Chapter 23: Wetlands

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Introduction

America lost the Battle of New Orleans long before 1814. This does not refer to General Andrew Jackson and the British-American war, but rather the earlier decision to build one of America's great cities in a wetland. Early 18th century French settlers argued among themselves whether or not a low lying marsh site was a practical location for a growing city. But when New Orleans was founded in 1718, the die was cast. In August of 2005 the city of New Orleans was nearly destroyed by massive flooding caused by Hurricane Katrina. Interestingly, many of the earliest settlement locations like the French Quarter, which were built on the higher ground nearer the levee, survived Katrina with little damage. However, the loss of life from this hurricane was in the thousands (approximately 1,300 in New Orleans and Louisiana alone) and the property damage will cost billions of dollars to repair since over 200,000 homes built on low lying former marshlands or areas that have subsided were destroyed. Moreover, the cultural life of the City of New Orleans has forever changed. Did the massive loss of wetlands around New Orleans, adjacent parishes and southern coastal areas aid in the near destruction of New Orleans? Did past drainage of marshes in New Orleans proper exacerbate the amount of devastation? These are questions that this report attempts to address through an assessment of know scientific information, interviews with experts in coastal and wetland ecology, and a review and synthesis of several current plans that have been developed regarding wetland land loss in Louisiana.

The data and information providing a basis for this report and analysis was obtained through direct contacts with a number of Federal, State and local agencies in Louisiana and particularly Drs. Robert Twilley, John Day, and Jim Chambers at LSU, Cliff Hupp at USGS as well as a review of key information provided by the NRC report (2005), LCA reports (Twilley 2003, USACE 2004) and the Boesch report (Boesch et. al., 2006). An extensive review was also done on the history of wetland formation geomorphology, wetland formations and losses in coastal Louisiana and in the New Orleans area through interviews with experts familiar with wetlands and sedimentation problems in general and problems created in New Orleans by Hurricane Katrina in particular. Sources of data and information included:

- Federal, State and local government agencies
- Research journals
- Research organizations
- State and local wetland reports
- Public news sources

Some of the data and information was corroborated from multiple sources and citations; however because of the short duration of this project important information was unattainable (e.g. a complete assessment of wetlands conditions, and wetland loss have not been completed after Hurricane Katrina) and thus data gaps exist and a number of questions and issues are unresolved at this time as highlighted in the final sections of this report.

This Chapter is organized into five sections:

- Wetland Formation and Losses in Louisiana provides the scientific basis for determining the magnitude of the problem as well as provides guidelines on how natural processes might aid in restoration of the marshes, which is of vital importance to FEMA and other coordinating Federal, State and local agencies.
- Pre-Katrina Status of Wetlands in New Orleans addresses the role of wetland in New Orleans before Katrina made landfall and thus provides the benchmark against which the Post-Katrina Consequence Assessment (CA) and Consequence Projections (CP) for future disasters can be made.
- Post-Katrina Wetland Consequence Assessment (CA) addresses structural and human consequences observed following Hurricane Katrina's landfall in the New Orleans area.
- Wetland Consequence Projection (CP) envisioning post-event consequences of wetland restoration for the New Orleans' area after future disasters of Hurricanes Katrina proportion.
- Recommendations to mitigate the human tragedy and consequences of repeated flooding of low lying areas (former drained marshes) and levee failure caused by future hurricanes impacting New Orleans and surrounding areas.

This report focuses on the role of wetland functions (primarily the restoration of hydrologic functions) as it relates to the ongoing complex and coexisting problems of sea level rise, land subsidence and increased intensity of hurricanes which New Orleans is now facing. These recommendations and guidelines should assist FEMA and other governmental agencies to address potential future challenges associated with the R&R of New Orleans after disasters of Hurricane Katrina proportion. It also provides the basis for using adaptive management approaches with large-scale demonstration projects designed to restore wetlands and protect the levee and coast areas of Louisiana, especially as it related to New Orleans

Wetland Background

Wetlands Problem Statement

Immediately following the passage of Hurricane Katrina in August 29th, 2005, rampant discussion began as to whether the unparalleled destruction to New Orleans and the Mississippi Delta witnessed by the nation could have been mitigated by the restoration of wetlands and stronger levees. In particular, debate arose as to whether the widespread, and widely reported, loss of coastal wetlands in southeastern Louisiana had increased the vulnerability of communities throughout the coastal zone to hurricane damage. This discussion is nothing new to many, as coastal land loss in southern Louisiana in general has been the subject of innumerable articles, reports and news stories in both the academic, governmental and popular press for decades. Much of the past analysis of the coastal land loss issue has been retrospective (e.g. could a destroyed wetland have prevented flood damage to a town or surrounding area from the recent hurricanes). However, the increasing realization that we have entered a new interdecadal period of increased tropical storm activity (Goldenberg et al. 2001), which arguably may be exacerbated by anthropogenic climate change (Emanuel 2005, Webster et al. 2005, Chan 2006) has led to more pressing questions: Should we now, more than ever, be undertaking a widespread effort to restore a wetland complex that could potentially mitigate, if not protect against, damage from the inevitable next storm to make landfall in southeastern Louisiana? Should former drained wetland areas within the city of New Orleans that are now well below sea level be used again as sites of residential housing or businesses?

The importance of the wetlands contained within the coastal zone of southern Louisiana should not be understated. There are multiple reasons to want to see Louisiana’s coastal wetlands restored, ranging from such divergent reasons as flood control to energy security or coastal fisheries support. Importantly, coastal Louisiana (Source Day et. al., 2005):

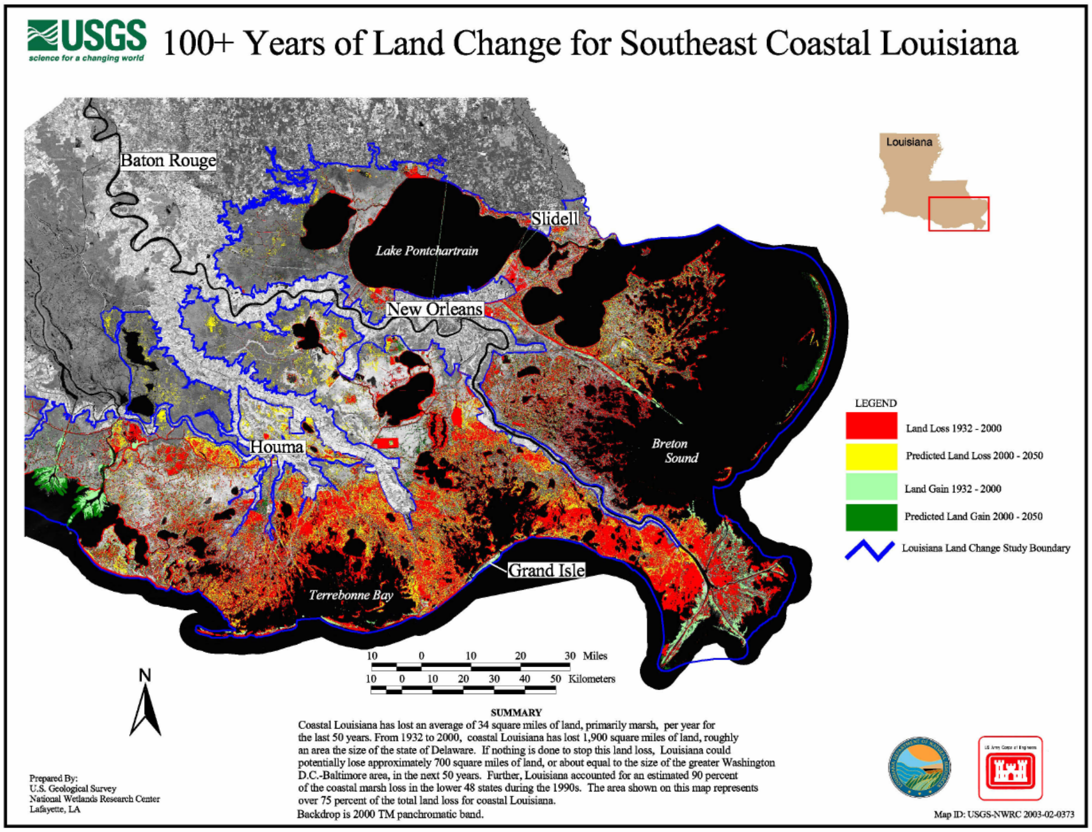
- Supplies the U.S. with 27% of its oil and 32% of its natural gas by infrastructure
- Its ports rank #1 in the Nation by tonnage
- It is linked to the Mississippi River Basin – Major access to national distribution centers
- Provides hurricane protection
- $Billion/Yr Fisheries--30% of Nation’s Production of seafood
- Habitat for Millions of Birds & other Animals

The Louisiana coastal zone occupies 26 coastal parishes. It is 483 km (300 miles) in length, and varies in width from 43 to 160 km (27-99 miles), with its northern boundary being the Pleistocene Terrace and the southern boundary being the state territorial limits in the Gulf of Mexico. The Louisiana coast is built of approximately 2.8 million hectares (ha; 7 million acres) of deposited Holocene sediments, on which are approximately 40% of the total wetlands of the conterminous United States (Williams 1995). Importantly, recent estimates of wetland loss in Louisiana vary from 2240 to 10,360 hectares (ha) yr-1 (Dahl 2006). Although coastal land loss is problematic throughout southeastern Louisiana, there are definite hot spots of land loss and formation (Figure 1).

Over 1,900 square miles (4,900 km^2) of coastal land, mainly tidal wetlands, have been lost since the 1930s, reversing the long-term trend of net land building

(Barras 2003, Figure 2). Boesch et al., 2006 report that the annual-equivalent rate of loss has decelerated somewhat from a peak of 40 square miles (100 km^2) per year in the 1960s and 1970s, but they report that it is estimated to have averaged 24 square miles (62 km^2) per year between 1990 and 2000. Approximately 500 square miles (1,300 km^2) of additional land loss is projected by 2050—a slower average rate of loss because the inventory of highly vulnerable wetlands is being depleted.

This section focuses primarily on the history, management and restoration potential of wetlands within the Mississippi River Deltaic Plain, which is one of two geologically distinct units within the Louisiana coastal zone. The Deltaic Plain is that part of the Louisiana coast built of Holocene (recent 12,000 years) sediments deposited by a series of prograding, sedimentary lobes of the Mississippi River over the last 7000 to 8000 years, and has an area of approximately 50,000 square kilometers (19,300 square miles). Our goal here is to present an understanding of the physical status of the wetlands of southeastern Louisiana immediately prior to the hurricanes of September 2005; which provides a basis for establishing the magnitude of the wetland loss rate problem and providing insights into the importance of restoring sedimentation to maintain marsh elevations. We begin this section by reviewing the formation of the Mississippi River Deltaic Plain and the natural cycle of progradation and transgression of deltaic landforms. Next we discuss the effects that human activities, primarily those post European settlements, had on the wetland resources of the southeastern Louisiana coastal zone. As we will demonstrate, the management of southeastern Louisiana is complicated by the inherently dynamic nature of the delta's landforms, on top of which have been overlain a series of anthropogenic disturbances that have altered the balance of land creation and loss.



SUMMARY

Coastal Louisiana has lost an average of 34 square miles of land, primarily marsh, per year for the last 50 years. From 1932 to 2000, coastal Louisiana has lost 1,900 square miles of land, roughly an area the size of the state of Delaware. If nothing is done to stop this land loss, Louisiana could potentially lose approximately 700 square miles of land, or about equal to the size of the greater Washington D.C.-Baltimore area, in the next 50 years. Further, Louisiana accounted for an estimated 90 percent of the coastal marsh loss in the lower 48 states during the 1990s. The area shown on this map represents over 75 percent of the total land loss for coastal Louisiana.

Backdrop is 2000 TM panchromatic band.

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Figure 1: This map shows the documented change of coastal wetland habitat in southeastern Louisiana from 1932-2000, and the predicted land gain and loss from 2000-2050 under a scenario of no wetland creation of restoration interventions. Figure courtesy of USGS.

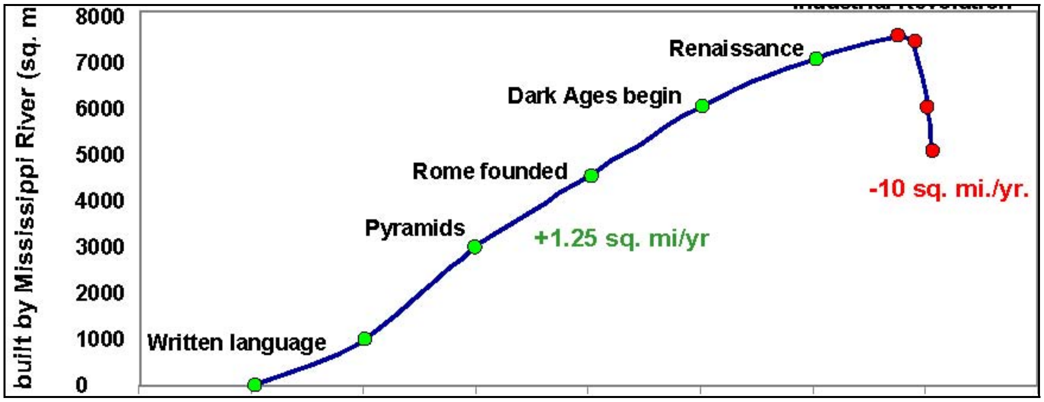
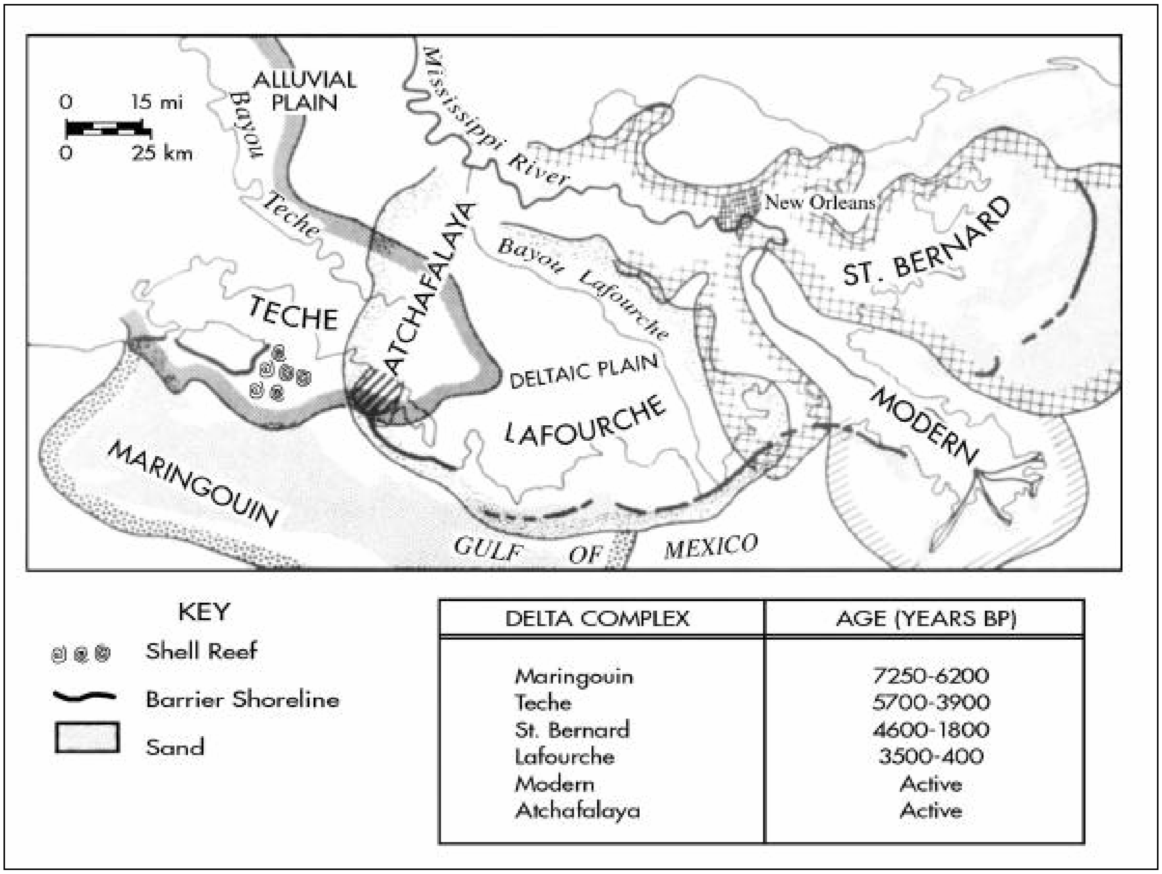


