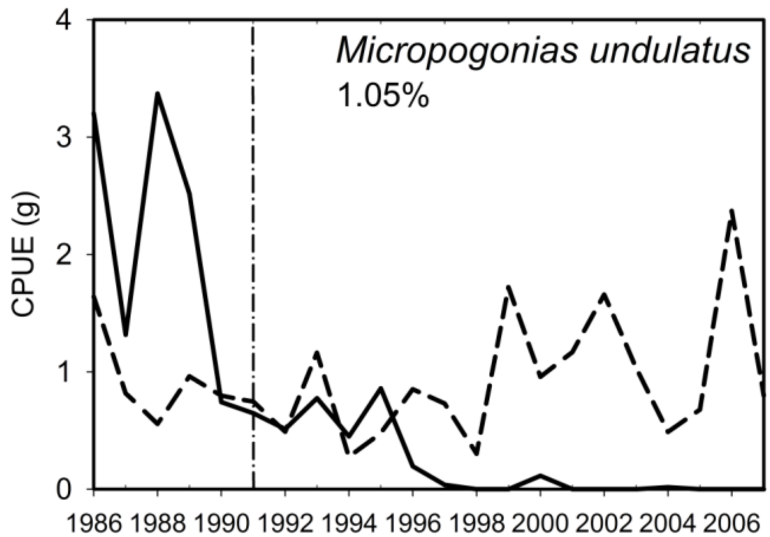


Figure 5-27. Atlantic croaker yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010).

5.3.5 Sand Seatrout

The catch of juvenile sand seatrout *(Cynoscion arenarius)* increased in the post-operation period in trawls and seines; particularly in 1991, when salinities were very low. Sand seatrout catch increased by 50 percent post-operation. This increase was greatest in 1991 and at the four stations of an intermediate distance from Caernarvon. Catch of sand seatrout in trawls increased by 48 percent (6-ft) and 193 percent (16-ft) post-operation; greatest increases occurred at the stations furthest from the diversion (USACE-LDWF 1998).

5.3.6 Spot

Spot *(Leiostomus xanthurus)* were caught in seines in slightly lower numbers (-20 percent) post-operation; the catch was significantly impacted by the Caernarvon structure (P=0.002). The pattern of fish abundance among the various stations changed significantly in the post-operation period; the greatest changes occurred nearest and farthest from the structure. Seine CPUE did not appear to be related to salinity. Trawl catches increased by 298 percent (6-ft) and 332 percent (16-ft) post-construction; catches were generally low at the stations near the structure and high at the stations farthest away.

Gill net catch increased by 98 percent post-operation; catch increased at all stations. Spot were only sporadically caught in trammel nets and the 2,058 percent increase in catch during the post-operation period was primarily due to an extremely high catch in October 1994.

No conclusions can be drawn from the trammel net data except trammel nets may not be the best gear to sample spot (USACE-LDWF 1998).

5.3.7 Sheepshead

Impacts of Caernarvon on sheepshead *(Archosargus probatocephalus)* were difficult to discern from the data. Although the catch in 16-ft trawls and gill nets decreased slightly post-operation, larger increases occurred in seine, trammel net, and 6-ft trawl catches. Catches of sheepshead in 16-ft trawls declined slightly (19 percent) and increased by 149 percent in the 6-ft trawl samples during the post-operation period.

The catch in seines increased by 63 percent post-operation; however, the high CPUE was limited to only three months in seven years, so conclusions are difficult.

The post-operation total catch of sheepshead increased by 52 percent in trammel nets and decreased slightly (-9 percent) in gill nets (USACE-LDWF 1998).

5.3.8 Gulf Menhaden

Catches of Gulf menhaden *(Brevoortia patronus)* in seines increased in the post-construction period by 503 percent and the greatest catch was at the station nearest the diversion; however the catch was very patchy. The menhaden is a schooling species; this results in patchy catches of large numbers. Seines and trawls tend to catch juveniles, whereas gill nets and trammel nets tend to catch larger fish. Trawl catches of menhaden increased by 325 percent (6-ft) and 85 percent (16-ft).

The trammel net catch increased by 3,264 percent post-construction; however, the catch was dominated by one month of samples and is not meaningful. Trammel nets were not deployed when Gulf menhaden were abundant.

Gill net catches decreased significantly ($P<0.05$) by 46 percent post-operation; however, the *station*operation* interaction term was not significant so the decrease was not attributable to the diversion. The large decrease in catch at the station closest to the diversion post-operation may have been due to the preference of larger menhaden for higher salinities (USACE-LDWF 1998).

Gulf menhaden abundance was significantly higher post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010) (Figure 5-28).

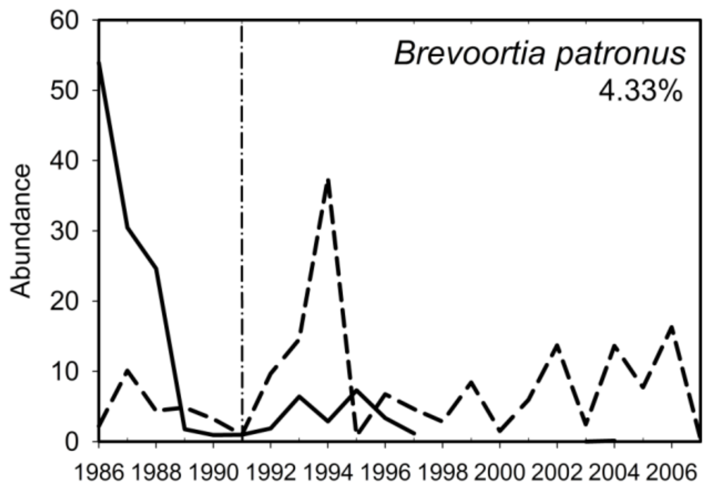


Figure 5-28. Gulf menhaden yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010)

5.3.9 Bay Anchovy

Bay anchovy *(Anchoa mitchilli)* abundance was significantly higher in seines in the post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010) (Figure 5-29).

5.3.10 Striped Mullet

Striped mullet *(Mugil cephalus)* CPUE was significantly higher post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010) (Figure 5-30).

5.3.11 Hardhead Catfish

Hardhead catfish *(Arius felis)* biomass in the Caernarvon impact area was less in the post-opening, as compared to pre-opening or the control area, although this difference was not significant (de Munsert 2010) (Figure 5-31).

5.3.12 Sheepshead Minnow

In seine catch, sheepshead minnow *(Cyprinodon variegatus)* abundance was significantly lower post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010) (Figure 5-32).

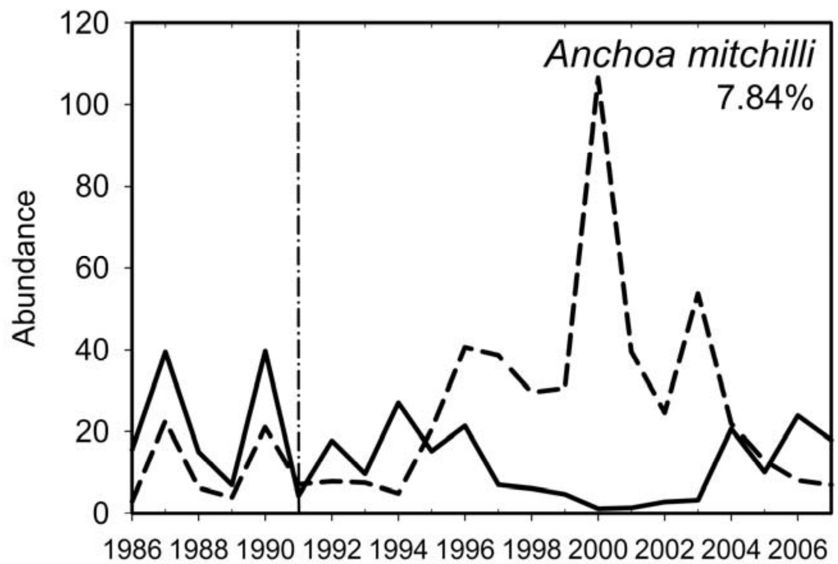


Figure 5-29. Bay anchovy yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010)

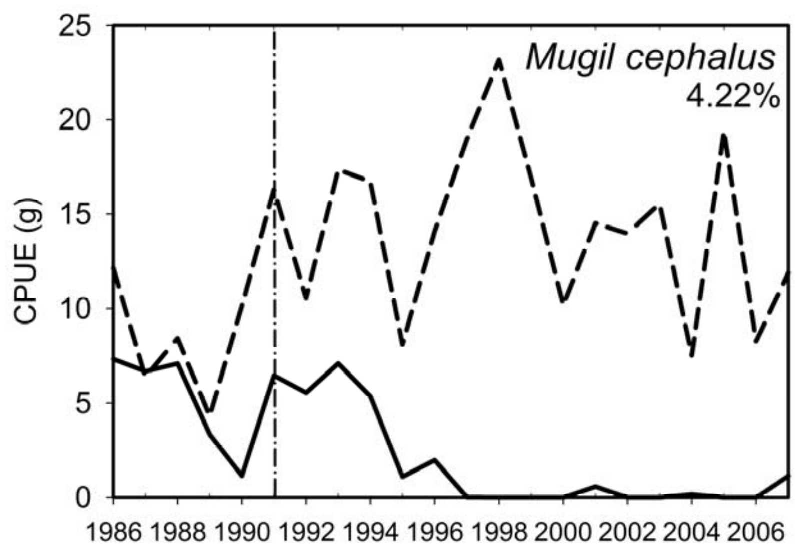


Figure 5-30. Striped mullet yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010)

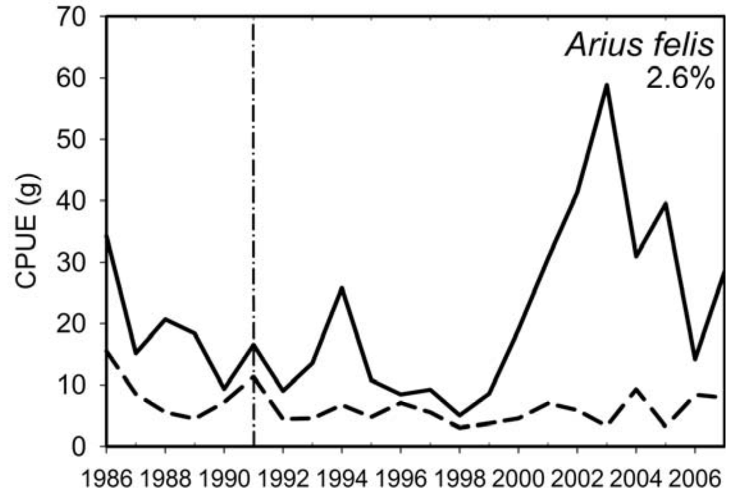


Figure 5-31. Hardhead catfish yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010)

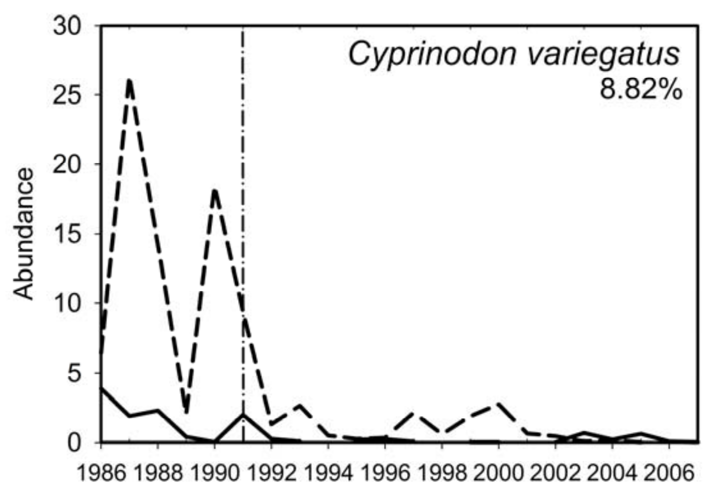


Figure 5-32. Sheepshead minnow yearly mean abundance for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010)

5.3.13 Western Mosquitofish

Growth rates of western mosquitofish (*Gambusia affinis)* were higher in the inflow area than in the reference area during experimental pulses of the Caernarvon Diversion (Piazza 2009).

5.3.14 Blue crab

5.3.14.1 Caernarvon

Post-operation catch of blue crab was almost double the pre-construction catch in seines and slightly changed in trawls. Seines primarily caught juvenile crabs, whereas trawls caught crabs of all sizes. CPUE increased by 88 percent post-operation, was highest in 1991 (a year of low salinities, although the river water was not introduced through Caernarvon), and catches increased at the most interior stations. Trawl crab catches increased slightly in the 6-ft trawls (18 percent) and decreased slightly (-3 percent) in the 16-ft trawls post-operation with no clear pattern among stations. Catch data for blue crab were inconclusive with respect to the diversion or salinity effects; however, blue crabs can be found in a wide range of salinities (USACE-LDWF 1998).

The mean blue crab catch in trawls was about 46 percent greater pre-operation than the post-operation; this appears to be due to a very abundant catch in 1990 (Figure 5-33). Above the 5 ppt isohaline, the catch is about equal between the pre- and post-operation periods. Below the 5 ppt isohaline, crabs were caught more frequently in trawls during the pre-operation period.

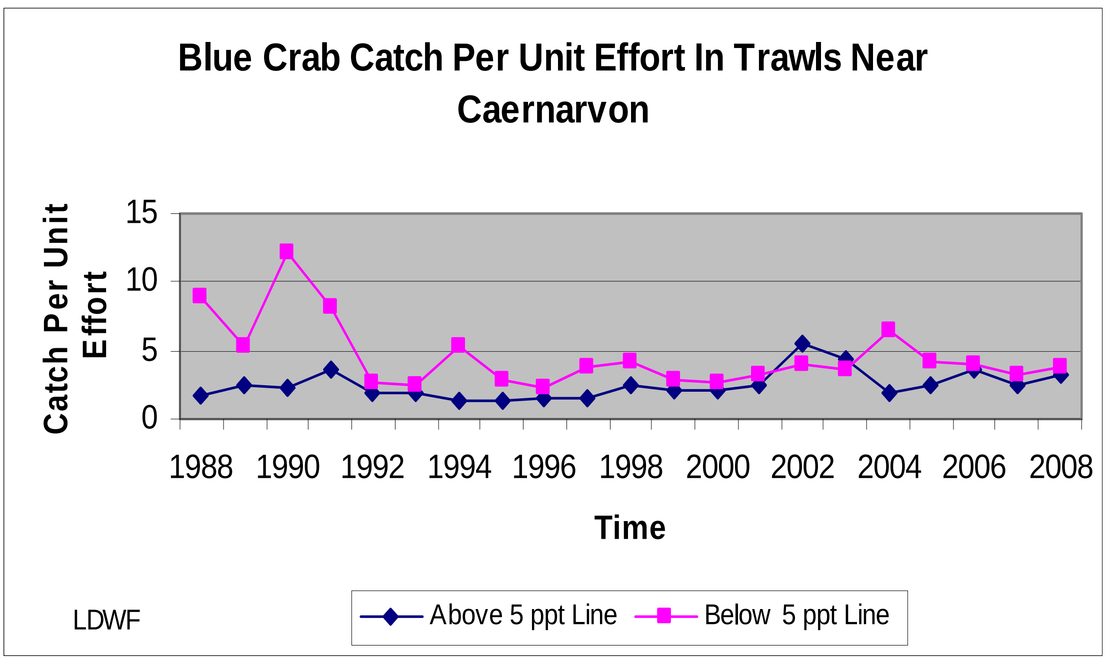


Figure 5-33. Blue crab CPUE in trawls near Caernarvon (LDWF) (from CPRA 2010a)

The mean catch in seines was 8 percent greater pre-operation. Crab trapping results were combined with the seine dataset from 2001 to 2004. The higher seine catches from 2001 to 2004 reflect this addition (Figure 5-34). Catches above the 5 ppt isohaline were higher from 1998 to 2004 (also partly reflects the crab trapping addition). Catches below the 5 ppt line generally decreased during this period. Mean crab catches for both types of trawls and seines are also presented in Figure 5-35.

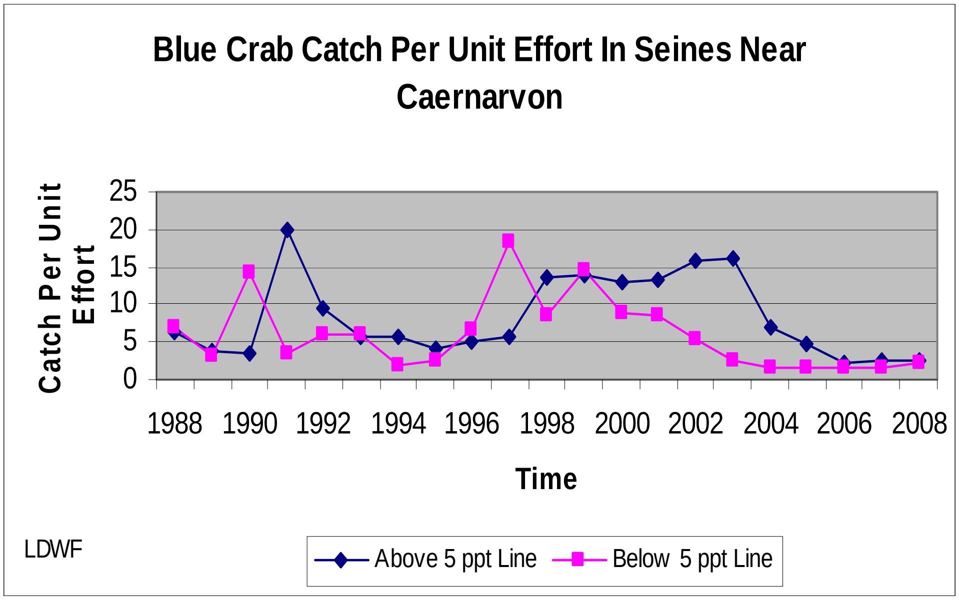


Figure 5-34. Blue crab CPUE in seines (plus crab traps from 2001-2004) near Caernarvon (LDWF) (from CPRA 2010a)

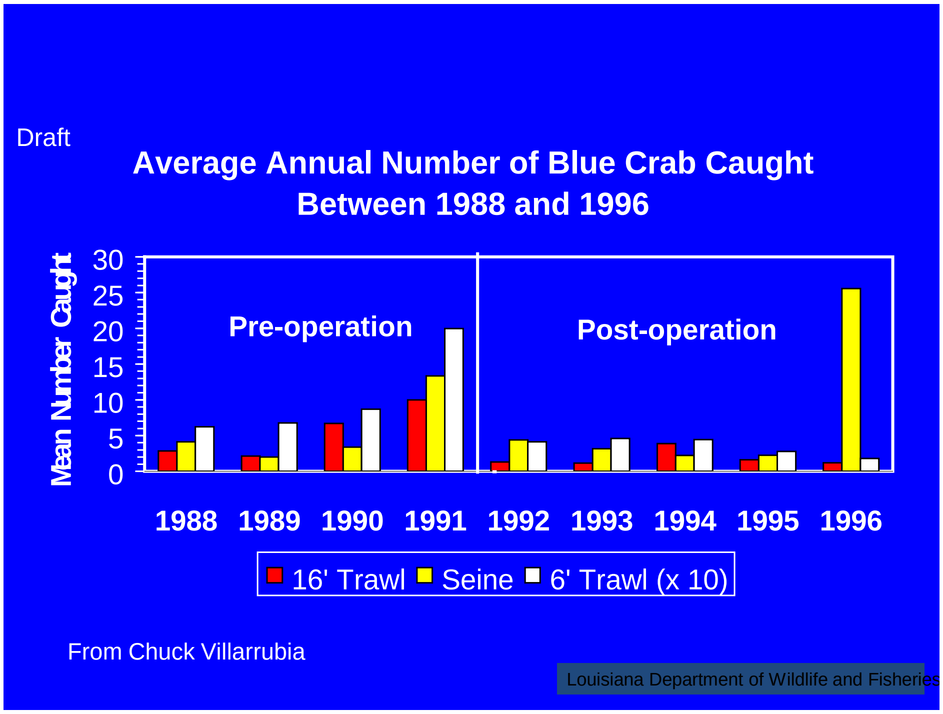


Figure 5-35. Mean number of blue crabs caught between 1988 and 1996 near Caernarvon pre- and post-operation (from C. Villarrubia, personal communication)

5.3.14.2 Davis Pond

Blue crab catches in trawls was more than 100 percent greater post-operation; catches were higher above the 5 ppt isohaline (Figure 5-36). The trawl catch of blue crab increased post-operation above and below the 5 ppt line; the greatest catch occurred in 2007. Blue crab CPUE in seine samples was equal between the pre- and post-operation periods (Figure 5-37). The catch of blue crabs above the 5 ppt line dropped from 1999-2004 but catches have generally been increasing since 2005 (USACE-LDWF 1998).

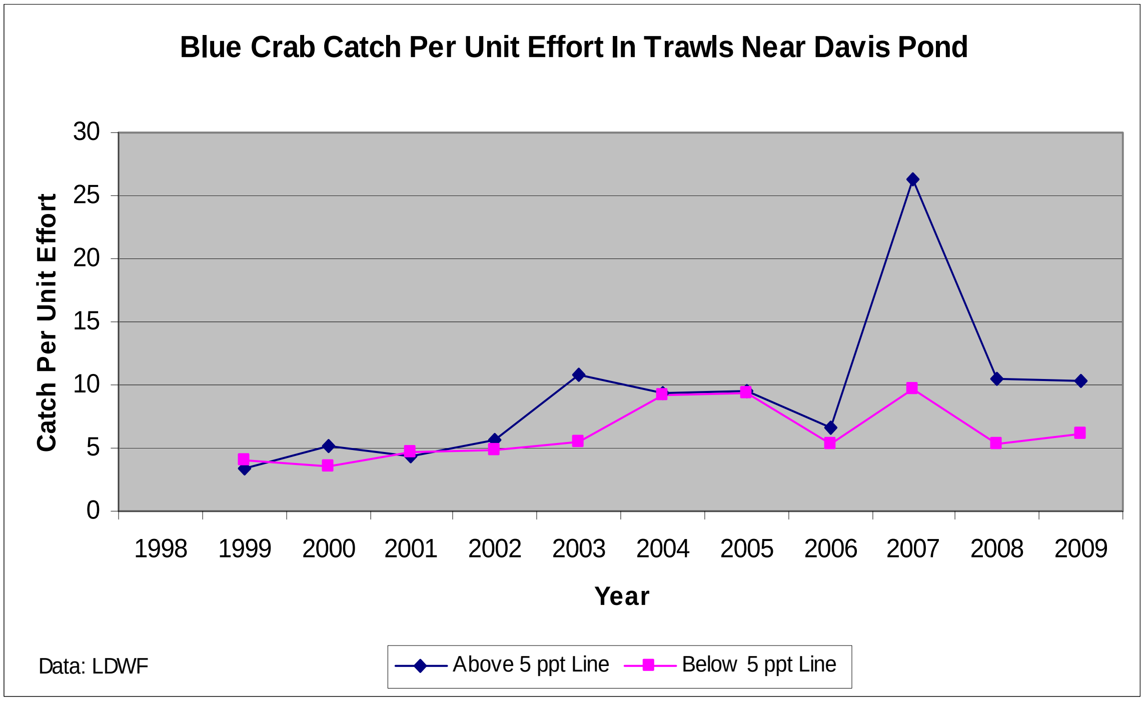


Figure 5-36. Blue crab CPUE in trawl samples in Barataria Basin near Davis Pond (LDWF) (from CPRA 2010b)

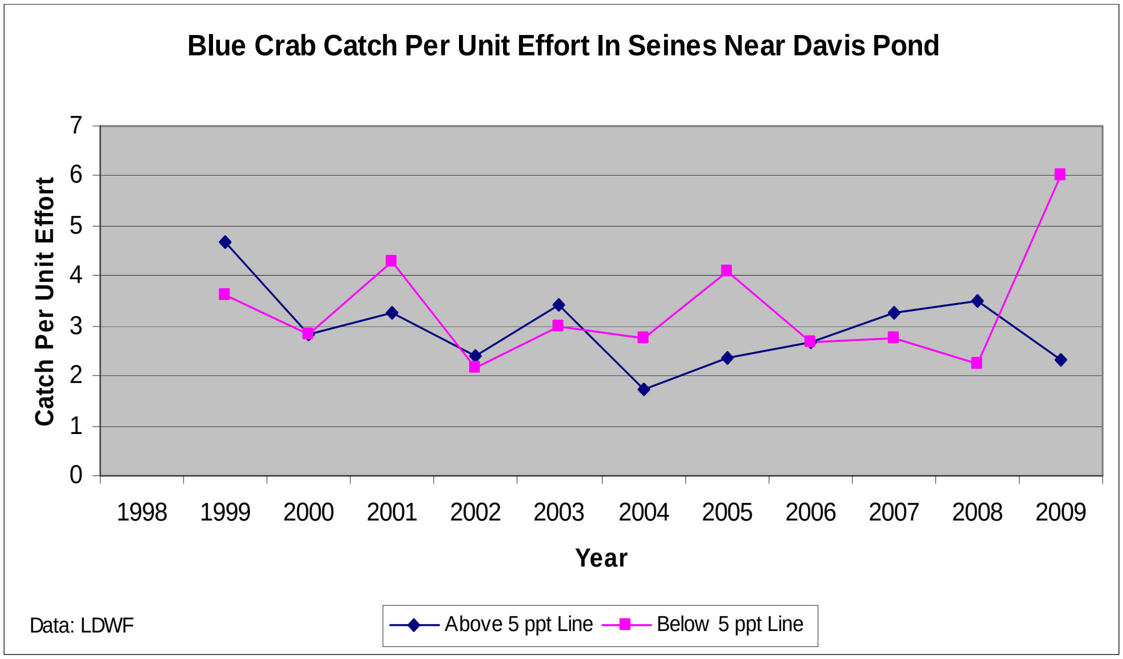


Figure 5-37. Blue crab CPUE in seine samples in Barataria Basin near Davis Pond (LDWF) (from CPRA 2010b)

5.3.15 Brown shrimp

5.3.15.1 Caernarvon

The total catch of brown shrimp *(Farfantepenaeus aztecus)* per year in seines was significantly less (63 percent) post-operation ($P<0.05$) (USACE-LDWF 1998). The change in the pattern of abundance of brown shrimp among stations sampled by seines may be due to the diversion; the *station*operation* interaction term was nearly significant ($P=0.0539$). The CPUE was greater pre-operation at all but one station, where the catch was nearly the same. Brown shrimp catches in seines appeared to follow similar patterns of low CPUE during years of low spring salinities and high CPUE during years of high spring salinities (USACE-LDWF 1998).

The brown shrimp catch was similar for pre- and post-operation in the 6-ft trawls (4 percent decrease post-operation) and decreased 56 percent in the 16-ft trawls post-operation, although this decrease was not significant. The report noted that the lack of an interaction did not imply that differences between the pre- and post-operation periods did not exist, but that high variability from other sources (year to year, month to month) reduced the chances of finding significant differences between the two periods. Factors other than salinity hypothesized in this report that may affect brown shrimp catch included the lack of finfish predators (possibly related to the fish kill related to the freeze of 1989) and the amount of postlarval recruitment (USACE-LDWF 1998).

The mean brown shrimp catch in trawls (6- and 16-ft combined) was slightly greater (2 percent) pre-operation. Catches were higher pre-operation below the 5 ppt isohaline and higher post-operation above the 5 ppt isohaline (Figure 5-38). The post-operation catch above the 5 ppt isohaline was nearly equal to the pre-operation catch below the 5 ppt isohaline. Catches above the 5 ppt isohaline were fairly consistent except for high catches in 1993 and 2003. Post-operation catches have been slightly increasing over time (CPRA 2010a).

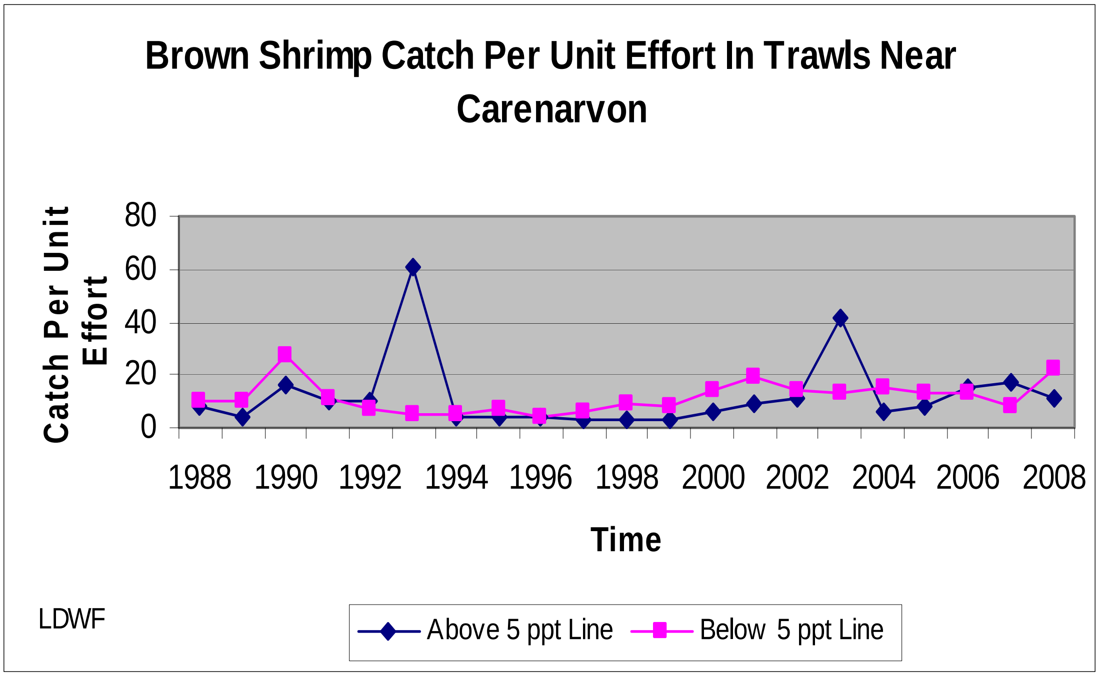


Figure 5-38. Brown shrimp CPUE in trawls near Caernarvon (LDWF) (from CPRA 2010a)

The mean catch in seines was 46 percent greater pre-operation. Mean catch of brown shrimp was below the 5 ppt isohaline pre- and post-operation (Figure 5-39). High post-operation catches below the 5 ppt isohaline have occurred frequently. Catches were variable below the 5 ppt isohaline until after 2000 when they remained low (CPRA 2010a). Mean numbers of brown shrimp caught in trawls and seines are also presented in Figure 5-40.

Brown shrimp did not appear to be negatively affected by the current flow regime of Caernarvon in a BACI analysis. The biomass was apparently declining before the diversion became operational and appears to be increasing in the inflow area since 1996 (Figure 5-41) (de Mutsert 2010).

Brown shrimp densities in drop samples near Caernarvon were relatively low, although they were comparable to values from other studies in similar habitat types and low-salinity areas. Densities did not differ significantly among the habitat types sampled; inflow area densities were similar to those in the reference area. Brown shrimp appeared to respond negatively to freshwater diversion inflows; no brown shrimp were caught in the first 7 km of the inflow area where salinities were 5 ppt or less (Rozas *et al.* 2005).

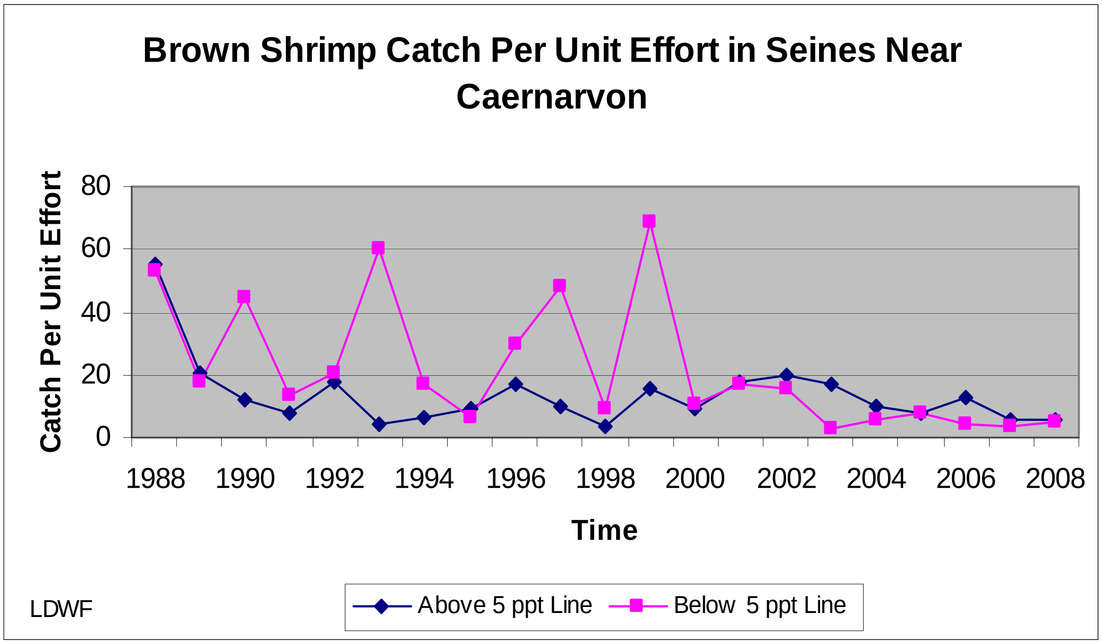


Figure 5-39. Brown shrimp CPUE in seines near Caernarvon (LDWF) (from CPRA 2010a)