Figure 2: Historical perspective on Louisiana coastal land building and loss (from Boesch et. al., 2006).

Natural Processes in the Lower Mississippi River Deltaic Plain

The Mississippi River Deltaic Plain, encompassing southeastern Louisiana, is approximately 7000 years old and was created as the mouth of the River migrated across the shallow continental shelf just below the Pleistocene Terrace (Figure 3). Where the River met the coastal ocean, the hydraulic gradient flattened and the river lost much of its energy, depositing much of its suspended sediment load within the shallow coastal waters of the Gulf of Mexico (GOM). Within any one particular locus of deposition, a distributary channel network was established, through which the newly deposited landforms grew both out into the GOM and up as new sediments were deposited on top of existing sediments during flood events. Eventually, the growth of the depositional landform began to work against the River, impairing flow to the point that it became more hydraulically efficient for the River to establish a new locus of deposition at another point within the coastal zone. It is important to note that establishment and abandonment of a new depositional locus was not an all-or-none state: as flow would become diverted into a new channel due to the new, more favorable hydraulic gradient, the former distributary network would remain active for hundreds of years (Figure 3). By this process of delta lobe switching, the Mississippi River Deltaic Plain slowly took shape over several thousand years.

As with continental river systems, during very high flow volumes the river can flood over the levees. The sands in the suspended load deposit on or adjacent to the levee itself, and the silts and clays subsequently fall out of suspension in the interior basins behind the levees. Shortly after these depositional features are created they are colonized by vegetation adapted to the soils and flood regimes of distinct zones within these predominantly freshwater systems. Thus, the levees are typically colonized by flood-intolerant woody vegetation such as *Quercus virginiana* Mill. (live oak) that can take advantage of the well-drained sandy soils. In comparison, in the back basins behind the levees, the increasingly fine silty and clayey soils do not drain readily and pose a more significant environmental challenge to the vegetation. Only those species that are adapted to these poorly drained wetland soils can persist under these conditions, be they woody species such as *Taxodium distichum* (L.) L.C. Rich (bald cypress) and *Nyssa aquatica* L. and *N. biflora* Walt. (tupelos), or herbaceous species such as *Sagittaria latifolia* Willd. (broadleaf arrowhead), *Panicum hemitomon* J.A. Schultes (maidencane) and *Leersia oryzoides* (L.) Sw. (rice cutgrass). On the extreme margins of these landforms and away from the distributary mouths, oligohaline vegetation such as *Sagittaria lancifolia* L. (bulltongue) and three squares such as *Schoenoplectus americanus* (Pers.) Volk. ex. Schinz & R. Keller may establish where the hydraulic head of riverine freshwater is weaker and marine saltwater is allowed to lap at the edges (Shiflet 1963, Gosselink 1984).



DELTA COMPLEX	AGE (YEARS BP)
Maringouin	7250-6200
Teche	5700-3900
St. Bernard	4600-1800
Lafourche	3500-400
Modern	Active
Atchafalaya	Active

Figure 3: The modern landscape of southeastern Louisiana is the result of six broadly segregated delta lobes created over the past 7000 years by the switching of the primary locus of deposition for Mississippi River sediments. Figure from Louisiana Wetland Protection Panel, 1985.

When the river abandoned these distributary landforms during delta lobe switching, the hydraulic head that kept the sea at bay weakens and inevitably the landforms created by the distributary channels began to collapse shortly after delta lobe abandonment. That which helps create deltaic environments in the first place, namely the rapid deposition of riverine sediments, is also their curse. Deposited with both organic and inorganic sediments are large amounts of water and dissolved gases. Over time, as settling and compaction aggregate those sediments, the water and gas are liberated in micro and macropores and transported to the surface during dewatering and degassing (Penland et al. 1991). This compaction and loss of elevation is termed subsidence, and is one of the single most important concepts to realize when discussing the past, present and future of the Mississippi River Deltaic Plain.

So in comparison an active delta lobe, the continued input of riverine sediments into these landforms counterbalances the process of subsidence, and the lobe grows spatially and may in fact gain elevation via accretion. However, following delta lobe switching, sediment inputs decline and subsidence becomes the dominant process governing soil elevation. The combination of subsidence and the loss of the riverine hydraulic head allows tidal saltwater to penetrate deep into the wetland complex through the complex network of drainage channels, as well as from the margins of the wetlands themselves. Tidal freshwater and oligohaline communities are by definition not tolerant of exposure to high concentrations of saltwater, which causes a wide range of physiological stresses to the vegetation as well as altering marsh soil biogeochemistry in such a manner as to accelerate soil decomposition (see below). In response, the freshwater and oligohaline communities that originally developed on the prograding landforms are replaced by species tolerant of moderate salinity such as the grasses *Distichlis spicata* (L.) Greene (salt grass), *Spartina cynosuroides* (L.) Roth (big cordgrass) and *S. patens* (Ait.) Muhl. (wiregrass), the shrub *Baccharis hamilifolia* (L.), and the succulent forbs *Batis maritma* L..and *Borrichia frutescens* (L.) DC (Gosselink 1984). As the influence of saltwater increases, the system will transition into a salt marsh, dominated by *Spartina alterniflora* Loisel. (saltmarsh cordgrass), with lesser inclusions of *Juncus romerianus* Scheele (black needlerush), *Salicornia* spp. (glassworts).

Additionally, the physical environment changes drastically following distributary abandonment. Specifically, tide and wave dominated marine processes become dominant over the transgressing riverine processes, resulting in the physical reworking of soils and sediments on the margins of the distributary landform. The most immediate result of this process is the loss of finer silts and clays, along with soil organic particles, and the accumulation of coarser sandy sediments on a slowly formed erosional headland. Over time continued wave action pulls these sandy sediments into linear strands that we recognize as barrier islands, behind which are the gradually collapsing and salinizing wetlands. Eventually, the wetlands succumb to open water and recede landward, and the barrier island arcs are the only remaining landform present on the landscape. Continued reworking of these barrier islands over time, particularly in the absence of a sediment source, lead to the collapse of a subaerial island into a subaqueous shoal, which eventually becomes buried under marine clays, returning us to the start point on what has been termed the deltaic cycle (Figure 4, Penland et al. 1988).

We have emphasized the processes of Mississippi River distributary lobe establishment, switching and transgression, because the delta cycle is the single most important concept to grasp when discussing the management of the southeastern Louisiana coastal zone. It has to be remembered that any one place within southeastern Louisiana is at some point on this cycle of progradation and transgression, that this is a naturally occurring cycle, and that human management of socio-economically important coastal zone infrastructure represents an effort to preserve a landform that was present at the time of the establishment of that infrastructure, even though that landform was moving through this highly dynamic cycle towards an inevitable collapse back to the sea.

For example, one of the regions of southeastern Louisiana's coastal zone that is of direct interest for restoration and it's role as a storm surge buffer to protect New Orleans are the Lake Borgne and Breton Sound basins, east of present day New

Orleans and adjacent to Mississippi Sound. The wetlands of Lake Borgne and the barrier island chain that defines its seaward boundary (the Chandeleurs) were formed between 2800-1000 years ago when the St. Bernard delta lobe was the primary distributary system for the Mississippi River. Consistent with the delta cycle model described above, the Chandeleurs in fact formed from the erosional headland that resulted when the Mississippi abandoned this lobe in favor of the Lafourche delta lobe south of present day New Orleans. The wetland complex has been in a state of gradual erosion and landward transgression, and the erosion of marsh to open water behind that headland in fact defined the Chandeleurs as a function barrier island chain (compare Appendix Figures A1-A2). Over time, progressive barrier island rollover has also pushed the Chandeleurs landward, and is the reason why the chain paradoxically shows as both an area of land loss and gain in Figure 1. The islands show as land lost because the chain migrated landward from its position in 1932 to its location in 2000. The overriding challenge, then, in terms of managing a post-Katrina/Rita landscape in southeastern Louisiana, is to discover management options that acknowledge these processes and which may in fact offer us the potential of utilizing the dynamics of a deltaic environment to responsibly manage activities in the long term.

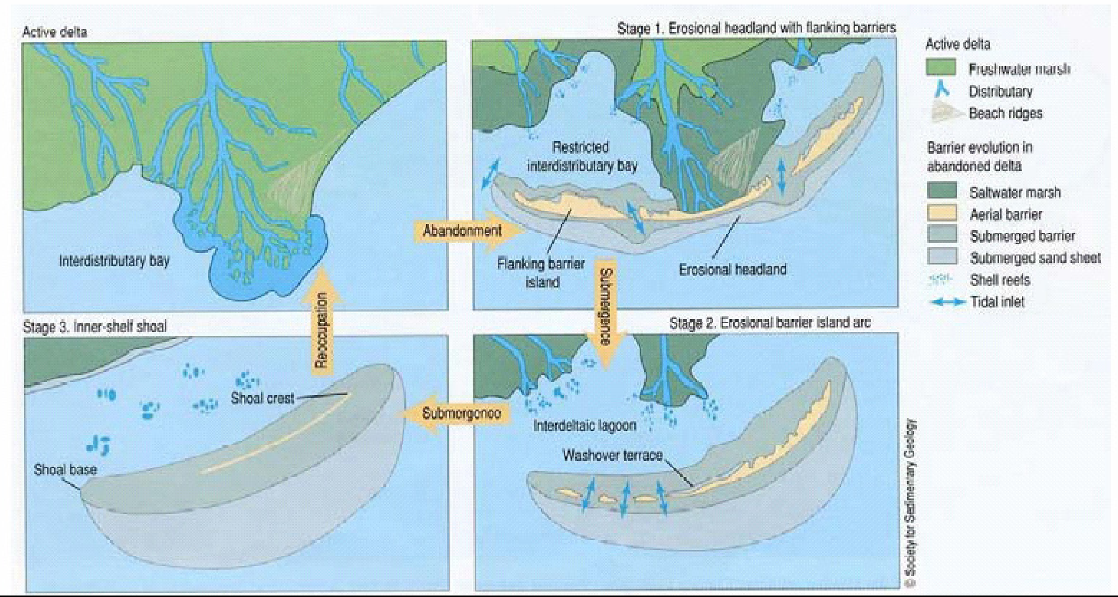


Figure 4: Evolution of barrier island chains from an active delta following distributary abandonment. Figure is an adaptation of Penland et al. (1988) from US ACE (2004).

Changes in Deltaic Processes Following European Colonization

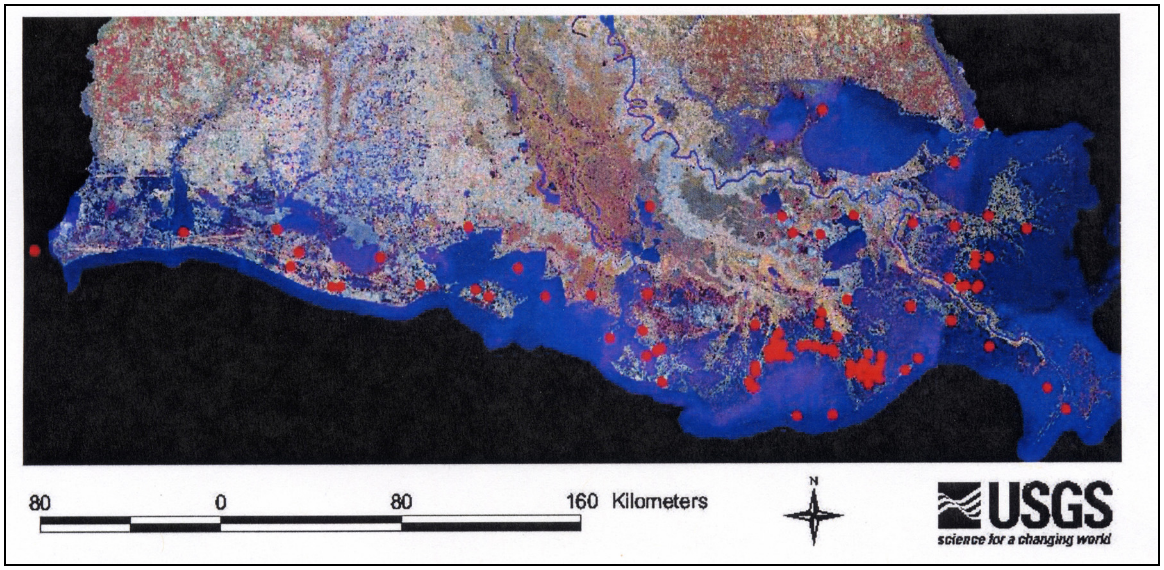
Coastal wetlands need to maintain their elevation with regard to sea level in order to persist. This is particularly the case in deltaic environments due to extremely high rates of relative sea-level rise (RSLR), which is the global or eustatic rise in sea level owing to changes in ocean volume corrected for local geologic conditions. For example, RSLR in northern Europe is less than eustatic SLR due to continuing continental rebound following the end of the last glacial maxima (Douglas and Peltier 2002). In deltaic systems, however, the high rates of subsidence due to natural compaction of river-deposited sediments, as described above, may lead to rates of relative sea level rise an order of magnitude higher than eustatic SLR. While Gornitz (1995) calculated a global SLR rate of between 1-2 mm yr-1 during the last century, Stumpf and Haines (1998) measured RLSR considerably higher than 1 cm yr-1 within the Mississippi River Deltaic Plain.

In order to persist under such high rates of subsidence, it is critical that the wetlands of southeastern Louisiana are supplied with the following: (1) sediments, (2) nutrients, and (3) freshwater. Sediments are necessary for maintaining a rate of accretion that is in excess of the relative rate of sea level rise. So long as wetlands accrete faster than they sink, saltwater intrusion is held at bay and the plants survive to hold together the soils of the wetland. Nutrients are needed to maintain plant productivity at high rates, which in turn results in an accelerated rate of organic matter production. Some wetlands can accrete solely based on the generation of autochthonous organic matter, but this is particularly rare in saline wetlands due to the increased rate of organic matter decomposition that results from the increased importance of the sulfur redox cycle (Mitsch and Gosselink 2000). Key to the rate of sediment accretion in the marshes (Figure 5) is the input of river sediments (Twilley 2003). Clearly only those locations with river sediment inputs had accretion rates above the 1 cm/yr value, a rate that is crucial to sustaining marshes in an area with > 1 cm/yr of SLR.

The historical intensive development of the southeastern Louisiana coastal zone over the past three hundred years, and the Mississippi River drainage basin as a whole, altered the supply of the three key factors (sediment, nutrients and freshwater) to Louisiana’s coastal wetlands. This likely accelerated local subsidence rates, reduced wetland productivity and thereby created a situation where wetland accretion could not outpace subsidence. For example, large-scale development (oil and gas etc.) over large areas explains in part the high rates of coastal land loss that we have witnessed over the past century and may have contributed to the extreme damage to southeastern Louisiana coastal communities from the passage of Hurricanes Katrina and Rita.

Dredging of Canals for Oil Exploration and Navigation

Oil was first discovered in Louisiana in the town of Jennings in 1901, and the US EIA (2005) estimates that Louisiana's 2004 total petroleum reserves total approximately 427 million barrels. Much of that oil is underneath the coastal wetlands, and industry activities within the Louisiana have been significant. Additionally, numerous canals have been dredged through the Louisiana coastal zone for the purposes of facilitating surface water commerce and navigation. Three of the best known are the Gulf Intracoastal Waterway (GIWW), the Houma Navigation Canal (HNC) and the Mississippi River Gulf Outlet (detailed separately below). The GIWW is 1770 km (1100 mile) transportation corridor linking Apalachee Bay, Florida to Brownsville, Texas. Concerns have been raised for the potential of the GIWW to serve as a conduit of saltwater to inland wetlands; however, there is also evidence that the GIWW helps distribute Atchafalaya River freshwater into the wetlands of the western Terrebonne Estuarine Basin. The HNC is a 48 km (30 mile) canal linking the Port of Houma with the Gulf of Mexico, and intersects with the GIWW. The HNC is authorized for a profile of 4.5 m (15 feet) deep x 91 m (300 feet) wide (USACE 2005). However, aerial photography also indicates a significant impact on adjacent wetlands due to dredge spoil placement on the immediate banks, which prevents sediment from leaving the channel.



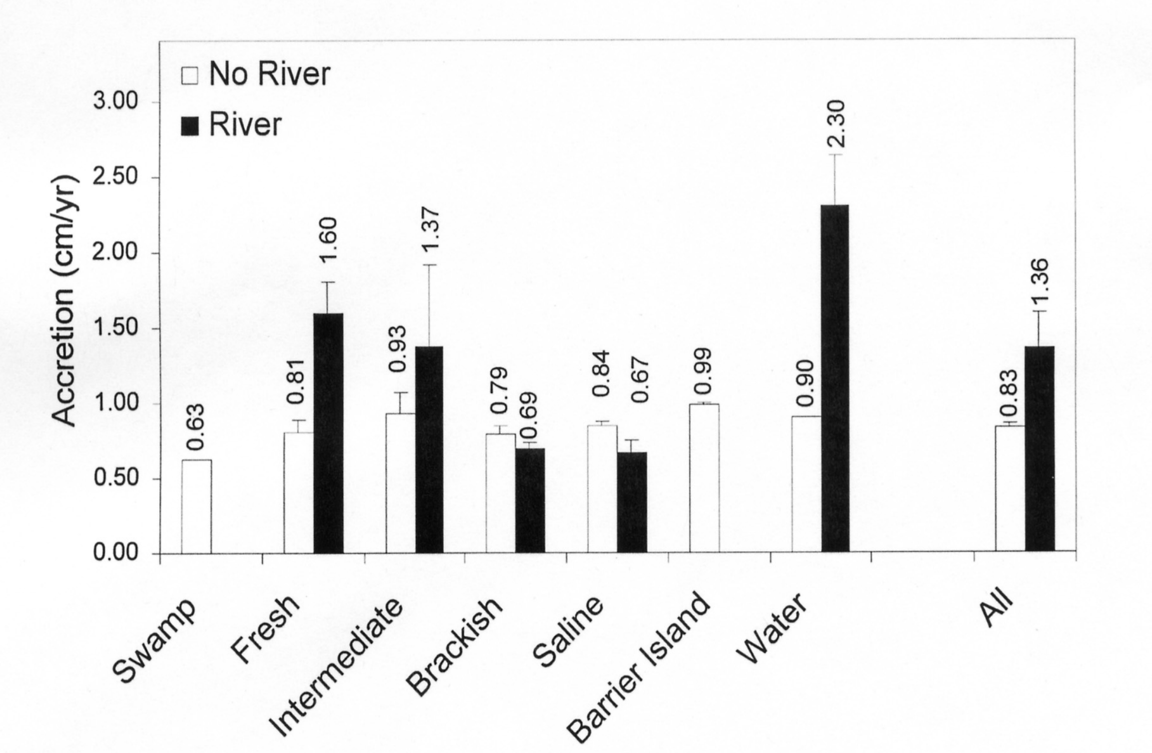


Figure 5: Accretion rates for multiple sites within the Louisiana coastal zone (top) were determined by measuring the ^{137}Cs profile, and aggregated by habitat and river influence. Error bars reflect one standard error. River influenced rates are based on four or fewer cores per marsh type. Source: Twilley 2003.

There are several modes of potential impacts that oil and gas extraction activities and navigation canal creation and maintenance can have on coastal wetlands (Schaife et al. 1983, Turner et al. 1984, Turner 1997, Day et al. 2000).

- Direct Surface Losses: Dredging of oilfield and navigation canals has an obvious direct effect on wetlands through both the physical impact of cutting into the wetlands to dredge the canals and also placing dredge spoil onto the surface marsh as a disposal option, which smothers the existing wetlands and creates upland habitat.
- Indirect surface losses: This issue has been somewhat more contentious, but the argument here is two-fold. First, the canal networks that are dredged into the wetlands typically link to large coastal saline water bodes such as saline lakes and embayments, if not directly to the GOM. These networks allow saltwater to intrude into wetlands that naturally were on the low-salinity end of the natural estuarine gradient that existed prior to widespread network installation activities. Second is the argument that the placement of spoil banks on the margins of the canal networks interrupts and altogether prevents overbank and tidal sheet flow flooding of the marsh surface. Not only does this starve the wetlands of floodwater sediments, in the same manner as the large Mississippi River levees described above, but many coastal wetlands rely on both freshwater inflows and saline tidal flows to remove accumulated toxic chemical species from the system (e.g. H_2S formed by the reduction of

sulfate in flooded soils) as well as rejuvenating the wetlands with new influxes of nutrients and dissolved oxygen, *sensu* Odum's (1980) tidal subsidy concept.

- Indirect subsurface losses: Removal of subterranean fluids during both mineral and groundwater extraction activities can exacerbate natural subsidence driven by dewatering and degassing leads to an acceleration of soil collapse. In coastal Mississippi, extreme rates of subsidence, approximately 20 mm/yr, were associated with subterranean fluid hydrocarbon withdrawals in the 1960s and 1970s, although subsidence rates declined significantly following subsequent production declines (Morton et al 2003). In Texas, fluid withdrawal has also been associated with block slumping along fault lines, contributing to increased subsidence rates in areas substantially distant from the actual site of fluid withdrawal. (Morton et al 2001). Research also suggests that subterranean fluid withdrawal promotes geologic slumping by promoting down warping along existing fault lines (Morton and Purcell 2001).

Pre-Katrina Status of Wetlands in New Orleans

European exploration and settlement of the Louisiana territory began in 1528, when a Spanish expedition led by Panfilo de Narváez discovered the mouth of the Mississippi River. French exploration through southeastern Louisiana did not occur until 1682, when Rene Robert Cavalier, Sieur de La Salle, traveled down the Mississippi River from Canada and claimed the entire Mississippi River Basin between the Rockies and the Appalachians for France. Although eager to secure the new French territory, Pierre Le Moyne d'Iberville was forced to establish Baton Rouge in 1699 because of the lack of adequate high ground on lower portions of the river. However, Baton Rouge, as well as the French forts in coastal Alabama and Mississippi, did not allow for secure control of the Mississippi River (McNabb and Madére 2003). Therefore, in 1718 New Orleans was established by Jean Baptiste La Moyne, Sieur de Bienville in order to control access to the new French colony upstream.

As McNabb and Madère (2003) point out:

> *"At first, however, New Orleans was more important as an image than it was in reality. Surrounded by the waters of river, lake and swamps, the French referred to New Orleans as the "Isle d'Orleans." And, indeed, New Orleans was an island, not just in the physical sense -- which was true after slight improvements were made at the site, namely a three-foot artificial levee which kept out all but the worst floods..."*

And thus began the efforts in south Louisiana to claim land from the delta for purposes of settlement and farming. However, those initial efforts were slow. Appendix Figure A3 shows the "Isle d'Orleans" of 1728 as a tenuous collection of buildings on the natural levee. In 1763, following the French defeat of the Seven Year's War (the French and Indian War in North America), control of

Louisiana was transferred to the Spanish, who ruled until 1802. By 1798, New Orleans resembled more a military colony, enclosed by defensive works (Figure A4). However, by that time several sizable canals had already been cut into the neighboring back swamps. Canal digging facilitated drainage, and drainage facilitated real estate development (Figures A5-A8), so that within 110 years, the former swamplands between the Mississippi River and Lake Pontchartrain had been completely converted to habitable land (Figure A9), or at least from a drainage standpoint; mosquitoes and the oppressive New Orleans summer heat still remained a significant issue until the advent of air conditioning in the middle of the 20th century.

There were ample opportunities to learn from the vulnerabilities that arose from living within the converted back swamps between the Mississippi River and the Lake. Figure A6 shows the extent of the flooding (and if your eyes are good enough, the depth of flooding) in New Orleans from an 1849 levee break upriver of the city proper, at the site of the Sauvé Plantation. The more darkly colored areas on Figure A6 are those areas that flooded to greater depths. Compare that pattern of flooding to that shown in Figure 10.

The improved levees that encircled the city, in conjunction with the drainage network of canals and pumps, succeeded in keeping the soils dry. Unfortunately, this only exacerbated the oxidation and subsequent settling of the soils within the protection levees, increasing the depth of "the bowl" and creating the situation within New Orleans illustrated in Figures 6. The effect of this historical subsidence was realized by the extent of flooding seen in homes throughout New Orleans (Figure 7).

The 1927 Flood

Much has been written about the 1927 Mississippi River flood, ecologically as well as socio-economically, in reference to Barry's seminal "Rising Tide" (1997) for those interested in details of the event. The relevance of the 1927 flood to this discussion is simple but eminently critical. Prior to the 1927 flood, the maintenance of the Mississippi River for navigation and flood control was piecemeal at best. The leveeing of floodplain communities from the vagaries of the River's periodic flood cycle that was begun by those first French settlers was in the hands of multiple agencies throughout the drainage basin as a whole. The destruction wrought by the river on the southeastern states within the Lower Mississippi Alluvial Valley was such that after 1927, there was a concerted effort by the US Army Corps of Engineers (USACE) to provide definitive protection of floodplain communities, the result being that at present, the Mississippi River is enclosed within a string of continuous concrete levees from Cairo, Illinois, to Venice, Louisiana, at the bottom of the Modern or Balize Delta.