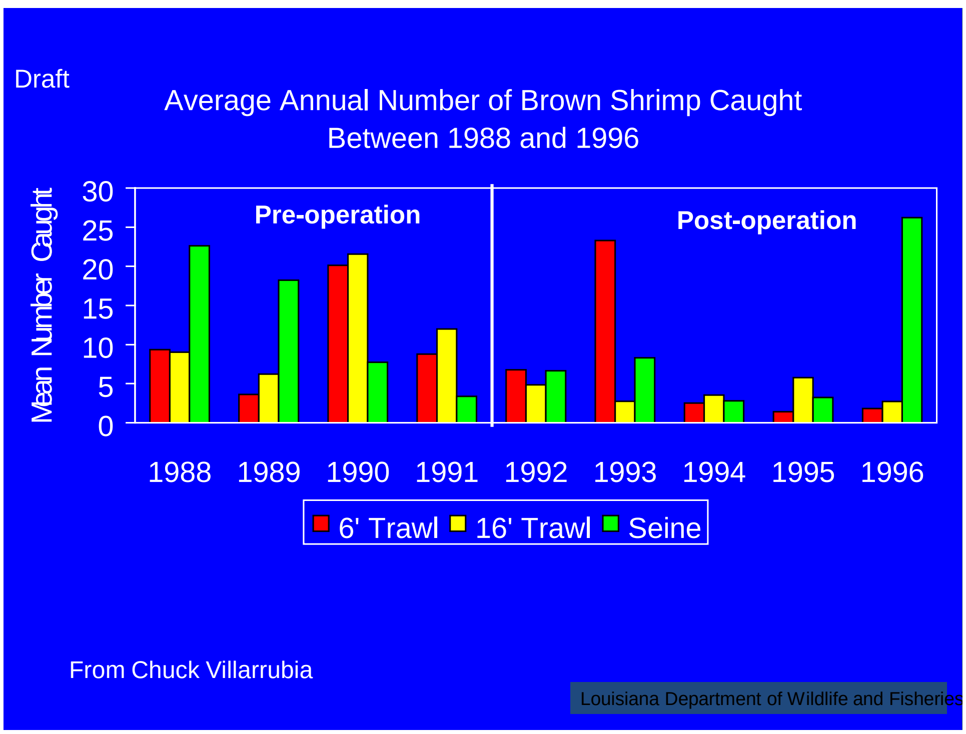


Figure 5-40. Mean number of brown shrimp caught between 1988 and 1996 near Caernarvon pre- and post-operation (from C. Villarrubia, personal communication)

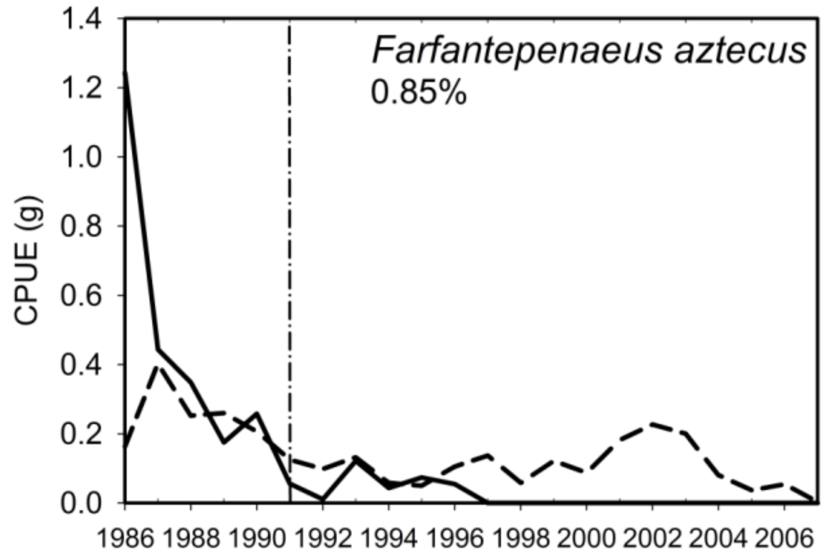


Figure 5-41. Brown shrimp yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010)

5.3.15.2 Davis Pond

Brown shrimp catch in trawls was slightly higher post-operation of Davis Pond; shrimp were caught more frequently below the 5 ppt isohaline during both periods (Figure 5-42) (CPRA 2010b). Brown shrimp CPUE in trawl samples peaked during April-May above and below the 5 ppt isohaline in each year; more extreme peaks below the 5 ppt isohaline. Brown shrimp catches were also slightly higher in seine samples post-operation and periods of high and low catch occurred (Figure 5-43).

5.3.16 White Shrimp

5.3.16.1 Caernarvon

White shrimp (*Litopenaeus setiferus*) total catch in seines did not change from pre- to post-operation (1 percent increase) (USACE-LDWF 1998). However, the catch among stations changed significantly (P=0.0149) post-operation, suggesting the change was due to the diversion. However, there was no clear pattern of change among the stations; stations near and far from the diversion increased post-operation, and stations of intermediate distance increased. There was a general trend of higher catch in years of high June salinity, except in 1993 (USACE-LDWF 1998).

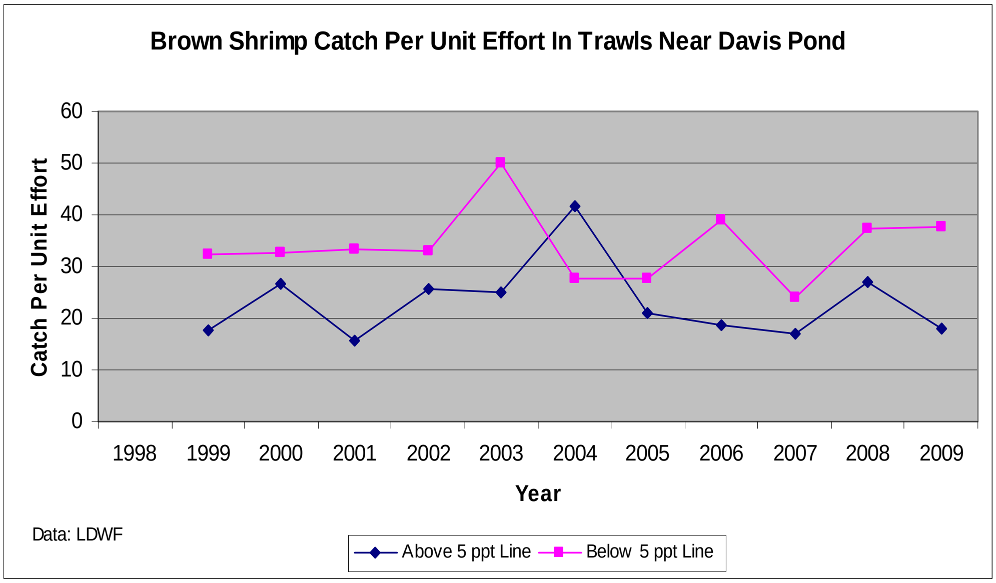


Figure 5-42. Brown shrimp CPUE in trawl samples in Barataria Basin (from CPRA 2010b)

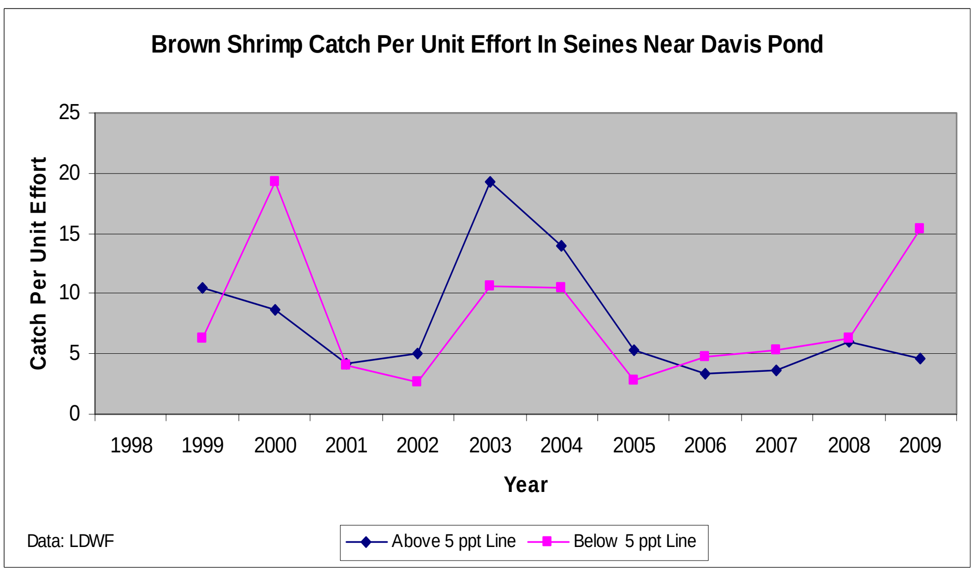


Figure 5-43. Brown shrimp CPUE in seine samples in Barataria Basin (from CPRA 2010b)

White shrimp catch in 6-ft trawls increased by 133 percent post-operation, primarily due to the large catches in 1991. Catches in the 16-ft trawls did not show a clear change post-operation (increase of 1.6 percent) (USACE-LDWF 1998). Catches either increased or stayed the same post-operation at all trawl stations, even those near the diversion. There was a trend of greater CPUE in years of lower mean August salinity in the 16-ft trawls and increased catches corresponded with low May-September salinities in the 6-ft trawl data (USACE-LDWF 1998).

The post-operation mean white shrimp catch in trawls (6- and 16-ft combined) was 77 percent greater; this increase occurred above and below the 5 ppt isohaline (Figure 5-44 – 5-46). Catches (primarily September-October) appear to have increased since 2001. The mean seine catch was about 11 percent lower in the post-operation period above and below the 5 ppt isohaline, except for a high catch in 1997 below the 5 ppt isohaline (Figure 5-45) (CPRA 2010a).

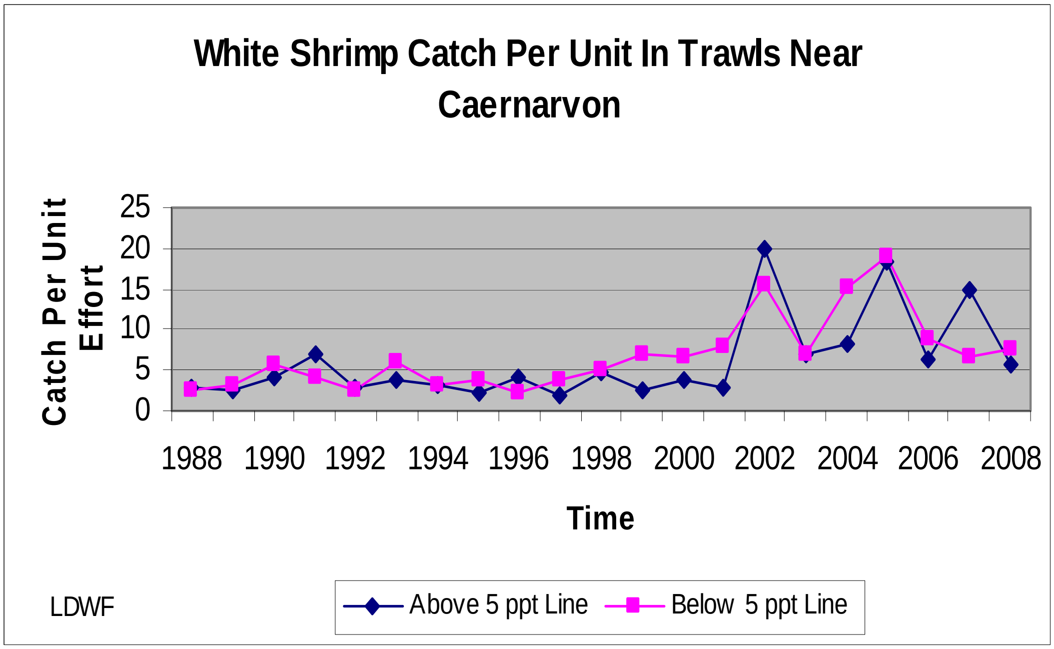


Figure 5-44. White shrimp CPUE in trawls near Caernarvon (LDWF) (from CPRA 2010a)

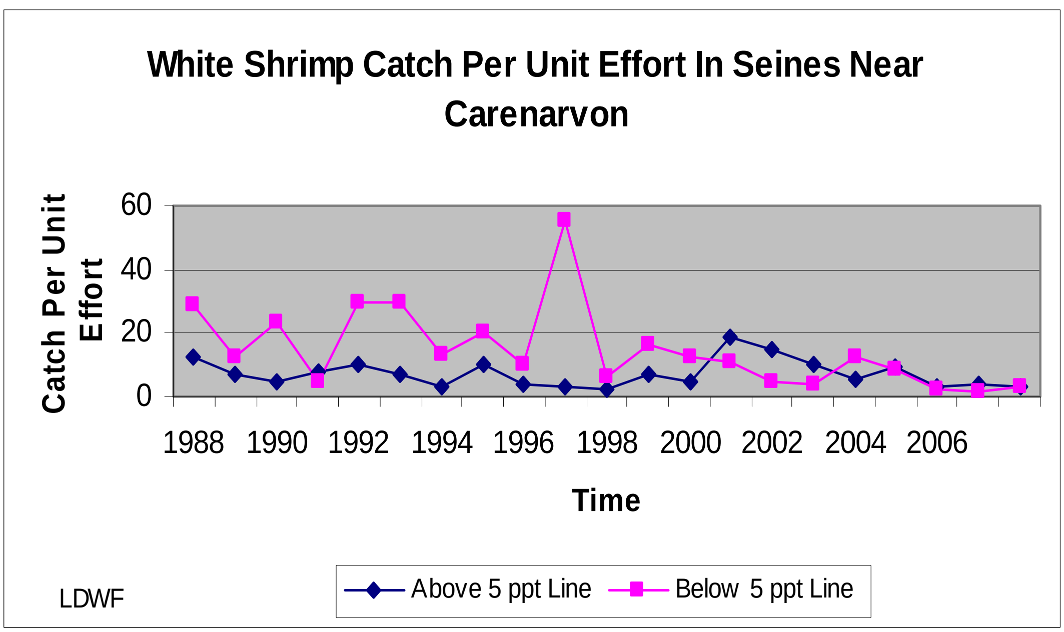


Figure 5-45. White shrimp CPUE in seines near Caernarvon (LDWF) (from CPRA 2010a)

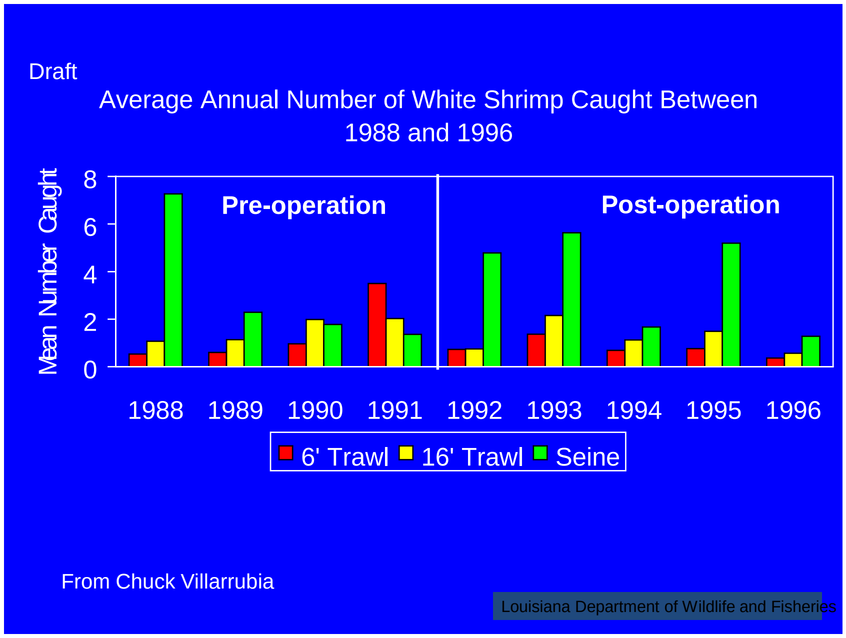


Figure 5-46. Mean number of white shrimp caught between 1988 and 1996 near Caernarvon pre- and post-operation (from C. Villarrubia, personal communication)

White shrimp biomass in seines was significantly higher post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010) (Figure 5-47).

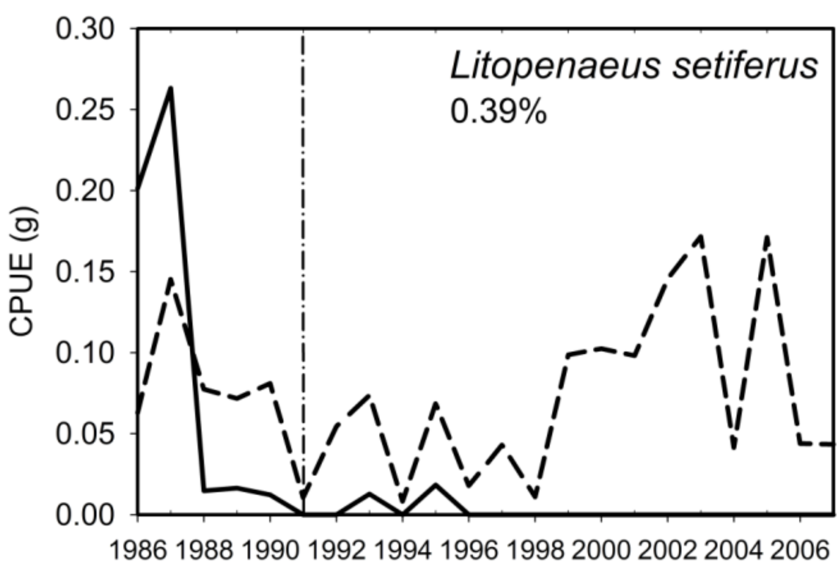


Figure 5-47. White shrimp yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010)

5.3.16.2 Davis Pond

White shrimp catch was about 150 percent higher in post-operation in trawls (6- and 16-ft combined) near Davis Pond. Catch increased substantially above and below the 5 ppt isohaline (Figure 5-48). The catch below the 5 ppt isohaline was about twice the catch above the 5 ppt isohaline in both periods. White shrimp catch in seines varied more than trawl catches. White shrimp abundance in seine samples was equal between pre- and post-operational periods. Peak catches occurred below the 5 ppt isohaline in 2001 and above the 5 ppt isohaline in 2009 (Figure 5-49).