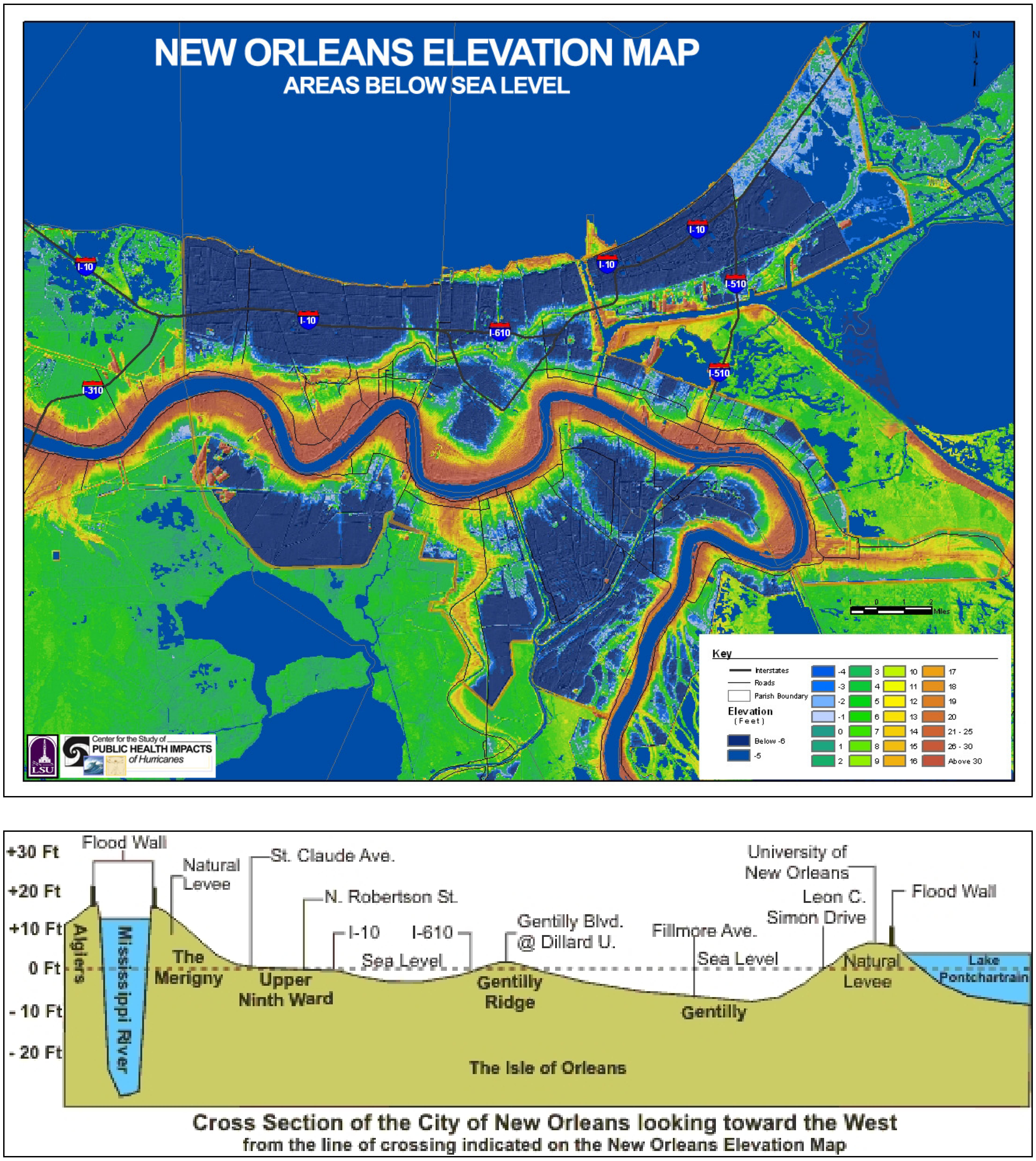


Figure 6: Both LIDAR-based elevation maps (top) and cross-sections (bottom) of present-day New Orleans illustrate the problem in which much of the New Orleans Metropolitan Area found itself in August 2005 after centuries of draining the former back swamps behind the natural levees of the Mississippi River in order to facilitate development. Although most of the back swamp areas between the natural river and lake levees were likely at or above sea level at the time that they were progressively drained over the past 200 years, many of those soils have since subsided due both to natural deltaic processes, tectonic movements and oxidation of the soil organic matter. Thus when Hurricane Katrina struck, many of these areas were actually below sea level, so that when the floodwalls failed, the water from the Industrial Canal and Lake Pontchartrain naturally flowed downhill into the resulting bowl, and had no way except for pumping to get back out. The area thus remains dependent on the network of flood control levees, floodwalls and canals maintained by local, State and Federal agencies. Top figure courtesy of the LSU Hurricane Center (http://hurricane.lsu.edu/floodprediction/NewOrleans/New_Orlean_Elevation2.jpg). Bottom figure courtesy of http://www.southbear.com/New_Orleans/Geography.html).

Figure 7: A house in a lower section of New Orleans that was flooded to nearly the roof, as shown by the series of water marks. Note the door height is a standard six ft six inches and thus the level of water was from the ground nearly 8 feet deep. The level of land subsidence is shown by the red arrow and indicates that the soil had a subsidence of nearly 6 + feet due to drainage of the wetland soils and compaction by dense building on soils of low bulk density.

The historical leveeing of the Mississippi River has been identified as the single most important driver of accelerated wetland loss within the Deltaic Plain (Day et al. 2000, 2005). As stated earlier, wetlands need freshwater, nutrients and sediment to survive. The levees work very well in their job of flood control, but in doing so they prevent the very over bank flooding that naturally provides the distributary basins within the Deltaic Plain with the freshwater, nutrients and sediments that the wetlands require. Only south of Venice are the levees such that over bank flooding or small-scale crevasse punctures possible. Elsewhere, because of the substantial infrastructure in place along the margins of the Mississippi River, larger scale, and consequently more expensive, engineering solutions to move water and sediments from the River over the levee to the wetlands are required.

Interestingly, upstream management of the individual tributary river basins within the overall Mississippi drainage has also complicated the stability of the wetlands of southeastern Louisiana. As Kesel (1988) describes, the placement of dams throughout the Mississippi River Drainage Basin for navigation, flood control and hydropower have resulted in an estimated 70% reduction in suspended sediment load within the River since 1850. Thus, the water that is transported into the distribution basins is less efficient in fostering accretion and promoting wetland sustainability.

Dredging of the MRGO

Every natural disaster has it's "villain du jour," and the emerging villain in the story of southeastern Louisiana and Hurricane Katrina is the Mississippi River Gulf Outlet (MRGO, or MisteR GO), a brief introduction to the history before discussing the role of the MRGO during Hurricane Katrina in the next section. MRGO is a 76-mile canal cut through the marshes of Breton Sound to allow large vessel traffic to access the Port of New Orleans without having to traverse the meanders of the lower Mississippi River. The project was built between 1958 and 1965 with a trapezoidal cross section 152 m wide at the base and 198 m wide at the surface (Caffey and LeBlanc 2002). However, shoreline erosion due to ship wakes quickly became a problem, and shortly before August 2005 the profile had changed drastically; the channel was approximately 600 meters (2000 feet) in width.

By cutting through the natural Bayou La Loutre levee, and three others (CCMRGO 2004), the canal provided a direct route for high salinity GOM water to intrude into the interior of the existing wetland complex. At the Shell Beach monitoring station near the center of the project area, US FWS reported that salinities increased from 3.5 ppt for the period 1959-1961 (pre-construction) to 12 ppt for the period 1972-1974 (Kerlin 1979). Additionally, the USACE estimated that almost 6500 hectares of cypress swamps, levee forests and fresh, brackish and salt marshes were either impacted or destroyed (USACE 1999), largely due to saltwater intrusion and impoundment, as well as smothered by spoil bank creation (Figure 8).

Critics of the project railed against the operating costs, arguing that a cost-benefit analysis of the project did not warrant its continued operation. Because of siltation, the USACE was forced to dredge the channel every year, at a cost of $22 million annually (Caffey and LeBlanc 2002; USACE reports $13 million yr^{-1} for the period 1985-2002, USACE 2003), to maintain the channel at a depth of 11 m (36 feet).

In 1965 Hurricane Betsy struck the southeastern Louisiana coast. The following description sounds unfortunately familiar.

> *"Betsy also drove a storm surge into Lake Pontchartrain, just north of New Orleans, and the Mississippi River Gulf Outlet, a deep-water shipping channel to the east and south. Levees for the Mississippi River Gulf Outlet along Florida Avenue in the lower Ninth Ward and on both sides of the Industrial Canal were overtopped and failed. The flood water reached the eaves of houses in some places and over some one story roofs in the Lower Ninth Ward. Some residents drowned in their attics trying to escape the rising waters… These levee breaches flooded parts of Gentilly, the Upper Ninth Ward, and the Lower 9th Ward of New Orleans as well as Arabi and Chalmette in neighboring St. Bernard Parish…*
>
> *The Army Corps of Engineers' Hurricane Protection Program came into existence as a result of Betsy. The Corps built new levees for New Orleans that were both taller and made of stronger material, designed specifically to resist a fast-moving Category 3 hurricane like Betsy."*[1]

Figure 8: Photos of the Mississippi River Gulf Outlet taken in 1960 (left) and 1989 (right), looking southeast at the junction between the MRGO and the Intracoastal Waterway. Notice the extent to which the MRGO has widened with its southward flow from the ICWW, and the decay of the adjacent wetlands in the left-center of the photos. Photos courtesy of *Louisiana Sportsman Magazine*.

Critics have worried that as the continued erosion of the channel only increased the risk that the surge from a catastrophic storm strike would follow the MRGO into populated areas (CCMRGO 2004). That concern would turn out to be unfortunately prescient.

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[1] Article for Hurricane Betsy, Wikipedia.org, accessed 21 April 2006.

Post-Katrina Wetland Consequence Assessment (CA)

Discussions about the aspects of the damage assessment and relevant information for Hurricanes Katrina and Rita, by following the storm as it came ashore will be address. Thus we'll begin at the barrier island chains in Barataria Bay, Breton Sound and the Mississippi and Alabama Gulf Coasts, move inland through Lower Plaquemines Parish and the wetlands around St. Bernard and the Rigolets, and finish with the effects of an amplified storm surge on eastern New Orleans. We will also address the effect of the storm surge from Hurricane Rita on the inland areas of the Barataria and Terrebonne Estuarine Basins, as that relates to the overall role of how human activities within the coastal zone have promoted avenues of storm surge transport into the interior of the distributary basins. This is not meant to be a complete damage assessment for all of southeastern Louisiana and the Mississippi and Gulf Coasts. It is instead meant to illustrate that there were areas in the path of the hurricane that could have benefited from a more significant wetland buffer. We will discuss how that buffer might best be addressed in the next section.

Northern Gulf Coastal Barrier Island Complexes

By their nature, barrier island chains are typically the first systems to see the effects of an incoming hurricane. With regard to Hurricane Katrina, we will focus this part of our discussion on three sets of islands, which experienced different degrees of damage. First are the Mississippi and Alabama coastal barrier island chains, second are the Barataria and Terrebonne Island chains (e.g. Grand Isle, Grand Terre), and third are the Chandeleur Islands separating the Gulf of Mexico from Breton Sound.

Earlier we mentioned the phenomenon of barrier island rollover when we discussed the Chandeleur Island chain. It is important to remember that barrier islands are mobile landscape features. Specifically, in periods of rising sea level, barrier island chains move landward over time. The mechanism of this movement is an episodic but continuous process called barrier island rollover (Dillon 1970). Individual storms may breach the primary dune of an individual island, and the storm surge will transport the sand from that breach and from the foreshore as an over wash fan that buries landward communities of the island such as barrier flats, salt marshes and lagoonal seagrass beds. These buried communities reestablish at a new point on the overwash fan further inland, and in time the entirety of the island will be moved landward in such a manner.

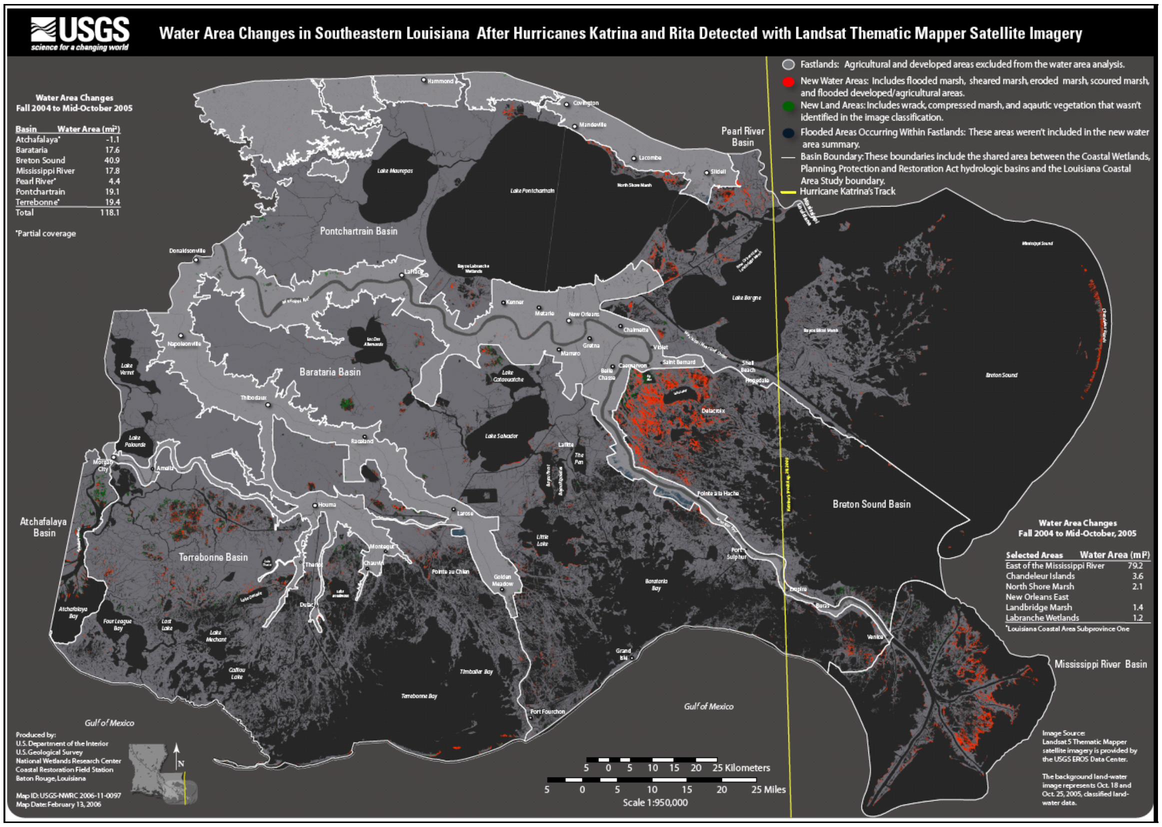
Nowhere was this better demonstrated after Hurricane Katrina than at Dauphin Island, which provides a poignant lesson on the issue of proper, or as the case may be, improper management of barrier islands with regards to storm effects and island resiliency. Photography and LIDAR data available from the USGS Coastal and Marine Geology Program's Hurricane and Extreme Event Impact Studies website illustrates the destruction on the western side of Dauphin Island. Katrina's storm surge at Dauphin Island was 2.0 m (6.63 feet) as reported by NOAA (http://www.srh.noaa.gov/mob/0805Katrina/). Overall, reports indicate that over 300 of 900 structures on the island were damaged, and an additional 200 were completed destroyed (PBS 2005). Most of the completely destroyed structures were on the western side of the island, where it is important to note in the USGS data for Dauphin Island, before Katrina, the lack of a seaward dune buffering the beach houses. The USGS topographic quad map for western Dauphin Island (Heron Bay Quad), dated 1981, does show at least a 1.5-m (5-foot) dune seaward of the western-most beach houses, but by April 1999, when the junior author visited the island, that dune was no longer present, and houses were positioned directly at the water's edge. Destruction on Mississippi's Sea Islands, within the National Park Service's Gulf Islands National Seashore, was also significant.

Damage to Grand Isle appeared more sporadic. Grand Isle received a storm surge of at least 2 m (NOAA Tide Gauge Record). Grand Isle and Grand Terre are transgressional elements remaining from the Lafourche Delta Lobe, and are about 1000 years old (Morton and Peterson 2005). For Grand Terre, the western part of the island showed obvious overwash fans, but aerial photography did not show any significant damage to the LA Department of Wildlife and Fisheries research laboratory. Interestingly, the eastern part of the island, where wetlands had been recently restored, saw little evident overwash fan creation. Grand Isle likewise saw little in the way of systematic severe destruction. The importance of these islands is that they intercept storm surge that would otherwise break against the inland wetlands within the Barataria Estuary. Thus, the continued resiliency of these and other barrier islands is necessary for the long-term survivability of Louisiana's coastal wetlands.

In comparison, damage to the Chandeleurs can only be described as catastrophic. These islands were severely damaged by the eye of Hurricane Katrina, which passed just to the west of the island chain, exposing the islands to the strongest winds and storm surge of the storm. USGS documentation of the islands pre- and post-Katrina show significant loss of acreage to open water, and MSNBC reported an LSU geologist's estimate that subaerial extent of the island change may have been reduced by half due to Hurricane Katrina (Llanos 2005). The Chandeleurs have been in the latter stages of the delta cycle for several millennia. Part of the St. Bernard delta lobe that ceased to be active approximately 1800 years ago (Figure 3), and have been in a stage of transgression since. The Chandeleurs have been migrating eastward at a significant speed since 1932. One aspect of continual transgression and barrier island migration for that long a period is that each subsequent rollover event consumes some of the sand in the island, and therefore as the island continues to move it gets smaller, and less resilient to each new storm event. Human habitation on the Chandeleurs is absent due to their small size and tenuous existence, but those exact factors threaten the long-term stability of the more fragile wetlands within the Breton Sound and Lake Borgne basins.

Coastal Wetland Complexes

Damage to both wetlands and community infrastructure was most severe within the basins east of the Mississippi River. The USGS estimated in February 2006 that combined, storm damage from Hurricanes Katrina and Rita converted approximately 306 square km (118 square miles) of southeastern Louisiana wetland to open water, based on Landsat analysis (USGS 2006). Approximately 106 square km (41 square miles) of that loss occurred in Breton Sound, where the eye of the storm crossed the region, and largely within the Caernarvon Freshwater Diversion Project area (Figure 9).



Water Area Changes
Fall 2004 to Mid-October 2005

Basin	Water Area (mi²)
Atchafalaya*	-1.1
Barataria	17.6
Breton Sound	40.9
Mississippi River	17.8
Pearl River*	4.4
Pontchartrain	19.1
Terrebonne*	19.4
Total	118.1

*Partial coverage

● Fastlands: Agricultural and developed areas excluded from the water area analysis.
● New Water Areas: Includes flooded marsh, sheared marsh, eroded marsh, scoured marsh, and flooded developed/agricultural areas.
● New Land Areas: Includes wrack, compressed marsh, and aqautic vegetation that wasn't identified in the image classification.
● Flooded Areas Occurring Within Fastlands: These areas weren't included in the new water area summary.
— Basin Boundary: These boundaries include the shared area between the Coastal Wetlands, Planning, Protection and Restoration Act hydrologic basins and the Louisiana Coastal Area Study boundary.
— Hurricane Katrina's Track

Water Area Changes
Fall 2004 to Mid-October, 2005

Selected Areas	Water Area (mi²)
East of the Mississippi River	79.2
Chandeleur Islands	3.6
North Shore Marsh	2.1
New Orleans East	
Landbridge Marsh	1.4
Labranche Wetlands	1.2

*Louisiana Coastal Area Subprovince One

Produced by:
U.S. Department of the Interior
U.S. Geological Survey
National Wetlands Research Center
Coastal Restoration Field Station
Baton Rouge, Louisiana

Map ID: USGS-NWRC 2006-11-0097
Map Date: February 13, 2006

Image Source:
Landsat 5 Thematic Mapper satellite imagery is provided by the USGS EROS Data Center.

The background land-water image represents Oct. 18 and Oct. 25, 2005, classified land-water data.

Figure 9: Wetland land loss in southeastern Louisiana due to the passages of Hurricanes Katrina and Rita was concentrated around the Balize Delta, the Caernarvon area of the Breton Sound Basin, and the mouth of Lake Pontchartrain. Map courtesy of USGS.

Damage from Hurricane Katrina to both the ecological and human communities in Plaquemines Parish as a whole, and lower Plaquemines Parish in particular, was severe. Plaquemines Parish government estimates that in total, wetland loss to open water within the parish was a total of 148 square km (57.2 square miles), which does include portions of the Breton Sound loss described above (Louisiana Speaks 2006).

Communities within the lower portions of the Balize Delta (lower Plaquemines Parish) are extremely vulnerable to hurricane induced wind and storm-surge damage. Plaquemines Parish reported that 5420 housing units were destroyed or received major damage, leaving only 2687 housing units potentially habitable. Always vulnerable due to its position in the middle of the Balize Delta, Pilot Town was completely destroyed except for the main pilots dormitory buildings. At Empire, Louisiana, the waters of the local bays are separated from those of Breton Sound on the north side of the peninsula by about 5 km, and the remainder of the inhabited peninsula to Venice is not much wider. In those communities, there was significant damage not only to structures but also infrastructure such as roads, bridges and floodgates.

Historically, large deltaic bay fills, landforms typified by mud flats and wetlands that were the result of crevasse splays punched through the slight natural levee of the Mississippi River, occupied the margins of the lower Balize Delta. However, due to the high rates of subsidence natural to the system as described above, most of these wetland landforms in the Balize Delta have a limited lifespan, typically no greater than 150 years. Additionally, with the River now leveed by the USACE all the way to Venice, creating bay-fills that would be capable of protecting the communities occupying the strands of solid land between the Mississippi and Barataria levees is difficult. The Federal Government seems to have recognized the inherent vulnerability of the lower portions of the Balize Delta, and that the costs of trying to protect its population may not be economically feasible. On Wednesday, 12 April 2006 Federal Coordinator of Gulf Coast Rebuilding, Donald Powell, announced that the rebuilding plan for southeastern Louisiana would not include funding to repair levees that protect Lower Plaquemines Parish (Thevenot, 2006), and that any future discussions of such efforts would require additional cost-benefit analyses.

Moving northward, the communities within the Breton Sound Basin, and particularly those outside the main protection levees such as Delacroix and Hopedale, showed significant damage. The Baton Rouge Advocate reported on September 14 2005 that "... in Delacroix Island, there are four structures left ... Hopedale, not one structure left." (http://www.hurricane-katrina.org/area_damage_reports/index.html). Further north, an examination of the USGS wetlands impact map for southeastern Louisiana also shows significant damage to the Rigolets / North Shore / Pearl River complex, which accounted for a total of 20.5 km^2 (7.9 square miles) of coastal wetlands loss. These areas sustained heavy damage as the storm surge was funneled into Lake Pontchartrain. As with some of the communities in lower Plaquemines Parish, "land bridge" communities such as Lake Catherine, centered around US 90 and outside the primary protection levees, were simply wiped out from the combination of wind damage and storm surge that hit them directly.

In contrast, communities within the wetland complexes west of the river were comparatively spared significant storm surge or wind damage from Hurricane Katrina. However, these communities did see some damage to varying extents from Hurricane Rita. Within southeastern Louisiana, the mechanism of storm damage was characterized more by intrusion of storm surge deep into the complex network of natural and man-made drainage networks (tidal channels, navigation and oilfield canals) which caused gradual but persistent flooding. Specifically, Hurricane Rita's storm surge penetrated into both Barataria and Terrebonne Bays through the navigation and oil field canal networks and flooded many of the low lying communities such as Lafitte.

The Greater New Orleans Metropolitan Area

Much has been written about the combination of factors that led to the tragic flooding of New Orleans. While the flooding of New Orleans and St. Bernard Parish was due to multiple floodwall and levee breaches throughout the metropolitan area, we will focus our efforts here on summarizing the series of events that led to the breaching of the floodwalls on the Industrial Canal and resulted in the well publicized flooding of the Lower Ninth Ward, Bywater and other areas around eastern New Orleans (Figure 10).

To do so, we have to revisit the controversy of the MRGO. Observations (Figure 11a) and modeling efforts confirm that, as with Hurricane Betsy, the storm surge from Katrina moved up through the MRGO, combined with significant surges generated through Lake Borgne and the GIWW, and concentrated in an area known as the funnel (Figure 11b), a triangular area paradoxically formed by the protection levees of the MRGO and GIWW. There were eight successive breaches of the west bank guide levee of the MRGO, allowing the storm surge to move into the adjacent marsh and against the St. Bernard Parish protection levee, which itself breached in five places, flooding the towns of St. Bernard and Violet. This concentration of water into the funnel increased both the magnitude (Figure 11b) and the velocity (Figure 11c) of the storm surge as it entered the neck of the funnel where the GIWW and MRGO meet, and this water was then directed south into the Turning Basin and towards the floodwalls on the Industrial Canal. The New Orleans Times-Picayune reported on the 24 September 2005 that Hurricane Katrina had damaged the canal locks in the Industrial Canal (Filosa and Krupa 2005), and that they were open at the time of Hurricane Rita's passage, which may have facilitated Rita's storm surge flooding the partially repaired Industrial Canal floodwall breach into the Lower Ninth Ward.

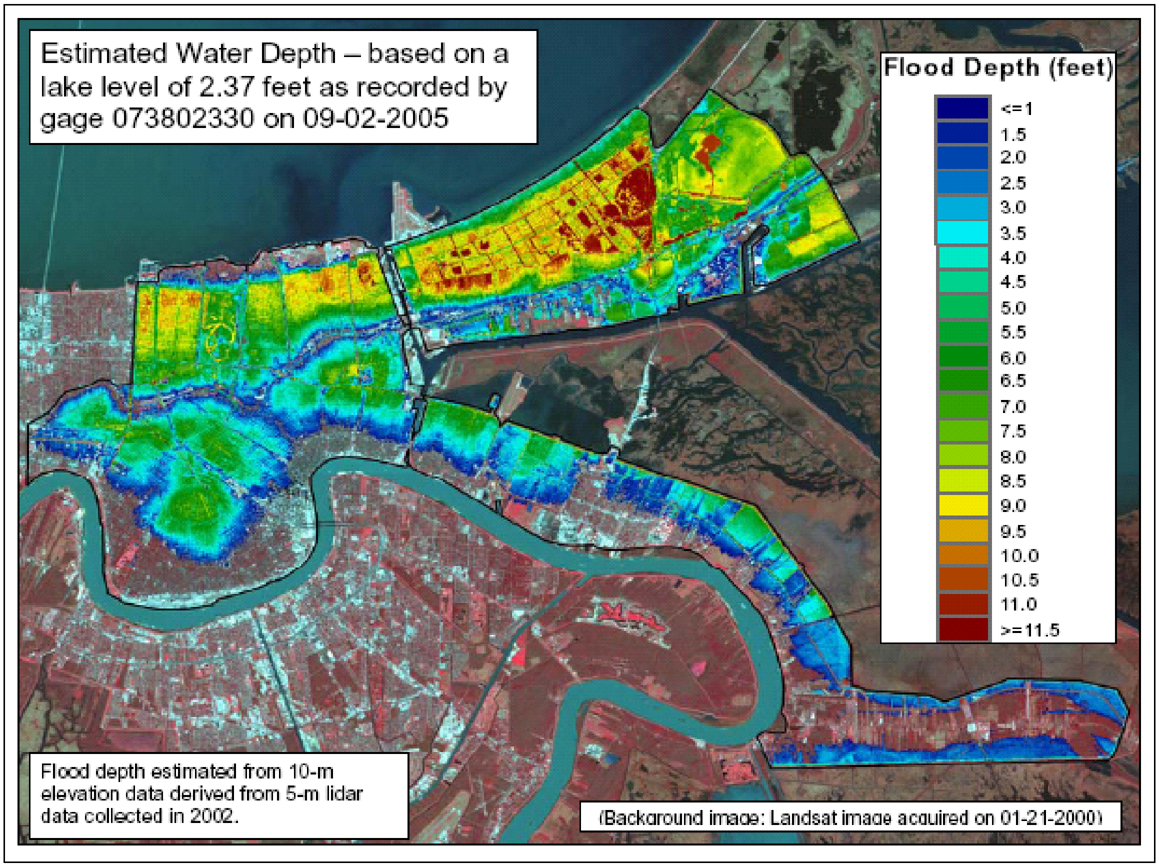


Figure 10: Flooding within Orleans and St. Bernard Parishes after the passage of Hurricane Katrina was concentrated along the shore of Lake Pontchartrain, the Mid-City area of New Orleans, and along the flood protection levee in St. Bernard.