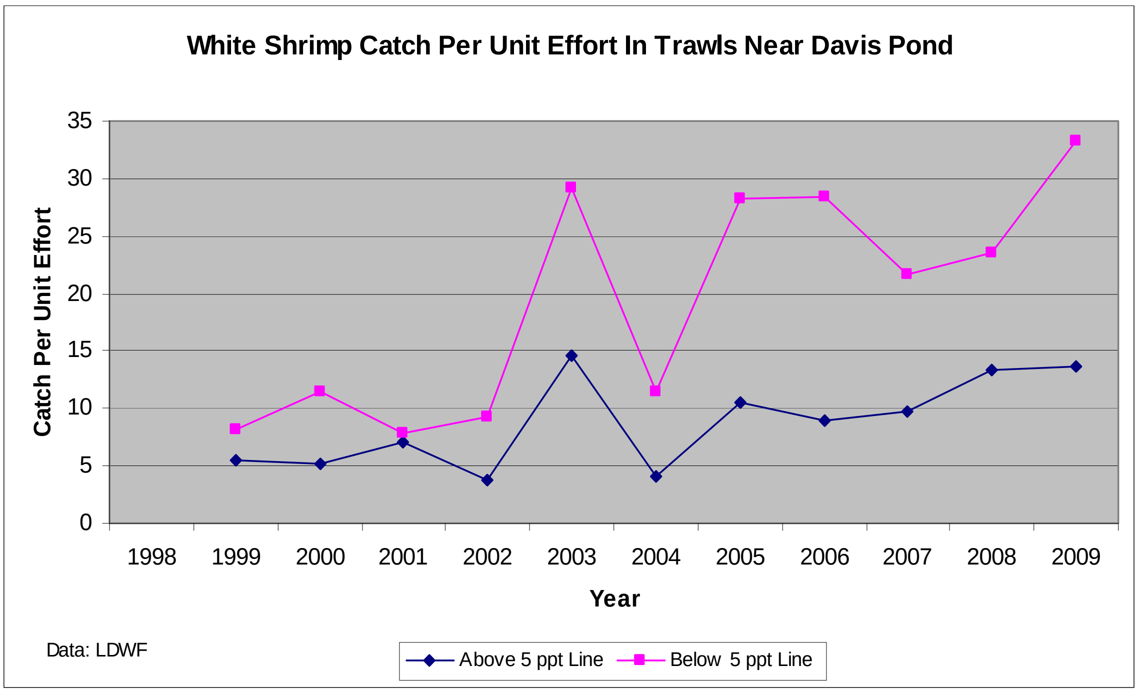


Figure 5-48. White shrimp CPUE in trawl samples in Barataria Basin (from CPRA 2010b)

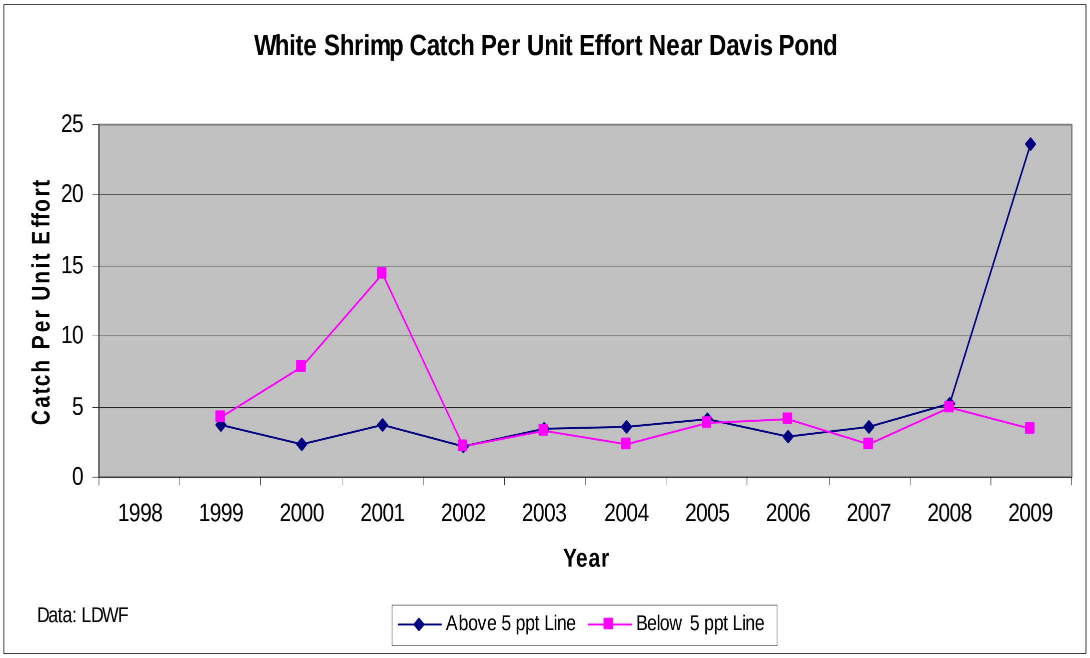


Figure 5-49. White shrimp CPUE in seine samples in Barataria Basin (from CPRA 2010b)

5.3.17 Grass Shrimp

Grass shrimp (*Palaemonetes* sp.) abundance in seines was significantly higher post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010) (Figure 5-50). The riverine grass shrimp was also more abundant in the inflow area than the reference area (Rozas *et al*. 2005).

5.3.18 Oysters

The effects of diversions on oysters are a complex combination of reef locations, salinity, presence of oyster predators (oyster drills, mussels) and diseases (Perkinsosis formerly dermo), pollution line closures, oyster condition, availability of market size oysters, availability of seed oysters, harvesting efforts, and other factors.

Salinity affects oyster distributions, and very low salinities can cause oyster mortalities, although the low salinity tolerance of oysters has been subject to debate. Adult oysters are typically found within a salinity range of 10 to 30 ppt in estuaries in the Gulf of Mexico; however, they can tolerate 2 to 40 ppt (Stanley and Sellers 1986). The susceptibility of oysters to low salinities appears to depend on the previous condition of the oyster (fatness), the length of time the oyster is exposed, and the water temperature (Gunter 1953). In general, lower temperatures are positively correlated with the quality or condition of the oysters (Owen and Walters 1950). Oyster abundance appears to increase one or two years after periods of increased freshwater inflow; lows appear to occur one to three years after declines in freshwater inflow (Buzan *et al.* 2009).

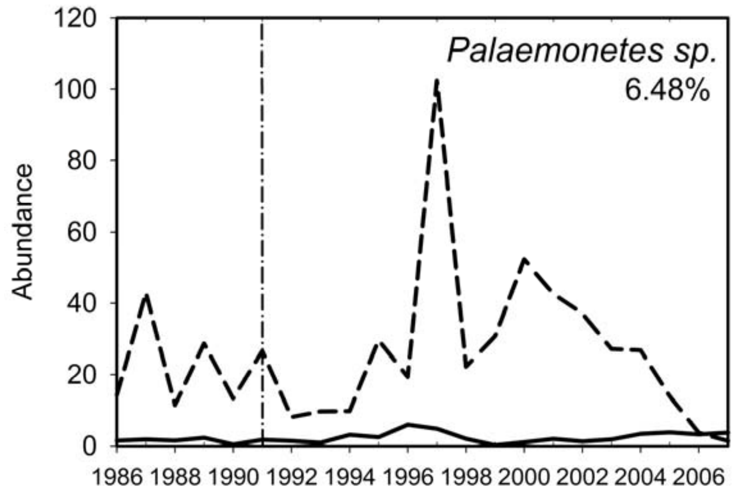


Figure 5-50. Grass shrimp yearly mean abundance for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation (from de Mutsert 2010)

Salinity also affects the distribution of oyster predators and parasites. Higher levels of parasitism generally occur in higher salinity waters (Gauthier *et al.* 2007). Susceptibility to infection by the protozoan, *Perkinsus mannus,* in oysters is significantly and positively correlated with salinity (Chu *et al.* 1993; Chu and La Peyre 1993). La Peyre *et al.* (2009) suggested that Perkinsosis infection intensities could be controlled with two to three week freshet (freshwater inflow) events through the Caernarvon Diversion.

The southern oyster drill is an important predator on oysters. Oyster drill populations fluctuate due to environmental changes, such as changes in salinity or temperature (Brown *et al.* 2004). Oyster drills are typically found in the higher salinity portions of estuaries, where salinities are greater than 15 ppt (Butler 1954). However, the salinity at which mortality occurs fluctuates depending upon the salinity the oyster drills were accustomed to and how quickly the salinity declines (Butler 1985). Water temperatures below 12°C also have been found to limit oyster drill feeding (Butler 1985). Black drum *(Pogonias cromis)* also prey on oysters (Brown *et al.* 2003) and are likely to be more abundant in higher salinity areas in the northern Gulf of Mexico.

5.3.18.1 Caernarvon

Since the opening of the Caernarvon Diversion, seed and sack oysters available on the public oyster seed grounds in the Caernarvon outfall have increased substantially (Figure 5-51) (CPRA 2010a).

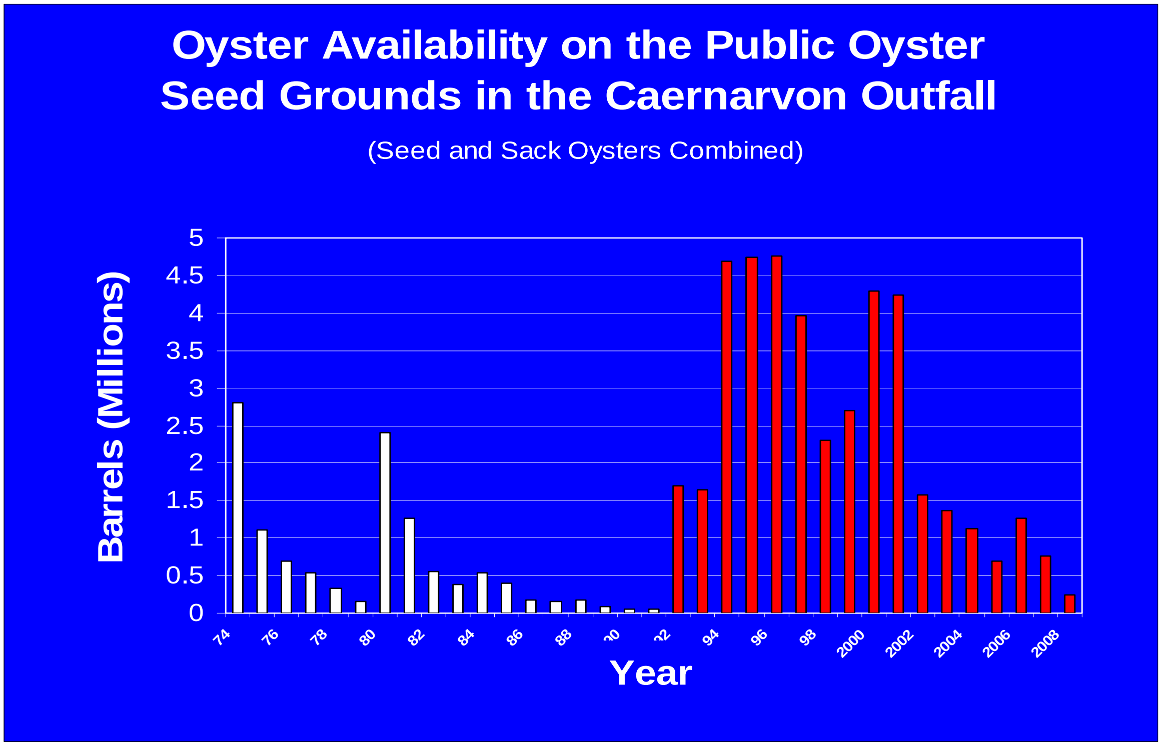


Figure 5-51. Oyster availability (seed and sack oysters combined) on the public oyster seed grounds in the Caernarvon outfall (LDWF). Pre-operation is white; post-operation is red (from CPRA 2010a)

Square Meter Samples

The number of seed oysters observed in the Caernarvon post-operation period was more than 12 times that of the pre-operation period. Square meter samples were used to evaluate oyster density on public grounds reefs at 27 stations (Figure 5-52) (USACE-LDWF 1998). The preconstruction period had low seed availability (Figure 5-53). The pre-operation (1982-1991) stock assessment seed oyster average was 74,741 barrels and the post-operation (1992-1994) average was 1,641,439 barrels (Table 5-4) (USACE-LDWF 1998).

Seed and sack oysters increased over 1,000 percent during the post-operation period (CPRA 2010a). Numbers of dead oysters increased by 96 percent; however, during pre-operation dead oysters were a much higher percentage of the total than post-operation. Mortality peaked in 1991 (56 percent) and was lowest in 2003 (2 percent); the overall percentage mortality dropped from pre-operation (36 percent) to post-operation (7 percent). Oyster abundance was higher during post-operation at all stations (CPRA 2010a).

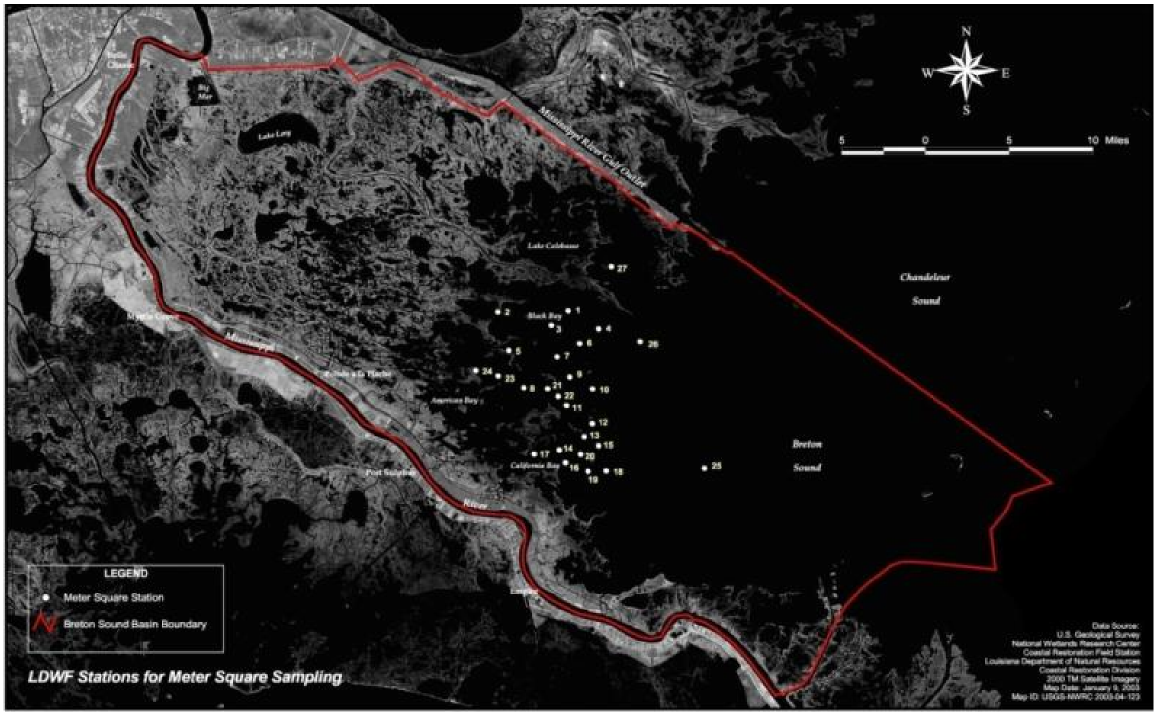


Figure 5-52. Location of oyster meter square stations at Caernarvon (from CPRA 2010a)