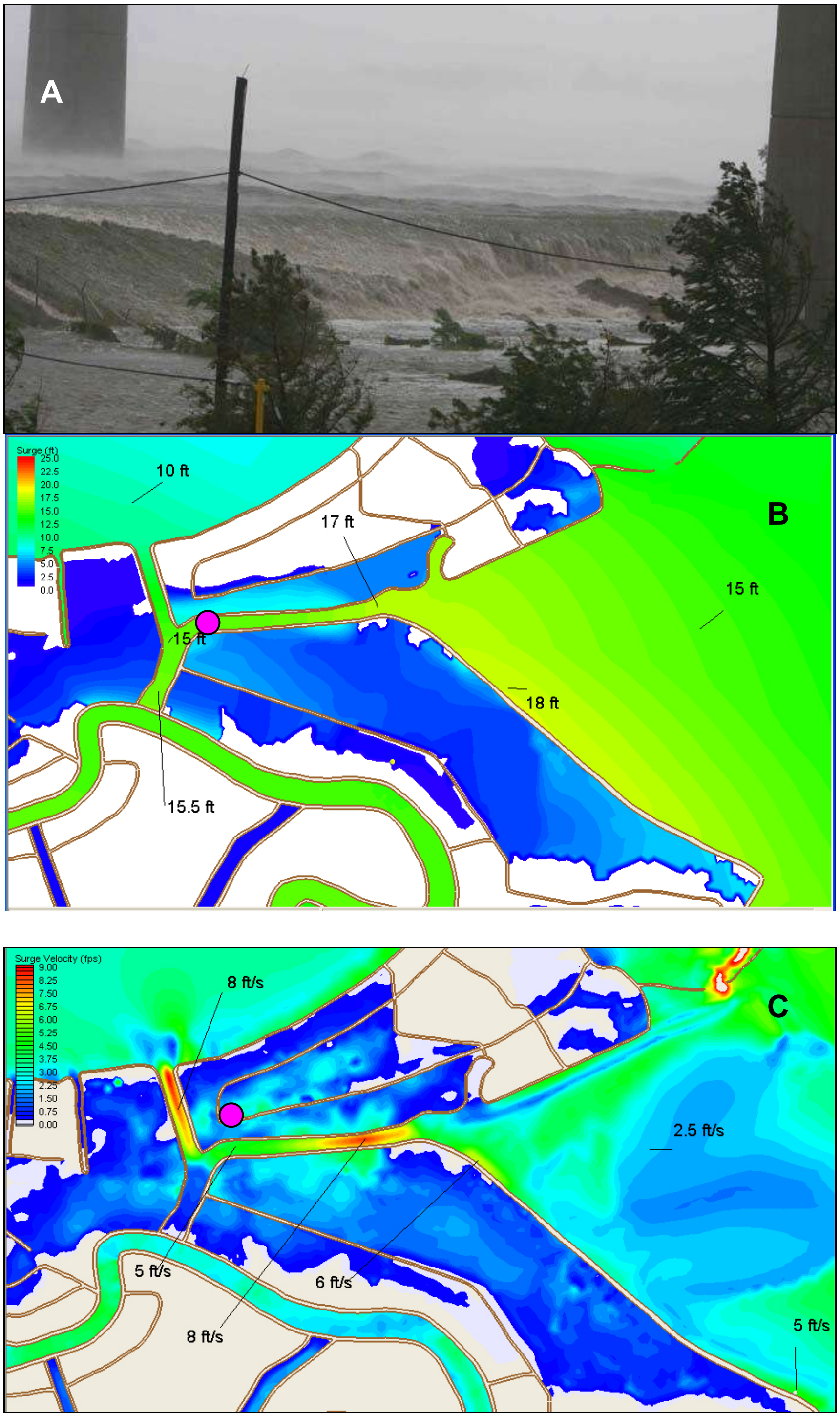


Figure 11: Photograph (a) of the Hurricane Katrina storm surge overtopping the north shore of the GIWW-MRGO levee near Michoud (http://www.mgcollins.com/Katrina/MRGOPage.html). The vantage point of the picture is illustrated as the pink dot in the bottom two figures, which show modeling results of the storm surge magnitude (b) and velocity (c), modeled by the LSU Hurricane Center (http://hurricane.lsu.edu/floodprediction/katrina/deadly_funnel1.jpg).

Post-Katrina Wetland Consequence Projection (CP)

We earlier documented the large-scale historic loss of wetland ecosystems from the lower Mississippi River Deltaic Plain prior to the hurricane strikes of August and September 2005, and have discussed the patterns of damage from the 2005 storms, which suggests that the loss of coastal wetland buffers and the subsidence of wetlands in are around New Orleans proper have contributed to the severity of destruction. It is beyond the scope of this report to cover in detail wetland restoration plans for the entire coastal areas but we can address the scientific community's overall analysis of the potential for coastal wetland restoration affects on New Orleans as well as provide a brief synthesis of the recommendations from two excellent recent reports that presented wetland loss and mapping in Coastal Louisiana (NRC 2005) and "A New Framework for Planning the Future of Coastal Louisiana after Hurricanes of 2005" (Boesch et al. 2006). The topics that we will now address in this section is then central to the future management of southeastern Louisiana and the reentry and reoccupation (R& R) in New Orleans: **Will the restoration of coastal wetlands reduce the vulnerability of human infrastructure, and if so, how might that restoration be best accomplished, in terms of the effective and efficient utilization of monies and restoration effort?**

Modeling Wetlands as Storm Surge Buffers

The idea that barrier islands, forested wetlands, shoals and marshes can serve as effective buffers against storm surge is consistent with observations of other coastal ecosystem responses to extreme storm surges. It has been well reported that the areas of the Indonesian coastline where fringing mangrove forests were intact suffered less damage following the tsunami of 26 December 2005 than adjacent coastal areas where the mangroves had been removed for development (Kathiresan and Rajendran 2005). A case in point is the report by Danielsen and colleagues (2005) that the catastrophic coastline destruction and death in India caused by the December 26th 2004 Asian Tsunami was unpreventable but further inland areas with coastal treed mangrove wetlands were markedly less damaged than areas without protective mangroves. A fact often not mentioned in the panic to rebuilt the levees before the next hurricane season is that most of the forested wetlands south of New Orleans have been destroyed or damaged by navigation channels, salt water intrusions and the loss of sediment from the Mississippi due to diking of the river. Importantly, it is these forested wetlands and marshes south and east of New Orleans that might have provided some additional surge protection to the city. Unfortunately, empirical and field evidence on the role of wetlands in damping storm surges is very limited as noted by Danielsen (2005) and the scientists at the Wetland Center at LSU. It has also been reported that storm surge elevation is suppressed one foot (0.3 m) for every 2.7 miles, or every square mile of wetlands over which it travels, but this number is 40 years old, is in dispute and the original studies used to support this are in question (Twilley, personnel communication, LCA 2004). It has been reported more recently that after Hurricane Andrew a storm surge reduction along the central Louisiana coast of about three inches (7 cm) per mile of marsh (Lovelace 1994).

It is known that forest canopies can greatly diminish wind penetration, thereby reducing the wind stress available to generate surface waves and storm surge (Reid and Whittaker 1976). The sheltering effect of these canopied areas also affects the fetch (the length of water over which a wind has blown) over which wave development occurs. Shallow water depths attenuate waves via bottom friction and breaking, while vegetation provides additional frictional drag and wave attenuation and also limits static wave setup (Boesch et al. 2006). Extracting energy from waves either by breaking or increased drag in front of levees would reduce the destructive storm wave action on the levees themselves. Importantly, where there were trees in front of overtopped levees they received little structural damage from Hurricane Katrina (USACE 2006).

The logic on which these statements are based involves Manning's equation, and specifically variations in the Manning's *n*, the roughness coefficient.

Eqn. 1. $Q = \left(\frac{1}{n}\right) AR^{2/3} S^{1/2}$

Where Q = flow velocity (m/sec)
n = roughness coefficient
A = cross section area of flow (m^2)
R = hydraulic radius (m) [R = A/wetted perimeter (m)]
S = channel slope (m/100 m)

As can be seen in Equation 1, the roughness coefficient is inversely related to flow velocity. Engineered concrete channels may have $n = 0.010$ in order to minimize drag and maximize transport velocity. However, Manning's *n* for vegetated surfaces can be several orders of magnitude higher (e.g. for medium to dense brush in summer, $n = 0.070$-0.160). Hall and Freeman (1994) calculated a maximum of $n \approx 0.50$-0.70 for dense stands (800 stems/m^2) of *Schoenoplectus tabernaemontani* (K.C. Gmel.) Palla (softstem bulrush). Additional research on *Cladium mariscus* (L.) Pohl ssp. *jamaicense* (Crantz) Kükenth. showed a Manning's $n = 0.61$ at a flow velocity of 4.5 cm/s and a flow depth of 0.76 m (Lee and Carter, undated). Schaffranek (2004) also reported decreases in flow velocity in a dense stand of *Eleocharis cellulosa* Torr. (Gulf Coast spikerush). Relative to the data on the response of Indonesian mangrove systems to the 26 December 2004 tsunami, the USFS reports that Manning's *n* for heavy timber stands where the storm surge reaches the branches to range between 0.100-0.170.

Extrapolating the variation in resistance found for wetland vegetation to a hypothetic situation of a storm surge moving across a 1000-m wide x 1-m tall area, an increase in *n* from a value of 0.01 (water moving across concrete) to 0.8 (slightly more rough than for the dense bulrush stand) would theoretically decrease flow velocity by 97.5% thus indicating the importance in vegetation reducing water velocity and storm surge buildup (Figure 12).

Some caution should be exercised, though, to prevent over-applying these results to the potential effects on a hurricane-driven storm surge. The calculations described above were based on the assumption of normal surface water flows across an herbaceous wetland. The extreme observations of Katrina-driven storm surges approach 7 meters, with velocities measured in "the funnel" (see earlier section) approaching 2.5 m/s (Figure 11 above). At those surge heights and velocities, much of the drag or resistance imposed by the vegetation is likely to be overwhelmed by sheer hydraulic force; however, the data do provide for strong evidence that storm surge can be dampened considerably during travel over an intact vegetated wetland. Moreover, the increased density of the wetland vegetation will increase resistance to flow and should further reduce water velocities and storm surges. This is especially true compared to former marsh areas in Louisiana, which now are open water and have vast fetch distances (Richardson 2003, personal observations). These data and analysis support the claim that wetlands would result in a reduction of water velocity and storm surges if enough vegetated wetland area is present in the path of the storm to come in direct contact with storm-driven waves. However, it is quite clear that considerably more research on the effects of marshes and vegetation on reducing storm surges need to be undertaken before definitive relationships can developed between wetlands and water surge reductions. Finally it should be noted that while the storm rolled up vast amounts of marsh soils and vegetation south of New Orleans. It also deposited 4-10 cm (1.5 to 4 inches) of sediments in some marsh areas in just two days (Boesch et al., 2006). Thus, hurricanes are also part of the marsh building processes.

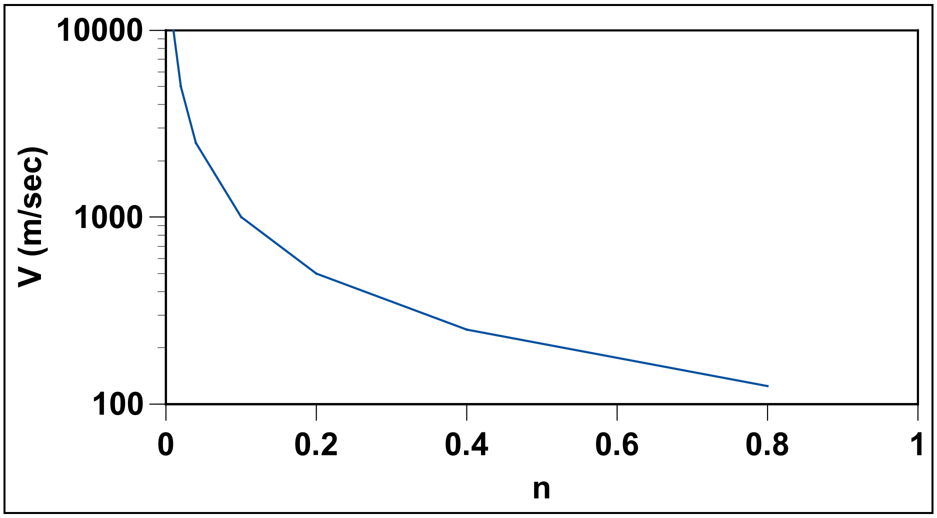


Figure 12: Results of a simple simulation to illustrate the effect of increasing the value of Manning's *n* on flow velocity of surface water (V). The simulation, based on Equation 1 above, assumed a cross sectional area (A) of 1000 m2 (1000-m width x 1-m height), hydraulic radius R = 1 (i.e. wetted bottom surface only), and a slope S = 0.10 (10 cm drop over 100 m, which is likely too large to realistically model wetland elevation change in southern Louisiana).

In comparison to the influence of wetland vegetation on storm surge, there is a very robust body of knowledge regarding the role of barrier island communities in intercepting storm surges and protecting landward wetlands, communities and infrastructure as noted earlier. There is also a strong body of literature on the restoration of barrier islands, with much of the experienced personnel already in Louisiana, due to past efforts to restore island complexes such as the Timbalier Islands and the Isles Dernieres.

The issue of where and how best to target restoration efforts is a contentious matter. In the past, prior to the extensive leveeing of the Mississippi River by the USACE, getting water and sediments out into the floodplain wetlands was a simple matter of creating a crevasse in the natural levee, which would result in a crevasse splay or bay fill. These structures are in essence miniature deltas; individual distributary networks forming as the deposited sediments accumulated in the shallow basins behind the levee. However, as stated earlier the placement of concrete lined levees on the river face of the Mississippi River down through Venice prevents the convenient use of crevasse splays in all but the lower Balize Delta.

In terms of cost, the use of crevasse splays provides a great deal of created wetland habitat for a very small amount of money (Turner and Boyer 1997). As a whole, the Balize Delta is an inefficient location in which to create marsh habitat. This invalidates much of the overt benefit that using this low-tech approach provides in this area. The depth of sedimentary deposits within the Delta, which has prograded to the edge of the continental shelf, is extreme (100 m in places). Because of that, the rate of subsidence in the Balize Delta is among the highest in the Louisiana coastal zone due to the elevated extent of dewatering and degassing occurring in those thick sediments.

The lack of applicability of crevasse splays for rapid land formation in all but the lower reaches of the Balize Delta also raises a significant question that needs to be addressed but that no one wants to answer, or even to admit asking in the first place. The pattern of destruction from Hurricane Katrina in Lower Plaquemines Parish illustrates the vulnerability of the lower Balize Delta as a distinct landform. Additionally, the scientific community has for some time realized that the present management of the Mississippi River is irresponsible in terms of placing river borne sediment where it is most needed, in the coastal plain wetlands. The majority of flow maintained down the Mississippi and the continual leveeing of the river creating a chute for the river's flow to the bottom of the present delta, much of the sediment that we need to get out into the coastal wetlands instead goes down the Mississippi Fan and into the bottom of the Gulf of Mexico.