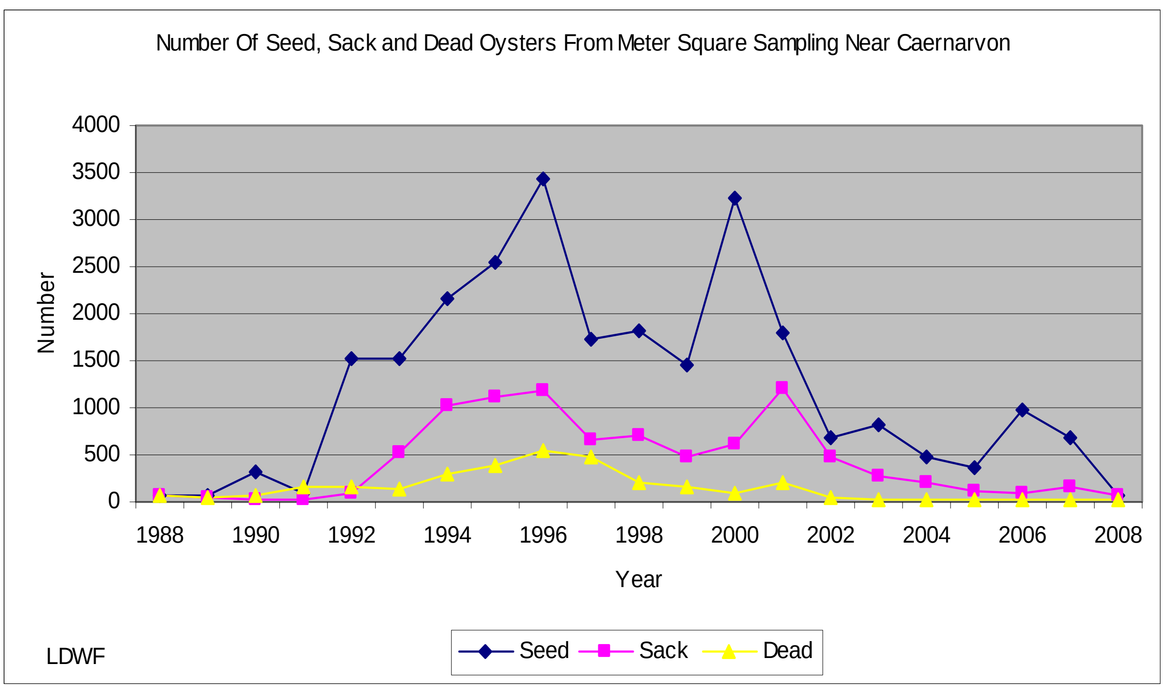


Figure 5-53. Number of seed, sack, and dead oysters from meter square sampling at Caernarvon pre- and post-operation (1991) (LDWF data) (from CPRA 2010a)

Table 5-4. Stock Assessment of Seed Oysters at Caernarvon Outfall (adapted from USACE-LDWF 1998)

Year	Barrels
Pre Operation	
1982	164,248
1983	68,602
1984	179,041
1985	150,874
1986	25,412
1987	52,048
1988	14,309
1989	13,031
1990	38,870
1991	40,977
Post Operation	
1992	1,242,598
1993	701,772
1994	2,979,946

Oyster productivity on the oyster seed grounds has been high post-operation. Oyster productivity typically peaks after a flood on the Mississippi River (as in 1974 and 1980). After Caernarvon began operating, productivity increased substantially but has been dropping since 2003 generally due to increased harvesting on the public seed grounds (Figure 5-54).

Oyster Harvest

The average production of sack oysters increased 277 percent since the pre-operation period. Oyster harvest is monitored by boarding and estimating the number of oysters on boats dredging in Breton Sound. Although inter-annual oyster harvest is variable, it has remained high post-operation. The average harvest was greatest in 2002 and lowest in 1990 (Figure 5-55).

Oyster Growth and Mortality

The overall survival post-operation was 32 percent and 64 percent pre-operation (CPRA 2010a). If stations above the 5 ppt isohaline are excluded, the overall survival is 64 percent pre-operation and 45 percent post-operation (CPRA 2010a). Nestier tray locations are presented in Figure 5-56. Survival of oysters varied among years (Figure 5-57). Analysis of variance performed on the interaction between station, time, and pre-versus-post-operation was significant (P=0.0001). The diversion did not affect all stations equally; stations closer to the diversion structure were impacted the most. The mortality rate was 100 percent mortality at stations 1 and 2 in all postconstruction years and the next greatest mortality was at station 3, the next closest station. During the preconstruction period, these stations had low mortality, suggesting the cause of the mortality was extremely low salinity (USACE-LDWF 1998) Hurricane Katrina destroyed all the nestier trays in August 2005. Nestier trays were not reestablished until July of 2006 so survival was relatively high in 2006 (CPRA 2010a).

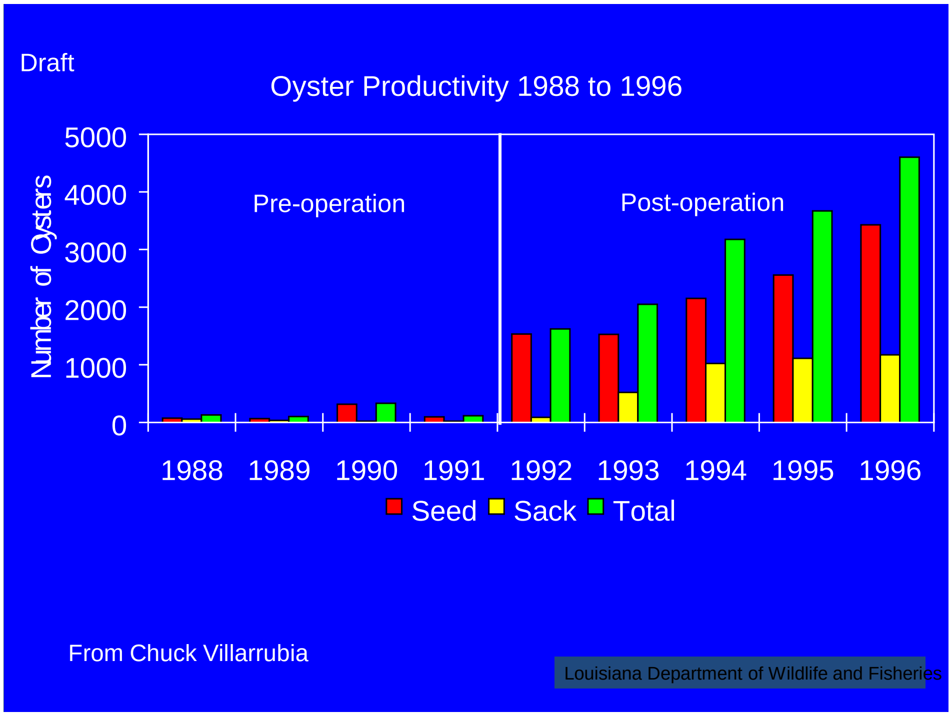


Figure 5-54. Oyster productivity (seed, sack, and total) between 1988 and 1996 near Caernarvon pre- and post-operation (1991) (LDWF data) (from C. Villarrubia, personal communication)

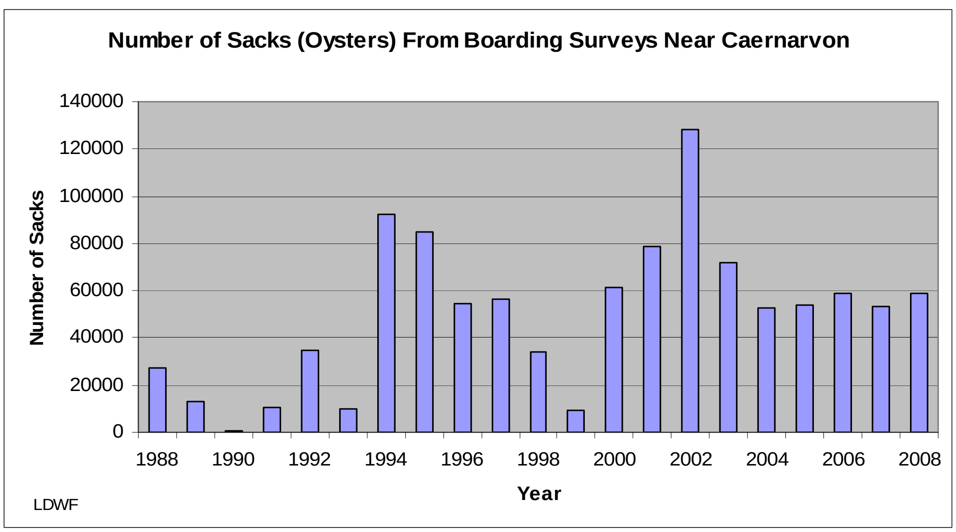


Figure 5-55. Number of oyster sacks from boarding surveys near Caernarvon pre- and post-operation (1991) (LDWF data) (from CPRA 2010a)

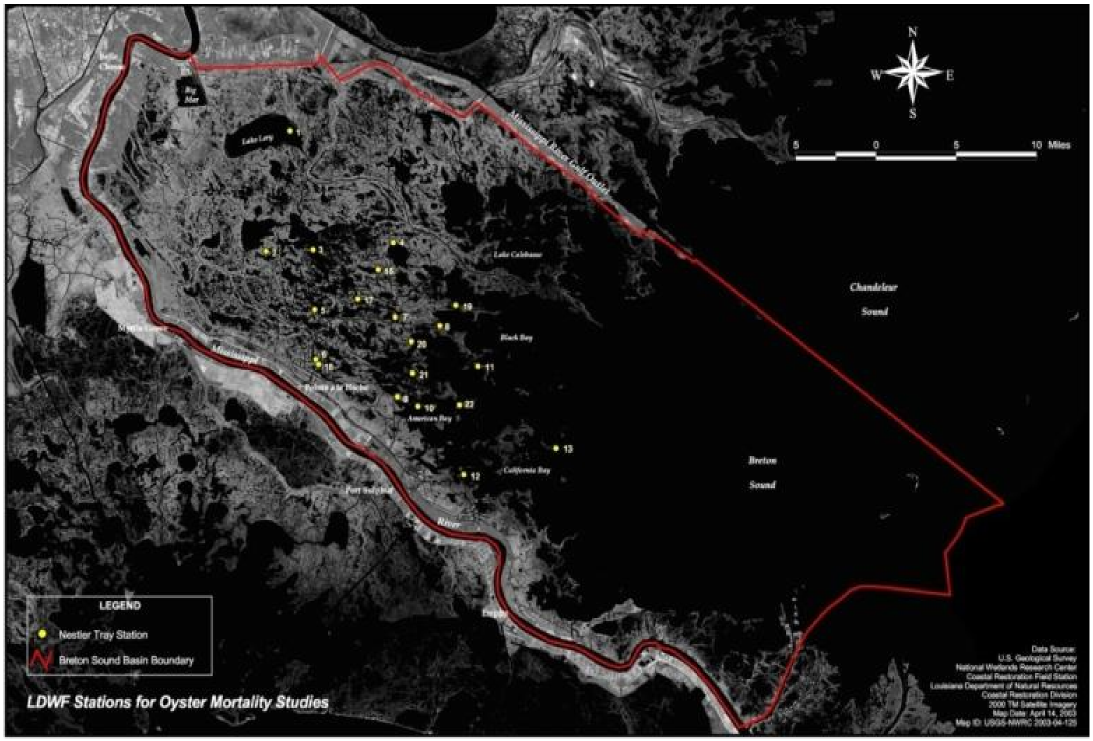


Figure 5-56. Location of nestier trays near Caernarvon (from CPRA 2010a)

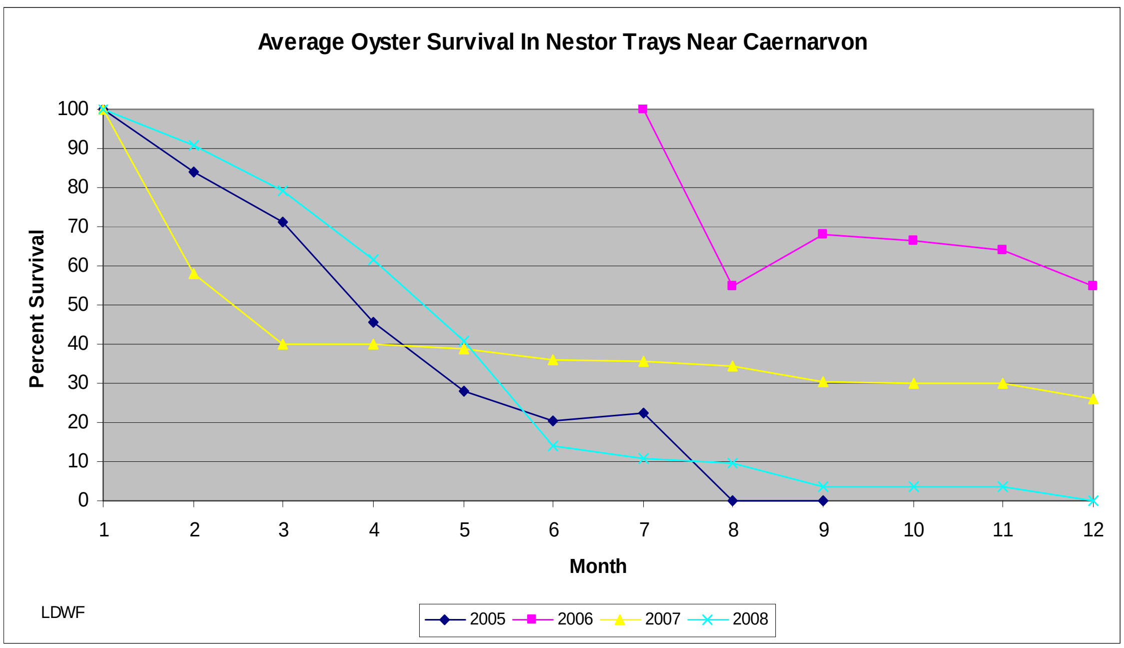


Figure 5-57. Average oyster survival in nestier trays near Caernarvon (from CPRA 2010a)

5.3.18.2 Davis Pond

Square Meter Samples

Seed oysters in meter square samples near Davis Pond remained low during post-operation except for an increase in 2005 (Figure 5-58). Locations of stations are presented in Figure 5-59. Numbers were high during the first pre-operation years then decreased during the next few years. Sack oysters were similar between pre- and post-operation except for increases in 2001 and 2007. Dead oysters increased slightly in the last pre-operation year and the first post-operation year, then decreased.

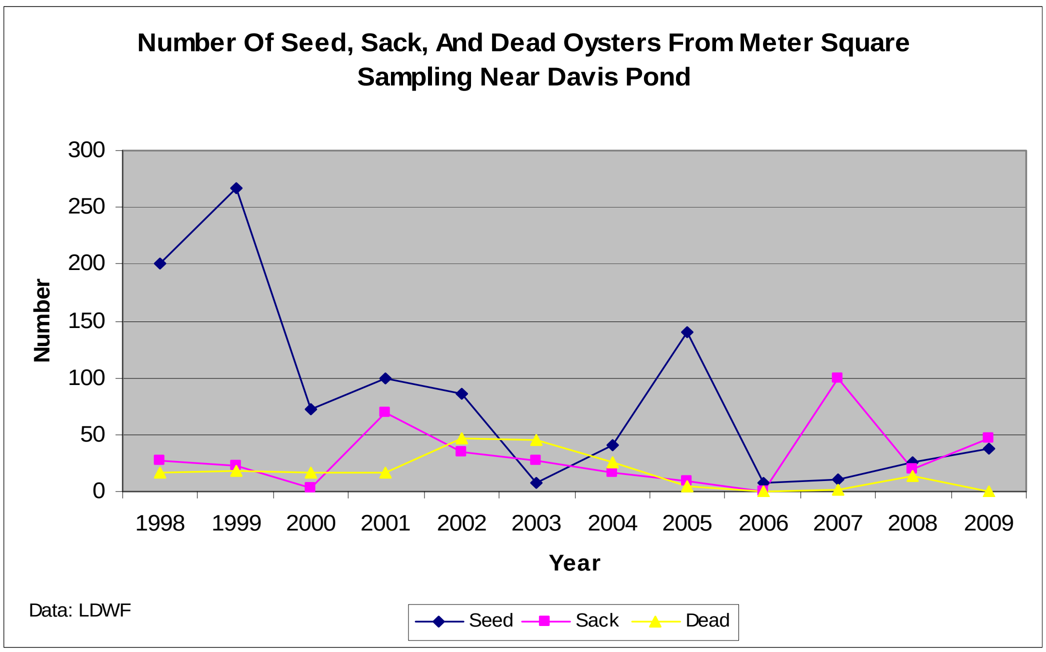


Figure 5-58. Number of seed, sack, and dead oysters from meter square sampling at Davis Pond pre- and post (limited) operations in July 2002 (LDWF data) (from CPRA 2010b)

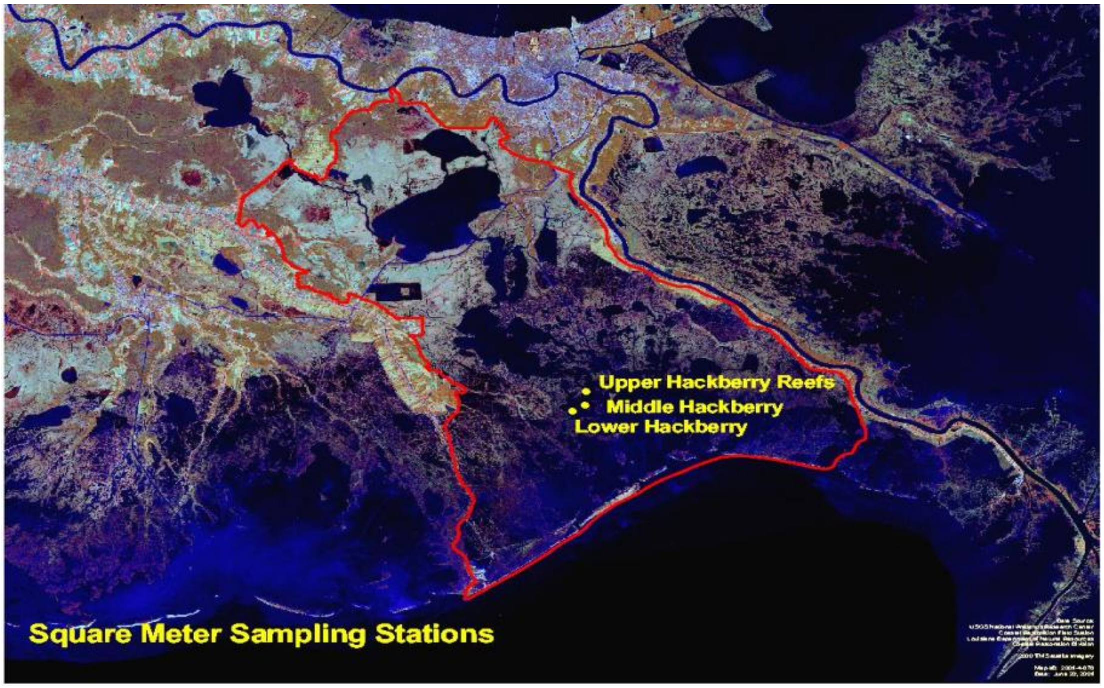


Figure 5-59. Location of oyster square meter sampling stations near Davis Pond (from CPRA 2010b)

Oyster Harvest

Oyster harvest levels dropped in 2005 and 2006 due to Hurricane Katrina and missing data and increased substantially in 2007 and 2009. Oyster harvest is monitored by boarding and estimating the number of oysters on boats dredging in the Barataria basin. Oyster dredging generally peaked in fall-winter with a more sustained harvest in the 1998-1999 seasons than the 1999-2000 season (Figure 5-60). Much of the data are missing for the 2000-2001 season, but the harvest is substantially reduced from previous years. Harvest increased substantially in the 2003 season due to a change in LDWF sampling procedure and the opening of the Little Lake seed grounds.

Oyster Growth and Mortality

The overall oyster survival rate since 2007 was twice the pre-operation years. The overall survival at Davis Pond is 18 percent. Oysters at the mid-area stations (Figure 5-61) generally survived; the other stations experienced 100 percent mortality early in the year (Figure 5-62).

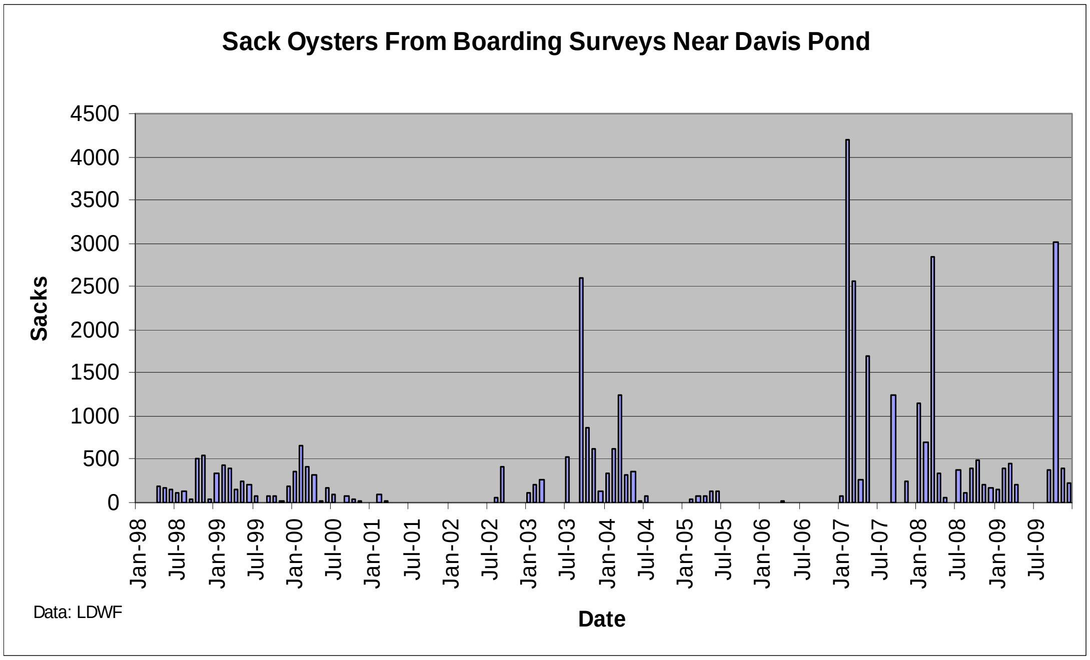


Figure 5-60. Number of oyster sacks from boarding surveys near Davis Pond pre- and post (limited) operations in July 2002 (LDWF data) (CPRA 2010b)

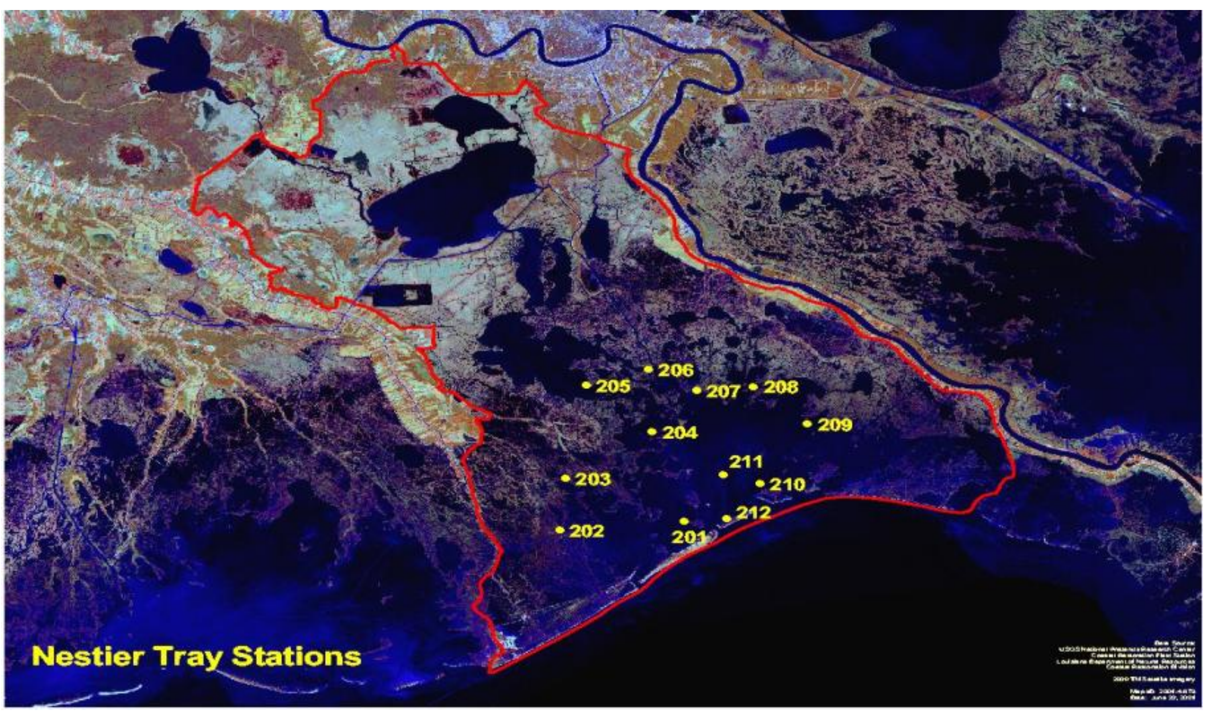


Figure 5-61. Location of oyster nestier tray stations near Davis Pond (CPRA 2010b)

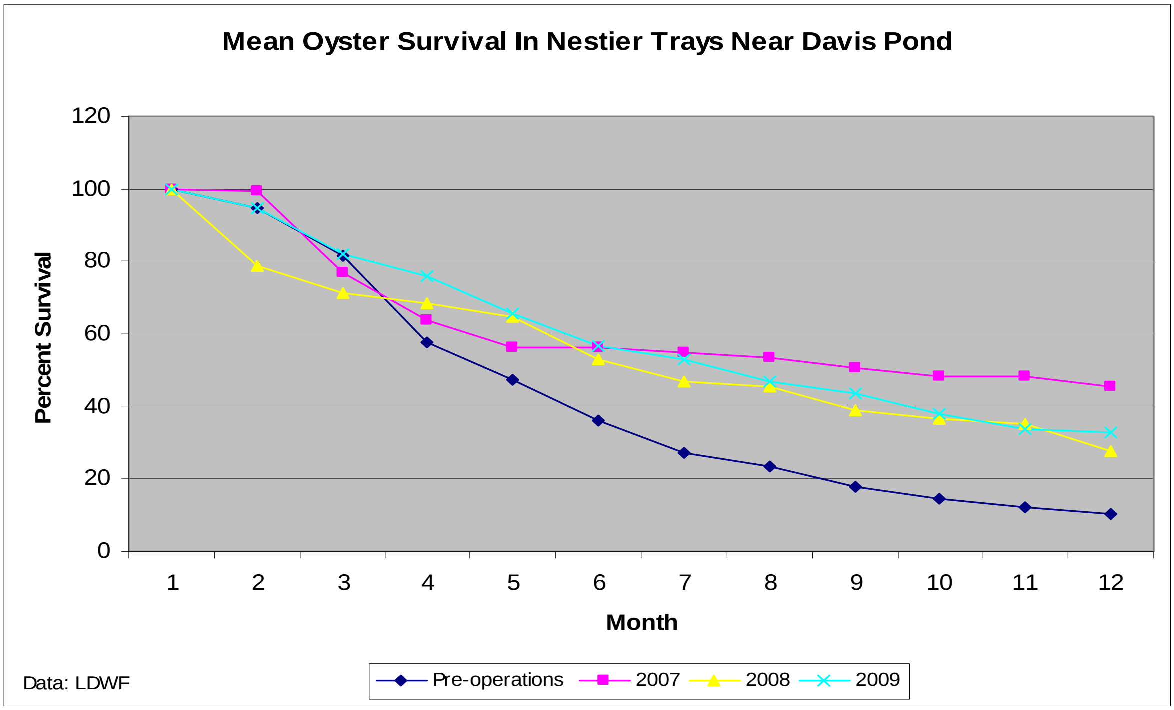


Figure 5-62. Average oyster survival in nestier trays near Davis Pond pre- and post (limited) operations in July 2002 (LDWF data) (CPRA 2010b)

5.3.18.3 Bonnet Carré

Effects of the Bonnet Carré Spillway on oysters in Mississippi Sound is complicated by flow from all rivers in the watershed, especially the Pearl River. High water periods in the Pearl River often coincide with high water in the Mississippi River; the combination of freshwater from both sources can increase mortality of oysters (Gunter 1953). Oysters in western Mississippi Sound are subject to frequent damage from Pearl River discharges (Butler 1949; Butler and Engle 1950; Owen and Walters 1950).

The quantity of Spillway discharge and the amount of time the freshwater remains on the oyster beds affect the level of oyster mortality. During years of heavy spillway discharge, 100 percent of the oysters in Mississippi Sound west of Bay St. Louis have been killed (Gunter 1953).

Gowanloch (1950) believed the 1937 opening was beneficial to oysters. The 1945 opening of the Bonnet Carré Spillway (which had nearly twice the flow of the 1937 and 1950 openings) was reported to have destroyed over $45 million of oysters in Louisiana and Mississippi (Gowanloch 1950). The 1950 opening did not cause any material damage to the oyster reefs in Louisiana because the opening was early in the year and of short duration (Owen and Walters 1950). In 1973, due to high water in the Mississippi River, the Bonnet Carré Spillway and the Morganza Spillway were opened. The freshwater, coupled with warm temperatures and high local rainfall resulted in oyster mortalities in Alabama, Mississippi, and Louisiana, including mortalities of 50 percent in the Lake Borgne complex (Dugas and Perret 1975). However, Dugas and Perret

(1975) noted that the oyster mortality was a temporary setback and the long range benefits would be considerable. The 2008 opening did not appear to have any obvious effects on oyster samples, at least on a short-term basis (GEC 2009). Similarly, the 1997 opening did not appear to have an effect on oysters in Louisiana (GEC-Steimle and Associates 1998) or Mississippi Sound (Perret *et al.* 1998).

Oysters farther away from the Spillway may benefit from the Spillway opening. Owen and Walters (1950) believed that the benefits to oysters in the southern Louisiana marsh and eastern Mississippi Sound far outweighed the adverse effects on the oysters in north Mississippi Sound and on reefs opposite the mouth of the Pearl River. Thick growths of young oysters can occur after freshwater events (Gunter 1952). Viosca (1927) suggested that although some oyster beds close to Mississippi River outputs are temporarily destroyed by excess freshwater, old reefs may be rehabilitated.

After the 1983 Spillway opening, Chatry and Millard (1986) reported oyster survival throughout the spring and early summer in salinities of 2 to 5 ppt; significant mortalities only occurred when salinities fell below 2 ppt for several weeks. Actively feeding oysters were encountered in this same study at salinities as low as 3 ppt and temperatures in excess of 30°C. Oyster mortalities after the 1950 opening were lower due to cooler temperatures and lower salinities during the three to four years prior to the opening (Gunter 1953). Gowanloch (1950) and others have suggested that in addition to the duration of time the spillway is open and the crest volumes involved, a more important factor may be the time of the year the spillway is open in relation to the spawning activities of the oysters.

The 1950 Spillway opening killed or greatly reduced the incidence of boring sponges, boring clams, oyster drills, and likely *Perkinsus marinus,* a microscopic parasite on oysters (Gunter 1953). The 1950 Spillway opening had a much greater discharge was much larger than the 2008 opening.

5.3.18.4 Bayou Lamoque Diversion

The Bayou Lamoque Freshwater Control Structure resulted in a 300 percent increase in oyster production of the area and a 200 percent increase in harvested yield (Bowman *et al.* 1995 cited in Meffert *et al.* 1996).

5.3.19 Largemouth Bass

5.3.19.1 Caernarvon

The Delacroix marsh after Caernarvon opened has become one of the state’s premier bass fishing area. Largemouth bass (*Micropterus salmoides)* catches in seines were twice as high after the Caernarvon diversion was opened; nearly all bass were collected above the 5 ppt isohaline (LDNR 2003). Largemouth bass catches were 23 percent higher post-operation in the seine data (Figure 5-63). Nearly all bass were caught above the 5 ppt isohaline (Figure 5-64). Bass were caught nearly year-round post-operation and on only a few occasions pre-operation. CPUE for bass peaked in 1998 and has dropped off in the last few years. Few largemouth bass were caught in trawls (6- and 16-ft combined) during the pre- or post- operational periods (CPRA 2010a). Largemouth bass biomass was significantly higher post-operation in the impact versus the control area since the opening of Caernarvon (de Mutsert 2010) (Figure 5-65).