It is therefore legitimate to ask whether the current maintenance of the river's course through the Balize Delta is the best practice. This is not an easy question to ask, nor is it an easy question to answer. This discussion would necessarily involve the long-term future of a significant portion of Plaquemines Parish, as well as taking into account the surviving infrastructure within the Balize Delta, particularly that of the oil and gas industry. However, with the Federal Government having announced a hold on levee repairs in Lower Plaquemines Parish (see earlier), and with FEMA suggesting fairly restrictive guidelines on rebuilding (FEMA 2006), now is the perfect time to have a responsible debate about the future of the Balize Delta. If undisciplined and significant R&R is allowed to occur, the opportunity for this conversation will be lost and we will be saddled with a continued management scheme that most experts would describe as burdensome and extremely costly. Regardless of the future of the Balize Delta, if the wetlands of the shallow continental-shelf distributary basins are to be restored, the only option for achieving large-scale wetland restoration within the shallow continental shelf region of coastal Louisiana is to use highly engineered river diversions to transport water and sediments into the existing historic distributary basins. Quite simply, the infrastructure development along the Mississippi River levee throughout southeastern Louisiana, from refineries to residential communities, as well as the hardened USACE levee system, precludes the simple movement of river-borne sediments.

Any decision regarding the reduced support for infrastructure building in the lower Mississippi is certainly not without its critics, and the existing large-scale diversions, Caernarvon and Davis Pond only serve to muddy the waters. Caernarvon and Davis Pond are the two showcase large-scale river diversion projects presently in place in southeastern Louisiana. The construction of the Caernarvon and Davis Pond Diversion Projects was predicated on the idea that providing River-borne freshwater and sediments into the Barataria and Breton Sound Estuarine Basins would alleviate marsh dieback caused by saltwater intrusion. Caernarvon was also intended to provide a source of mineral matter to the sediment-starved Breton Sound wetland complex, facilitating marsh accretion and counteracting high rates of subsidence in the area. Caernarvon was constructed between 1988 and 1991, and is now fully operational. Davis Pond, originally authorized by Congress as part of the Flood Control Act of 1965, was constructed between 1997 and 2002 and began a 4-year post-construction intensive monitoring phase in 2002 (LA DNR 2005).

Caernarvon, by most metrics, has been a success. The project has achieved its goal of pushing seaward the target salinity isohalines (LA DNR 2005a), and reestablishing a prevalence of tidal freshwater and oligohaline (intermediate) marsh within the upper Breton Sound basin. This is important, because if we apply the delta cycle model described earlier (Frazier 1967, Penland et. al. 1988) to restoration goals and therefore recognize brackish and saline wetlands as symptoms of a transgressing system, our desire would be to create a sustained prograding distributary basin at strategic points within the coastal zone, characterized by actively accreting freshwater and oligohaline wetlands.

However, Caernarvon is not without it’s problems. Using land-cover data supplied by the last available annual report on the project (LA DNR 2005a), it is significant that the operation of Caernarvon has not resulted an increase in wetland area, and in fact the report indicates that there was actually a net loss of almost 1330 ha (3300 acres) of wetlands between 1988 (pre-construction) and 2000. The report does mention that investigations into the adoption of spring pulsing events are underway as a mechanism to move sediments further downstream, whereas under normal operations they appear to be precipitating just outside of the diversion outfall. This may be a valid solution, but the report also highlights that there are concerns regarding spring pulses among seafood interests within the Breton Sound Basin.

More problematic has been the operation of the Davis Pond Freshwater Diversion, just south of New Orleans. The Davis Pond Freshwater Diversion Project was build at a cost of $119.6 million and over a period of five years. Project specifications call for a sustained flow capacity of 300 $m^3 s^{-1}$ (10,650 cfs), which, by increasing the hydraulic head within the Barataria Basin and therefore pushing back salt water encroaching from the GOM, was modeled to preserve or benefit 324,000 ha of wetlands (USACE, undated). However, Davis Pond was beset by design corrections immediately after the 4-year post-construction phase began in 2002. Specifically, excess water retention occurred in the ponding area (DPAC 2004). These design issues kept operations of the diversion to a minimum through September 2004, the final reporting date for the 2005 Annual Report. In terms of project objectives, all monitoring stations within the Barataria Basin did show lower salinities during the monitored post-construction phase than prior to construction, although it is not known from that report how statistically significant those differences are. From the report, there was high variability in salinity values depending on the time of year, but results were in excess of the targeted ranges established in the May 2001 Operational Plan (LA DNR 2005). Additionally, although Davis Pond should be capable of delivering freshwater flows of 300 m^3s^{-1} (10,650 cfs) to the Barataria Estuary, little delivery of sediment is expected. It is believed that the ponding area that receives the flows from the Mississippi River retains most of the sediments in the diverted flows (LA DNR 2005). The latest Annual Report for Davis Pond suggests that operations might be amended to include pulse events, which could facilitate sediment transfer into the upper reaches of the Barataria Basin, dependent on the results of similar experiments being performed at Caernarvon. The USACE has estimated that re-engineering the structure to serve as a significant sediment diversion would costs approximately $100 million, almost doubling the cost of the project so far (Brown 2006).

Wetlands, FEMA and Rebuilding

The social, economic and ecological complexities of these issues are enormous and almost overwhelming in the context of the political arena of today. However, FEMA has just released it rules for rebuilding New Orleans and surrounding areas (FEMA 2006). While the rules vary from location to location the agency's guidelines state "that inside of levee-protected areas (like Orleans Parish) that new construction and substantially damaged homes and businesses (> 50%) within a FEMA floodplain should be elevated to either the Base Flood Elevation (BFE) shown on the current effective Flood Insurance Rate Map (FIRM) or at least 3 feet above the highest adjacent existing ground elevation at the building site, whichever is higher; and new construction and substantially damaged homes and businesses (> 50%) not located within a FEMA floodplain should be elevated at least 3 feet above the highest adjacent existing ground elevation at the building site". "For areas outside of levee-protected areas like large portions of St. Bernard Parish located to the north and east of MRGO a freeboard (freeboard means a factor of safety in feet above a flood level for purposes of floodplain management) of 1 foot should be applied, that is structures should be elevated at least 1 foot above the current BFE. For outside-levee areas south and west of MRGO FEMA recommends a freeboard of at least 3 feet above current BFE. For other areas south of New Orleans like Plaquemines Parish the elevations have not been fully established.

Full social, economic and ecological assessments of the FEMA guidelines for rebuilding are clearly needed prior to the full implementation of R &R in Louisiana. However, the loss of population and current destruction of over 200,000 homes in New Orleans provides an opportunity to address several alternative solutions to the future flooding in the city. For the first time in over a century there is an opportunity to correct some of the problems related to building on drained lands that have greatly subsided. For example some of those areas that are determined to be the most vulnerable to extreme flooding in the future can be taken out of the intense development scenario and placed back into more sustainable environments that will not be destroyed by future floods. Therefore, while FEMA has established new advisory flood elevations and rules for rebuilding there is also an opportunity to assess which areas in the city meet a social, economic and ecological set of standards that most closely meet long term sustainability. There is no doubt that the establishment of new flood elevations in such a short timeframe was also confounded by economic, social, ecological and engineering complexities of establishing fair and realistic guidelines that meet multiple local, state and federal requirements. Realizing these constraints it is still necessary to determine if it makes social, ecological and economic sense to allow building in the lowest areas of New Orleans realizing that the proposed rules will not fully protect those individuals who rebuilt in former marsh areas that have subsided below 9-10 feet below sea level according to FEMA's "raising rules" as released in April 2006.

Recommendations

Our analysis indicate that restoration efforts within the southeastern Louisiana coastal zone should be focused on a coordinated set of projects within the Lake Borgne, Barataria and eastern Terrebonne Basins. As highlighted earlier, these basins are experiencing the greatest rate of land loss within the coastal zone; they contain or are adjacent to the largest concentration of human infrastructure. On face value, the cost-benefit decision making regarding the MRGO seems apparent and in favor of closure. There is significant political pressure from groups such as the Coalition to Close the Mississippi River Gulf Outlet, however, the detailed socio-economic- ecological debate behind the closure of the MRGO is beyond the scope of this report and should be involve a thorough debate among all relevant stakeholders.

Specific recommendations from our assessment include the following:

- Development of an integrated wetland restoration plan that includes social, economic and ecological components, the basis for modern environmental sustainability planning, is needed.
- Restoration of wetland sites should be prioritized, with a focus on protecting the most important human and economic locations first, i.e. New Orleans and surrounding port facilities, other major population centers and businesses vital to Louisiana.
- Large and small scale demonstration projects utilizing adaptive management as a basis for altering future approaches and designs for wetland restoration should be developed to reduce hurricane and storm damage,
- The LCA studies have provided valuable scientific information focused on approaches for restoration of coastal Louisiana, but future long-term restoration strategies should prioritize projects for the four sub-provinces and efforts must now focus on New Orleans and surrounding areas,
- Specifically, we recommend that the restoration of wetlands in and around New Orleans be given highest priority for the future protection of the city and its levee system. Wetlands in the Lake Borgne area and along MRGO need to restored as well as wetlands along Lake Pontchartrain,

- An assessment of low lying former marsh areas in New Orleans and outlying areas needs to be completed to determine if it is socially, economically and ecologically better to allow these areas to revert to marshes or be restored as marshes or sustainable green spaces and not allow future building in these areas.
- The original forested wetland southeast of New Orleans needs to be reestablished as a protective barrier for storm surges to the city. Additional forest reestablishment should be researched and tested in areas around New Orleans in conjunction with freshwater and sediment diversions.
- A scientific basis for determining the reduction in storm surges and water velocity needs to be researched immediately to aid in the design of future wetland planting densities and conditions.
- The future of the Mississippi River Gulf Outlet (MRGO) needs to be carefully considered in lieu of the fact that it was a key reason that water was funneled into New Orleans proper.
- An outside scientific review board (including social, economic and ecological scientist) should be established to review all proposed restoration projects prior to and during restoration so that adaptive management strategies can be utilized to improve overall project success as well as abandon poor projects.

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Appendix

Figure A1: This map of southeastern Louisiana from 1720 shows Lake Borgne as a more isolated estuarine lake than now, with a significant wetland complex surrounding it. Map courtesy of National Park Service (http://www.cr.nps.gov/nr/twhp/wwwlps/lessons/20vieux/20images/20MAP2Ch.JPG)

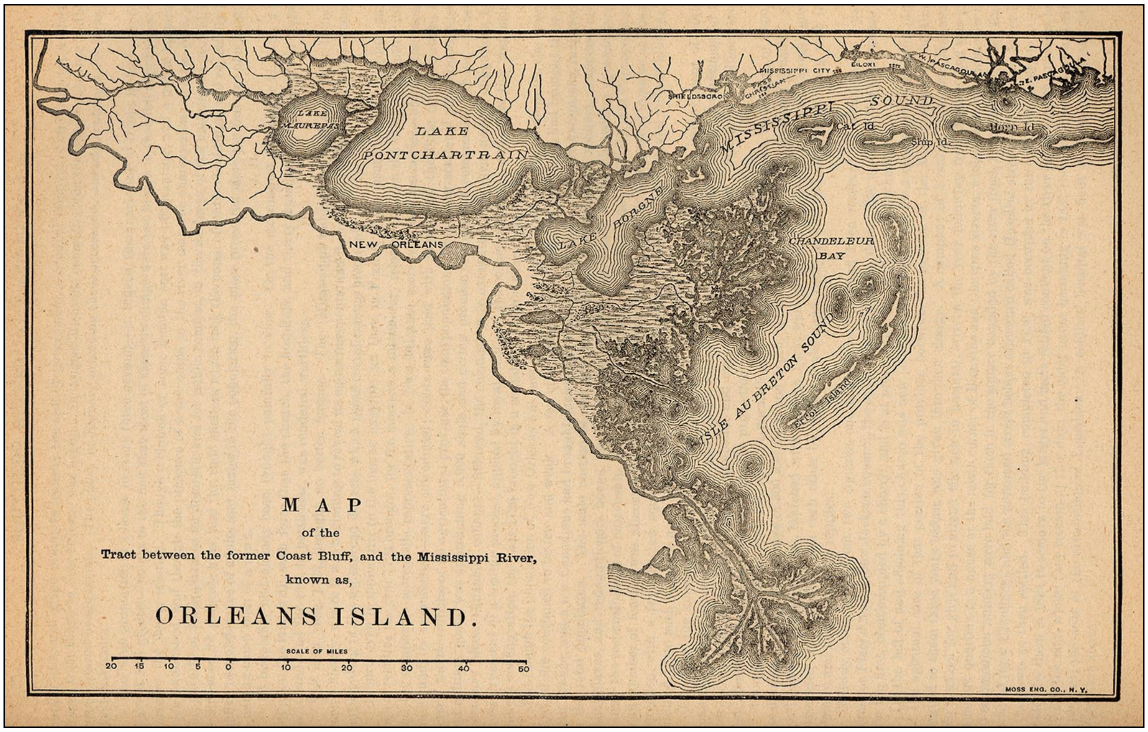

Figure A2: Even if the map in Figure A1 over-represents the extent of the wetlands remaining from the St. Bernard delta lobe, between Lake Borgne and Breton Sound, a comparison with this map of the same region from 1880 suggests than in the intervening 140 years there was significant land loss in those wetlands, exposing Lake Borgne to a greater tidal signal from Mississippi Sound and increasing the fetch between the Chandeleur Islands and the remaining back marshes. Map courtesy of the University of Texas Library (http://www.lib.utexas.edu/maps/historical/orleans_island_1880.jpg).