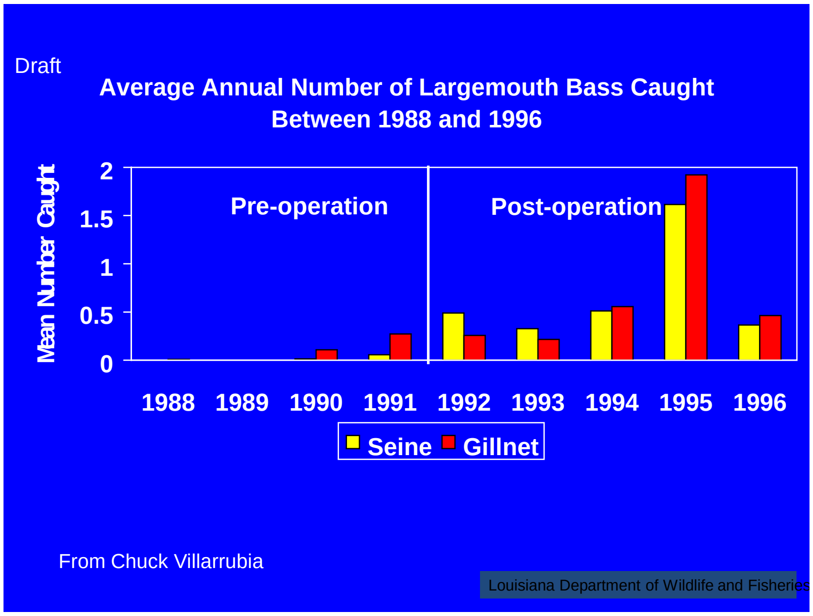


Figure 5-63. Mean number of largemouth bass caught between 1988 and 1996 near Caernarvon pre- and post-operation (from Chuck Villarrubia, personal communication)

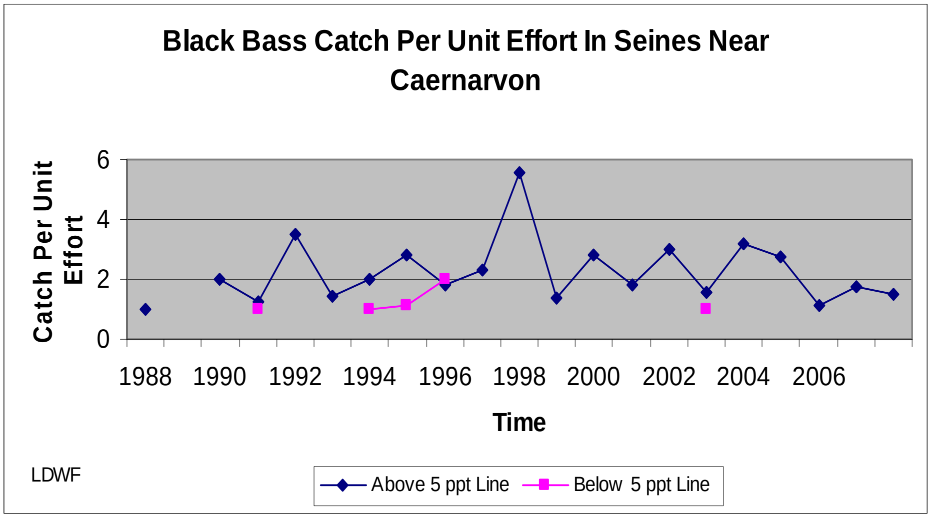


Figure 5-64. Largemouth bass CPUE in seines near Caernarvon (LDWF) (from CPRA 2010a)

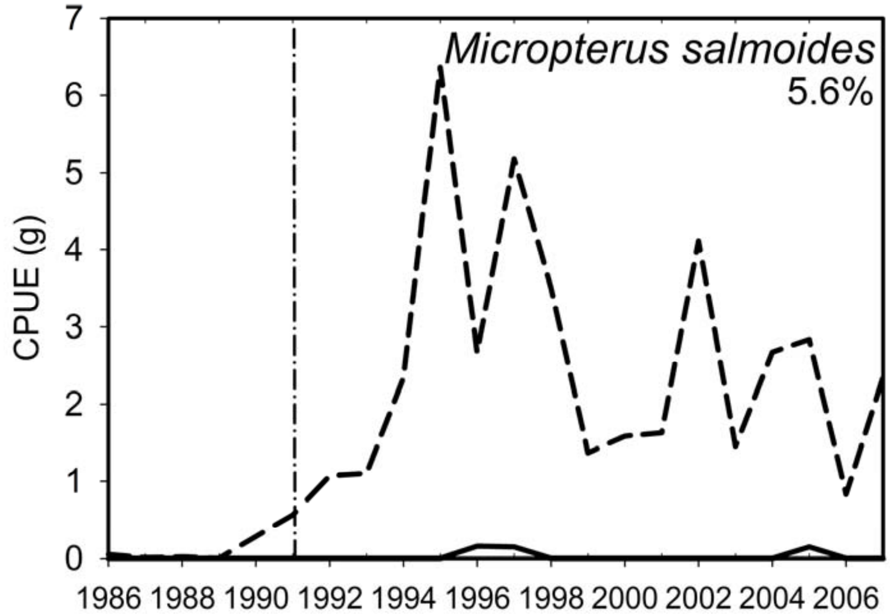


Figure 5-65. Largemouth bass yearly mean CPUE for seines downstream of Caernarvon pre- and post-operation (LDWF). Impact area is denoted by the dashed line, the control area is denoted by a solid line; vertical dashed line denotes Caernarvon operation. (from de Mutsert 2010)

5.3.19.2 Davis Pond

Freshwater fish were sampled using rotenone, electrofishing, hoop nets, and gill nets near Davis Pond. The most abundant freshwater fish collected were: channel catfish *(Ictalurus punctatus)*, blue catfish *(I. furcatus)*, and largemouth bass (Figure 5-66). Catches peaked in 1999, dropped in 2000 (may have been due to drought conditions), and have risen from 2002 to 2009 (CPRA 2010b). Few largemouth bass were seined during the pre-operation and the initial operation period; slightly more bass were collected post-operation (Figure 5-67) (CPRA 2010b). Lake Cataouache below Davis Pond has become one of the state's premier bass lakes (LDNR 2003).

5.4 Submerged Aquatic Vegetation

Freshwater releases through the Caernarvon Diversion have increased the amount of submerged aquatic vegetation (SAV) coverage (Rozas *et al.* 2005; Day *et al.* 2009). The nekton community near the Caernarvon Diversion shifted to species that use SAV in low salinity sites, such as clown goby (*Microgobius gulosus)*, Gulf pipefish (*Syngnathus scovelli)*, naked goby (*Gobiosoma bosc)*, and rainwater killifish (*Lucania parva)* (de Mutsert 2010). Inflow SAV contained the highest mean densities of Gulf pipefish and riverine grass shrimp (*Palaemonetes paludosus)* and highest mean biomass for blue crab and rainwater killifish. Brown shrimp density and biomass did not differ and blue crab densities were not significantly different among habitat types (Rozas *et al.* 2005).

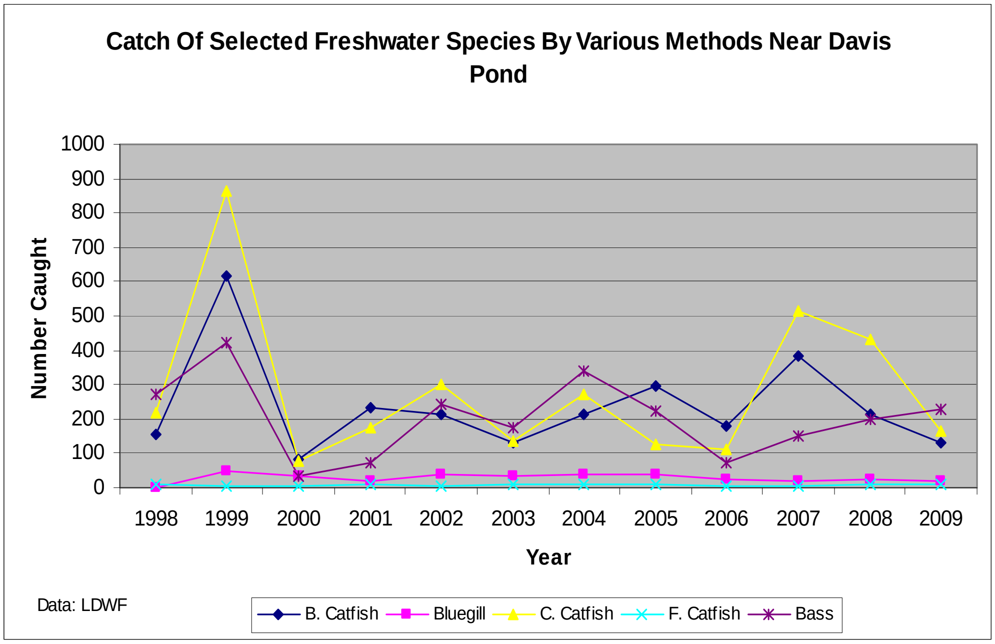


Figure 5-66. Catch of Selected Freshwater Species by Various Methods in Barataria Basin near Davis Pond (CPRA 2010b)

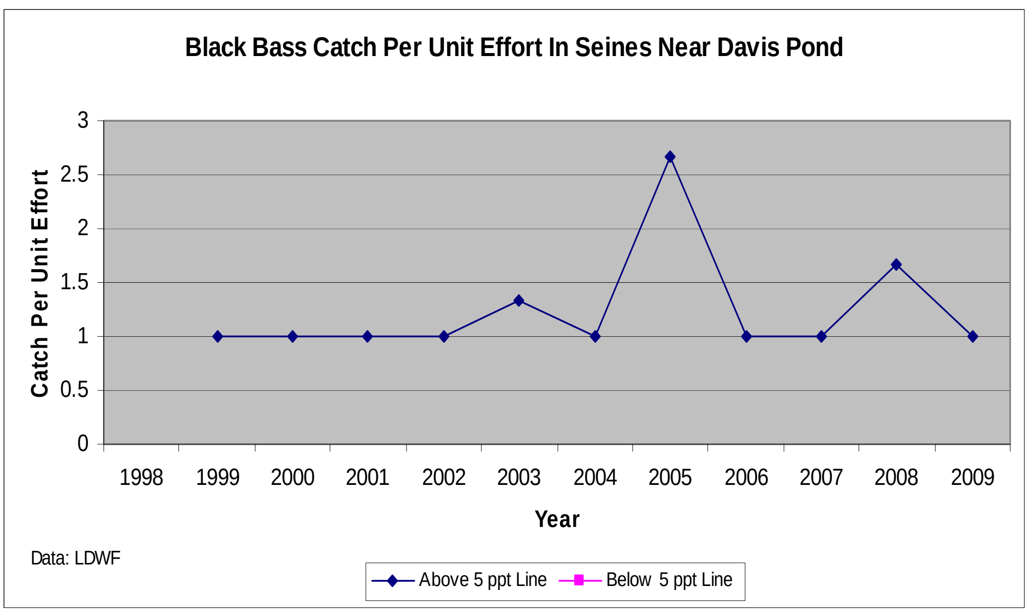


Figure 5-67. Largemouth bass CPUE in seine and gill net samples in Barataria Basin near Davis Pond (CPRA 2010b)

All 34 open-water sites sampled by Rozas *et al.* (2005) contained submerged vegetation (rooted vascular plants or macroalgae); only 59 percent of the open-water sites in the reference area contained aquatic plants. Aerial coverage was approximately 66 percent in the inflow area and 18 percent in the reference area. This increase in SAV coverage expanded the area available for macrofauna. Areas of SAV (as well as marsh edge habitat) generally supported higher mean densities of fish (9.5 and 18.8 times higher in inflow and reference SAV areas, respectively) and decapod crustaceans (1.6 and 3.0 times higher in inflow and reference SAV areas, respectively) than nearby nonvegetated sites. Daytime dissolved oxygen concentrations were higher in the inflow area, likely due to the presence of SAV. This expansion of SAV is expected to benefit nekton unless SAV growth becomes excessive and reduces water quality (Rozas *et al.*, 2005; Day *et al.* 2009).

5.5 Endangered Species

Diversions can redistribute endangered species from the Mississippi River such as pallid sturgeon *(Scaphirhynchus albus)*. A total of 14 pallid sturgeon were collected in Barbar's Canal downstream of the Bonnet Carré Spillway over a three-week period after the 2008 Bonnet Carré Spillway Opening (Killgore *et al.* 2009). All sturgeon were returned to the Mississippi River and Killgore *et al.* (2009) noted that the take of this Federally endangered species entrained during operation of the Spillway could be minimized by a *rescue* effort. One week prior to the opening of the Spillway, one pallid sturgeon was captured over the flooded bank of the Mississippi River adjacent to the Bonnet Carré Spillway (USACE 2009a).

Entrainment of pallid sturgeon has also been documented for the Davis Pond diversion (USACE 2010). Pallid sturgeon occur throughout the Mississippi River, including reaches above and below the sites of all proposed diversions (Killgore *et al.* 2007). Between 2001 and 2009, 49 pallid sturgeon were collected by the USACE-ERDC between Mississippi River miles (RM) 100 and 200, the reach including Davis Pond and the Bonnet Carré Spillway (USACE 2010); nine pallid sturgeon were collected between RM 200 and 300, and only one pallid sturgeon was collected between RM 70 and 100, where the Violet Siphon and Caernarvon are located (USACE 2010). Pallid sturgeon are frequently found in the vicinity of man-made structures such as dikes in the Mississippi River. Such structures provide attractive shelter areas from the main channel water velocities and also provides hard, permanent substrates for benthic invertebrates and fishes that are eaten by pallid sturgeon (Kirk *et al.* 2008).

5.6 Invasive Species

Diversions can introduce invasive species from the Mississippi River, including bighead carp (*Hypophthalmichthys nobilis*), grass carp *(Ctenopharyngodon idella*), silver carp *(H. molitrix*), and zebra mussel veliger larvae (*Dreissena polymorpha*). Black carp (*Mylopharyngodon piceus*), Asian clams *(Corbicula fluminea*), and other invasive species can also potentially be introduced. Populations of silver carp, bighead carp, grass carp, and common carp are established in the Davis Pond freshwater outflow (USGS 2011). Silver carp, bighead carp, common carp, black carp, and zebra mussel populations are also established in the Atchafalaya River and drainage area downstream of the Old River Control Structure (USGS 2011). In mid-April 2009, large numbers of juvenile silver carp were collected from the pools of the Bonnet Carré Floodway (USACE 2009b). Zebra mussels were found in the Bonnet Carré Spillway after the 2008 opening (Font 2009). These zebra mussels survived and grew through the late spring and summer. Although some mortality of the zebra mussels occurred during the late summer when the water temperature increased, a portion of the population survived into the fall and studies are still underway (Font 2009). Font (2009) noted that it is unknown whether zebra mussels can establish, grow, mature and reproduce in wetlands or whether populations will be limited by high salinities and high summer temperatures.

Diversions can also facilitate the expansion of the habitat of freshwater invasive species. The Rio Grande cichlid (*Cichlasoma cyanoguttatum*) was released into Lake Pontchartrain from the aquarium trade in the early 1990s. The reduction of salinity in Lake Pontchartrain by the freshwater diverted through the Bonnet Carré Spillway, coupled with the closing of the Mississippi River Gulf Outlet, will likely aid in the expansion of this species (O'Connell *et al.* 2002). The expansion of invasive submerged vegetation such as hydrilla and other aquatic plants in Lake Cataouache that has been attributed to the Davis Pond Diversion can also affect populations of fish and other aquatic organisms.

5.7 Infaunal Macroinvertebrates

Infaunal macrofaunal abundance did not decrease significantly during the Bonnet Carré Spillway opening in 1997 (Figure 5-68; Brammer *et al.* 2007). The abundance at most sites decreased, except for the site closed to the Spillway where abundances increased significantly. A significant decline in abundance occurred one month after the Spillway was closed; the decline was particularly evident at the highest salinity site. Similarly, one month after the Spillway was closed, the number of taxa significantly declined (Figure 5-69). Nearly five months after the Spillway was closed, the number of taxa increased significantly from the number collected one month after the Spillway was closed. In general, the number of taxa increased with salinity. The benthic community experienced changes in dominance and, to a lesser extent, in composition over time and among sites sampled. Brammer *et al.* (2007) suggested that the changes observed resulted from reduced salinity, cyanobacterial blooms, and hypoxia/anoxia. Although the macroinvertebrate abundance and common rangia clam *(Rangia cuneata)* biomass recovered (Figure 5-70), there was no evidence of increased benthic invertebrate productivity.

5.8 Eutrophication and Fish Kills

Nutrients from diversions may cause algal blooms that may result in fish kills. Following the 1997 opening of the Bonnet Carré Spillway, toxic cyanobacterial blooms occurred on Lake Pontchartrain (Dortch *et al.* 1998). The blooms caused decreases of dissolved oxygen in the lake, and fish kills occurred in some places in June and July (Chao *et al.* 2010). Blue green algal blooms during the summers of 1994, 1995, and 1997 and the presence of local fish kills during the 1995 and 1997 blooms were reported by Poirrier and King (1998). During the summer of 1997, after the March opening of the Spillway, an extensive and persistent blue-green algal bloom occurred; fish kills occurred at the mouth of Bayou St. John (June 15), near the mouth of Bayou Lacombe (June 22), and eastward from Goose Point (July 29) (Poirrier and King 1998).

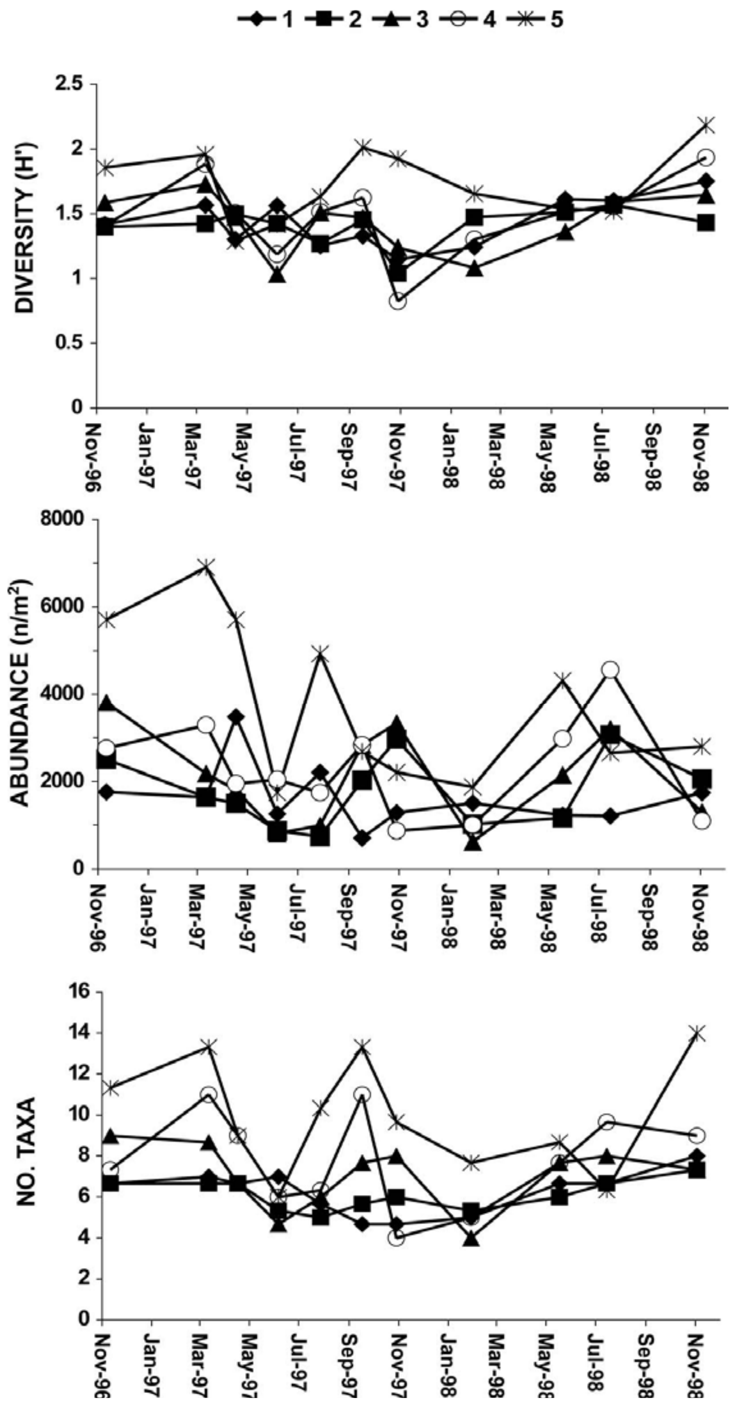


Figure 5-68. Benthic macroinvertebrate responses at sites 1 through 5 over time: diversity (H_), abundance, and number of taxa. The Bonnet Carré Spillway was opened on March 17, 1997 and closed on April 18, 1997. (from Brammer *et al.* 2007)

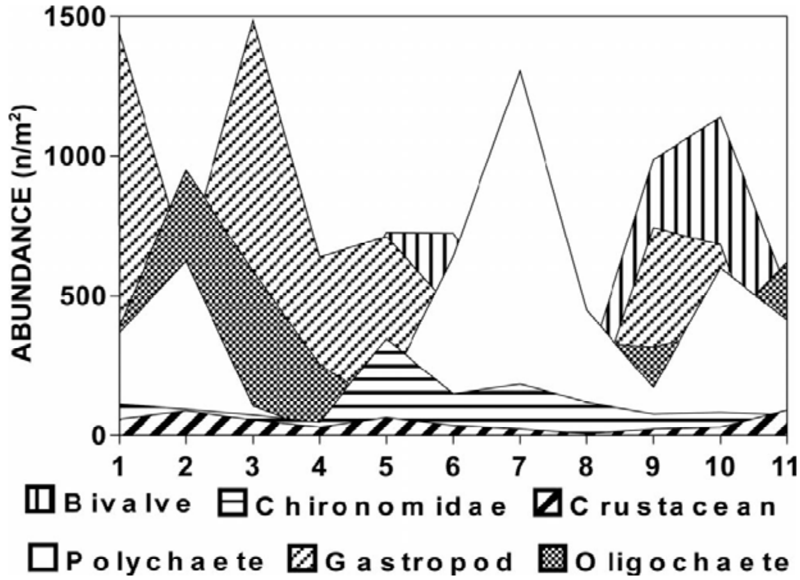


Figure 5-69. Abundance of higher taxa in lake Pontchartrain averaged across sites for each sampling date: 1 _ November 11, 1996; 2 _ March 12, 1997; 3 _ April 17, 1997; 4 _ June 6, 1997; 5 _ July 28, 1997; 6 _ September 17, 1997; 7 _ October 29, 1997; 8 _ January 29, 1998; 9 _ May 18, 1998; 10 _ July 15, 1998; 11 _ November 3, 1998. The spillway was opened on March 17, 1997 and closed on April 18, 1997. (from Brammer *et al.* 2007)

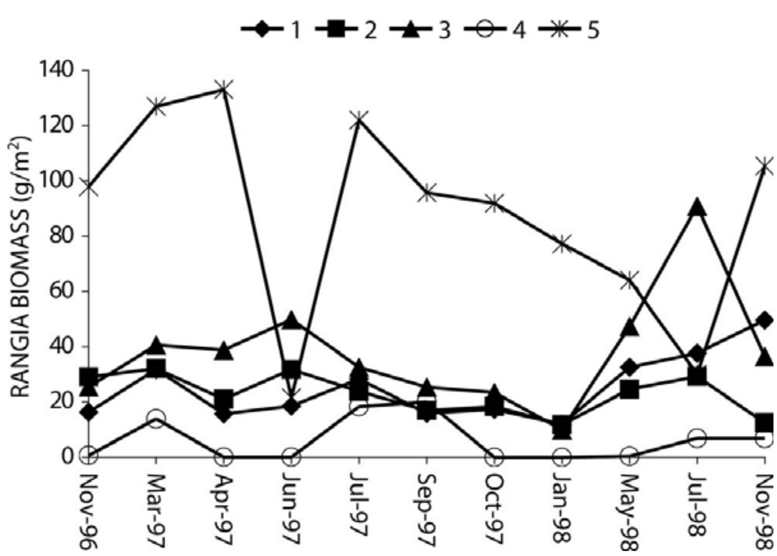


Figure 5-70. Common rangia *(Rangia cuneata)* dry-weight biomass at sites 1 through 5 over time in Lake Pontchartrain. The Bonnet Carré Spillway was opened on March 17, 1997, and closed on April 18, 1997. (from Brammer *et al.* 2007)

5.9 Food Web

Carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), and sulfur ($\delta^{34}S$) stable isotopes were examined to determine the extent of the influence of the Caernarvon Diversion on the food web. Caernarvon supported 75 percent and 25 percent of local benthic and pelagic food webs in the upper and middle parts of the estuary, respectively (Day *et al.* 2009). The strongest influence was found along known pathways and closest to the diversion (Day *et al.* 2009; de Mutsert 2010). Isotopes also traced seasonal changes in river contributions because river-associated sources were especially important during and shortly after high discharge periods. However, the river-influenced source regime at the marine end did not show seasonality related to the diversion (Day *et al.* 2009).

Samples of plants and animals at Caernarvon inflow and reference sites were collected for stable isotope analysis. The primary producers in the control area had significantly lower $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values than the Caernarvon inflow and reference areas (de Mutsert 2010). The $\delta^{15}N$ values for grass shrimp muscle tissue showed a strong gradient throughout the sampling area, with highest values close to the Caernarvon diversion and decreasing values further away from it. River-derived nitrogen was strongly incorporated into the food web, resulting in grass shrimp with elevated $\delta^{15}N$ values in much of the estuary. However, at marsh-influenced sites, this effect was much diminished. There is likely a nitrogen source of low $\delta^{15}N$ values in marsh-influenced sites (Day *et al.* 2009).

The $\delta^{15}N$ values of brown shrimp and grass shrimp *(Palaemonetes paludosus* and *P. intermedius)* were significantly higher ($P<0.0001$) for shrimp collected in the Caernarvon inflow area than for those collected in the reference area. The two areas had similar $\delta^{13}C$ with values increasing towards higher salinity sites nearer the coast; marsh samples had significantly higher $\delta^{13}C$ ($P=0.005$) values than open water sites. The grass shrimp had higher $\delta^{34}S$ isotope values down-estuary, but the brown shrimp in the inflow area had higher values in the inflow area where salinities were lower relative to the reference area. They suggested the brown shrimp may have been moving back up the estuary after being displaced earlier in the year by freshwater diversion inflows (Rozas *et al.* 2005).

The Caernarvon diversion contributed substantially to consumer nutrition in the impacted area and marsh productivity generally increased along the major flow path of nutrient-rich diversion water. Analysis of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ in grass shrimp (*Palaemonetes* sp.), barnacles (*Balanus* sp.), and bay anchovies showed that the relative support of the diversion to the consumer food web averaged approximately 50 percent for grass shrimp and barnacle consumers in the upper parts of the Breton Sound estuary and 25 percent for mid-estuary consumers. Anchovies collected in lower Breton Sound still had up to 10 percent of the food web contribution that could be assigned to Caernarvon (Wissel and Fry 2005).

5.10 Lessons Learned

- Salinities were significantly lower in the Caernarvon outfall area (USACE-LDWF 1998), except in the lower estuary (Lane *et al*. 1999).

- The Caernarvon impact area had significantly higher total nekton abundance than the control area ($t = -4.54$, $p = 0.0003$); however, the total biomass of nekton in the control and impact areas did not significantly differ post-operation. The number of species in the impact area seine samples did not change post-operation; however, the number of species in the control area samples significantly decreased ($t = -5.74$, $p < 0.0001$). Post-operation, the mean weight of individuals in the impact area samples was significantly lower than those from the control area ($t = 2.94$, $p = 0.006$); the mean weight did not significantly differ between areas before operation (de Mutsert 2010).

- Pulsed freshwater inflows from Caernarvon increased nekton density and biomass in 1-m^2 drop samples taken on flooded marsh sites and along the vegetated shoreline. Communities in the two areas were similar and consisted primarily of marsh resident species (Rozas *et al.* 2005; Piazza and La Peyre 2007). Nekton density and biomass was significantly higher at flooded marsh sites near Caernarvon than the reference marsh sites (Figures 5-7 and 5-8). Inflow marsh sites had significantly deeper water and were flooded more than twice as long as reference marshes not affected by the diversion (Piazza and La Peyre 2007). The Caernarvon area had increased coverage of SAV (Rozas *et al.* 2005). Nekton communities were similar and were dominated by marsh resident species. Differences in density and biomass were attributed primarily to differences in water depth and duration of flooding (Piazza and La Peyre 2007) and increased submerged aquatic vegetation coverage (Rozas *et al.* 2005) caused by the pulses.

- The 2008 opening had little overall effect on the distribution and abundance of fishes and aquatic organisms (GEC 2009). Trawl catches of bay anchovy, blue crab, and brown shrimp in Lake Pontchartrain and bay anchovy, Atlantic croaker, northern white shrimp, and sand seatrout in Lake Borgne were higher in 2008 than in the other years tested. Trawl catches of Gulf menhaden in Lake Pontchartrain; and blue crab, Gulf menhaden, hardhead catfish, and northern brown shrimp in Lake Borgne were not significantly different. The only species with significantly lower catches in 2008 after the Spillway opening were Atlantic croaker and sand seatrout in Lake Pontchartrain and spot in Lake Borgne. Gill net catches of Gulf menhaden and hardhead catfish, and seine catches of bay anchovy, Gulf menhaden, and inland silversides were not significantly different among the years tested. Catches of some of the less abundant species may have been lower in 2008 after the Spillway opening, but these species were collected in insufficient numbers to analyze (GEC 2009).

- Catches of many nekton species were generally higher in the post-operation Caernarvon area; however, only some were statistically significant. Some species had higher catches in one or more of the sampling gears used. A few increases could be attributed to the diversion, others could not. Brown shrimp indicated some slight decreases after the operation of the structure. No species had drastic drops in abundance after the operation of the structure.

- Spotted seatrout was generally higher in the post-operation period for Caernarvon in some gears and lower in others (USACE-LDWF 1998, CPRA 2010a), but only the trammel net catches were significantly higher ($P<0.05$, USACE-LDWF 1998). Biomass was not affected relative to the control area after the opening of Caernarvon (de Mutsert 2010).

- Red drum catches were generally higher in the post-operation, with samples by gill net being significantly higher ($P<0.05$, USACE-LDWF 1998). Red drum biomass was significantly higher in the post-operation impact area as compared to the control area (de Mutsert 2010).

- Black drum was generally higher during the post-operation at Caernarvon, with the trammel nets being significantly higher. However, since the *station*operation* interaction term was not significant, this increase cannot be attributed to the diversion (USACE- LDWF 1998).

- Atlantic croaker catches were significantly higher during the post-operation period at Caernarvon ($P<0.05$, USACE-LDWF 1998); however, since the *station*operation* interaction term was not significant, thus the higher catches cannot be attributed to the diversion.

- Sand seatrout catches increased during the post-operation at Caernarvon, but were not statistically significant (USACE-LDWF 1998).

- Spot catches by seines were significantly lower ($P=.002$; USACE-LDWF 1998) and were attributable to the diversion. Catches were higher in the other sampling gears, but were not significant.

- Sheepshead did not have a clear catch, higher in some gears and lower in others. Catch patterns were not significant (USACE-LDWF 1998).

- Gulf menhaden catches generally increased in the post-operation period at Caernarvon, but none of these were significant. Catches were significantly lower in the trammel net ($P<0.05$, USACE-LDWF 1998), but the *station*operation* interaction term was not significant and thus the lower catches could not be attributable to the diversion. Menhaden abundance was significantly higher during the post-operation in the impact area versus the control area (de Mutsert 2010).

- Bay anchovy abundance was significantly higher during the post-operation in the impact area versus the control area (de Mutsert 2010).

- Striped mullet abundance was significantly higher during the post-operation in the impact area versus the control area (de Mutsert 2010).

- Hardhead catfish had no real discernable pattern of abundance changes associated with Caernarvon.

- Sheepshead minnow abundance was significantly lower during the post-operation in the impact area versus the control area (de Mutsert 2010).

- Growth rates of the western mosquitofish were higher in the inflow area than in the reference area during the experimental pulses at Caernarvon (Piazza 2009).

- Blue crab abundance in the post-operation phases Caernarvon and Davis Pond indicate no real pattern. Catches were somewhat higher, but were not significant.

- Brown shrimp catches were significantly less in the seine samples during the post-operation period at Caernarvon ($P<0.05$, USACE-LDWF) and the interaction term was significant indicating the lower catches may be due to the diversion. Trawl catches were lower in the post-operation period, but not statistically significant. Likely these changes are due to the fact the diversion operates mainly during the period of time when the brown shrimp post larvae and juveniles are recruiting the coastal marshes.

- White shrimp did not change during the post-operation period at Caernarvon (USACE-LDWF 1998).

- Grass shrimp abundance was higher in seines during the post-operation period in the impact area versus the control area at Caernarvon (de Mutsert 2010). They were also more abundant in the inflow area than in the reference area (Rozas *et al*. 2005).

- Oyster availability increased more than 12 times during the post-operation period at Caernarvon (CPRA 2010a). Average production of sack oysters has increased 277 percent in the post-operation period (C. Villarubia, personal communication). The 1997 and 2008 opening of the Bonnet Carré did not appear to have any major impacts on oysters (GEC/Steimle and Associates 1998, GEC 2008).

- Largemouth bass was significantly higher in the post-operation period in the impact area versus the control area at Caernarvon (de Mutsert 2010). Lake Cataouache, below Davis Pond, has become one of the states's premier bass lakes (LDNR 2003).

- SAV has increased in the outfall area of Caernarvon (Rozas *et al*. 2005; Day *et al*. 2009). Associated nekton, such as pipefishes, killifishes, and gobies, had increased abundance in the SAV areas (de Mutsert 2010).

- Pallid sturgeon has been collected in the outfall of Bonnet Carré (Kilgore *et al.* 2009) and David Pond (USACE 2010).

- Populations of silver carp, bighead carp, grass carp, and common carp are established in the outfall of Davis Pond (USGS 2011). Silver carp, bighead carp, common carp, black carp, and zebra mussel populations are also established in the Atchafalaya River and drainage area downstream of the Old River Control Structure (USGS 2011). In mid-April 2009, large numbers of juvenile silver carp were collected from the pools of the Bonnet Carré Floodway (USACE 2009b).

- Following the 1997 opening of the Bonnet Carré Spillway, toxic cyanobacterial blooms occurred on Lake Pontchartrain (Dortch *et al.* 1998). The blooms caused decreases of dissolved oxygen in the lake, and fish kills occurred in some places in June and July (Chao *et al.* 2010). Blue green algal blooms during the summers of 1994, 1995, and 1997 and the presence of local fish kills during the 1995 and 1997 blooms were reported by Poirrier and King (1998).

5.11 Recommendations

Recommendations for fishery species are essentially the same as for wildlife. More conclusive data and analysis is needed to ascertain the effects of a diversion on fishery species. Likely there are other sources of data and information that were not readily available concerning the effects of diversions on fishery populations.

It is recommended that adequate data be collected in the pre- and post-operation phases of diversions to evaluate the actual affects of the diversions on fisheries. This may require data collection at appropriate stations and may require a long-term program to actually determine the trend. Other information should be collected and analyzed to filter out other parameters that can affect populations, such as harvests, regional and global population trends (waterfowl), weather patterns as they can affect data collection, and any other factor that can affect populations. Likely there are additional data that have been collected that could be analyzed to add to the lessons learned from diversions.

It is also recommended that sufficient data are collected in a manner to enable the pre- and post-operation periods to be compared statistically. Although fisheries abundances may appear higher post-operation, they may not be significantly higher. And although counts may be significantly higher or lower post-operation, the differences observed may not be due to the operation of the diversion. Analysis should also account for other factors that control populations, such as harvests, weather patterns, intrinsic population dynamics, offshore spawning success, factors that affect juvenile recruitment, coastal currents, etc.

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Appendix A

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Appendix B

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Appendix D

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