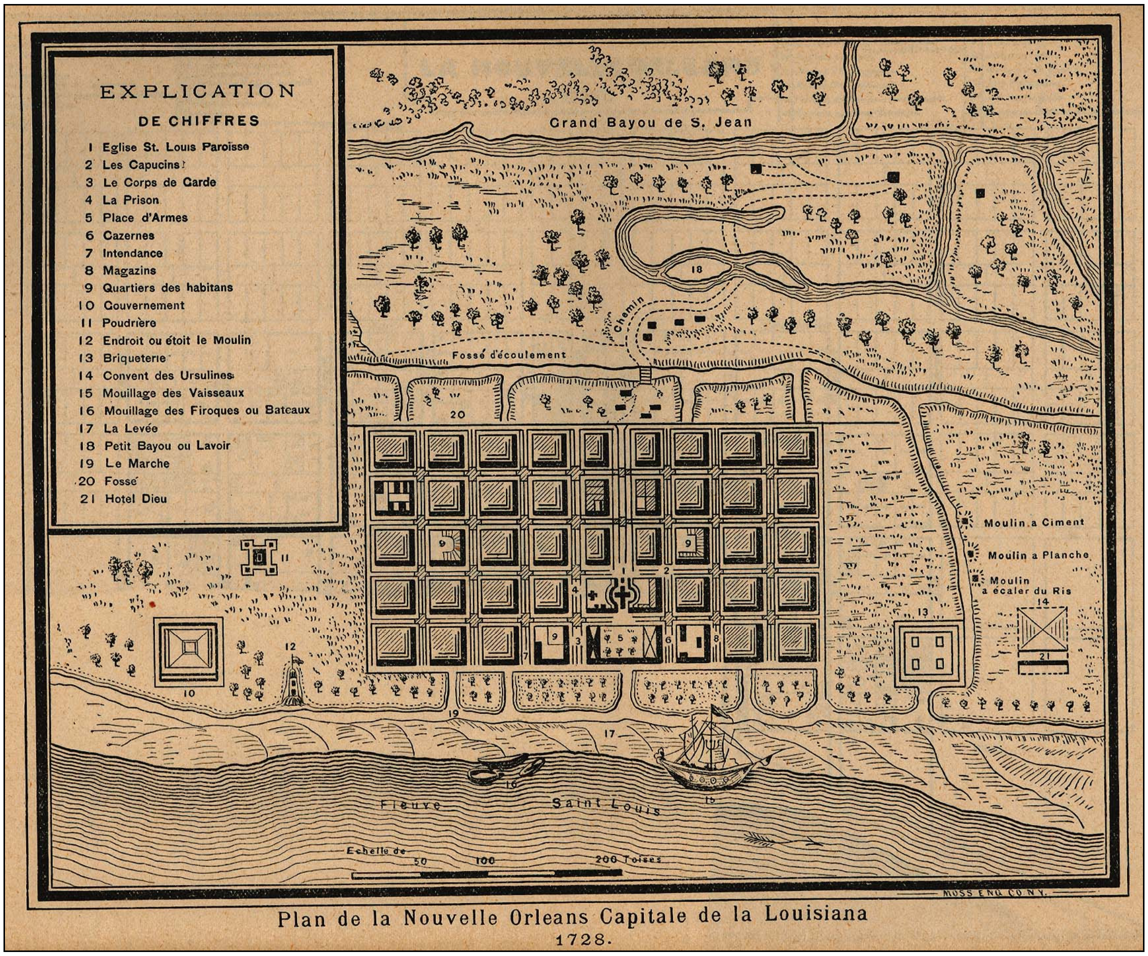

Figure A3: In 1728, New Orleans was only a small settlement on the north levee of the Mississippi River, surrounded by relatively undeveloped wetlands. This settlement corresponds to the modern French Quarter. Map courtesy of the University of Texas Library (http://www.lib.utexas.edu/maps/historical/new_orleans_plan_1728.jpg).

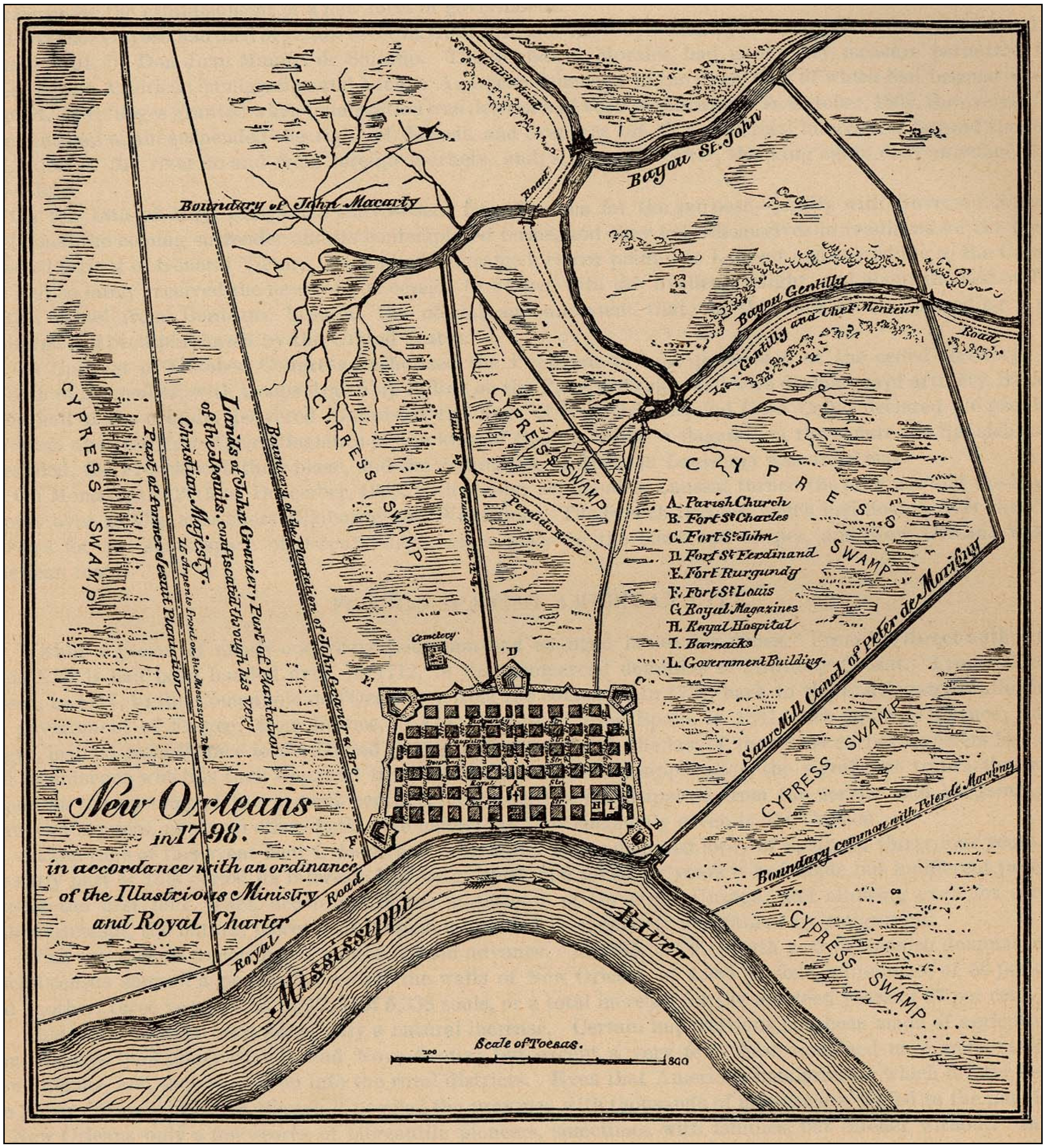

Figure A4: By 1798, New Orleans was in the hands of the Spanish, who would cede Louisiana back to France in 1801. Between 1728 and 1798, New Orleans had also burned, twice. Note the defense works surrounding the settlement, as well as the canals that were dug to drain excess water in the adjacent cypress swamps into the Mississippi River and the neighboring bayous (Gentilly and St. John). Note also the clarification on this map of the Gentilly Ridge: this ridge was one of the few areas of high ground in central New Orleans following the breaching of the floodwalls by Hurricane Katrina. Map courtesy of the University of Texas Library (http://www.lib.utexas.edu/maps/historical/new_orleans_1798.jpg).

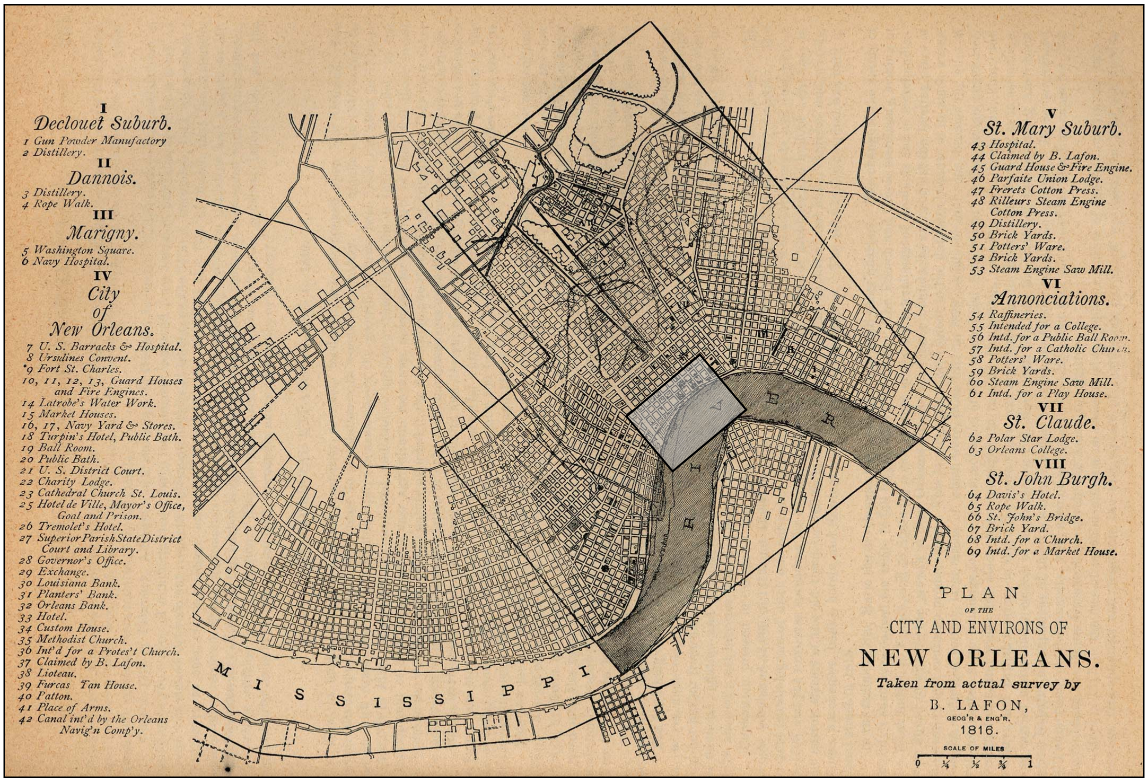

Figure A5: Growth of New Orleans was rapid between 1798 (Figure A2) and 1816, shown here, after Louisiana was sold by Napoleon to the nascent United States. Development had spread upstream along the natural levee ridge as well as into the interior following the digging of canals to drain the swamps. The grey box illustrates the French Quarter, the original French settlement shown in Figure A1, the modern French Quarter. Notice also the lack of development in the modern Mid-City/Broadmoor area, a low elevation swamp where significant post-Katrina flooding occurred.. Map courtesy of the University of Texas Library (http://www.lib.utexas.edu/maps/historical/new_orleans_1816.jpg

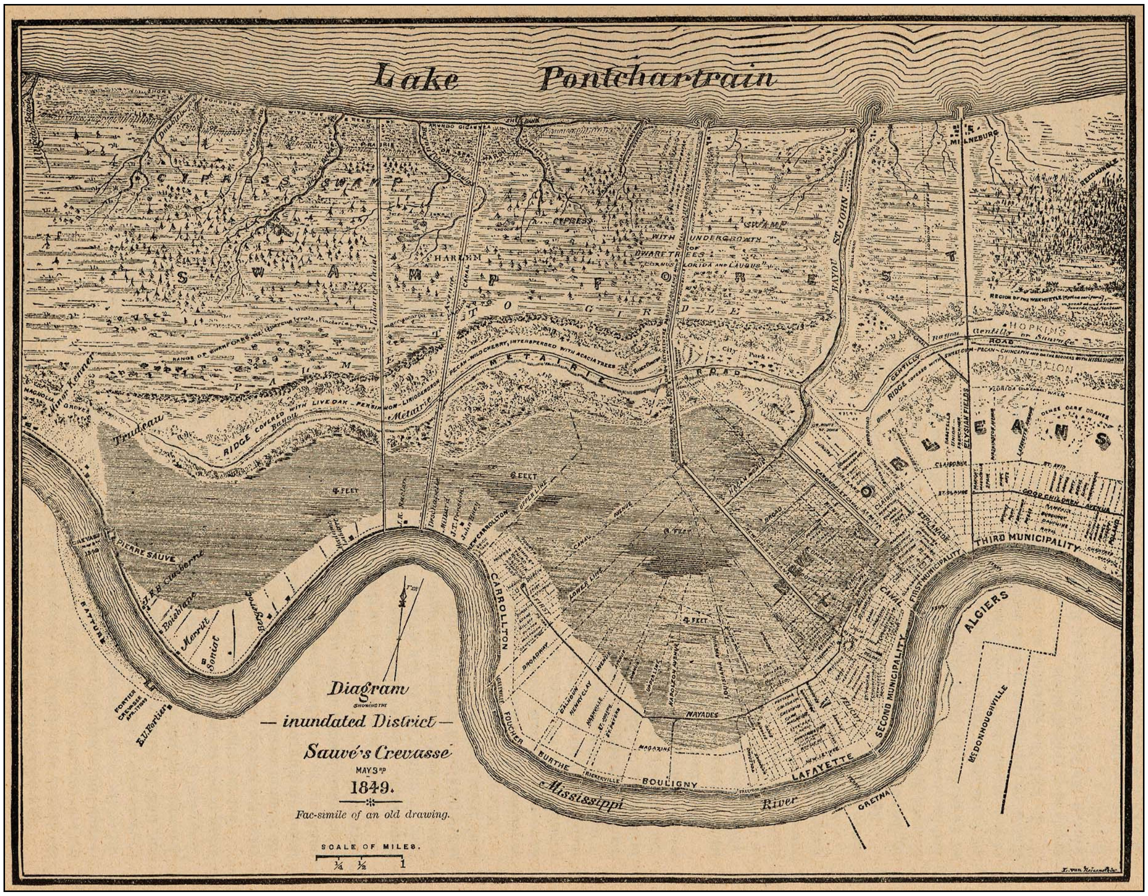

Figure A6: By 1849, although growth in New Orleans was substantial, there were still significant areas within the modern city along the shore of Lake Pontchartrain that were not yet developed due to drainage and flooding problems, even with the prominent digging of canals. This map is significant for the present discussion of Hurricane Katrina response because the grey area on this map shows the territory inundated when the Mississippi River levee failed in present-day Jefferson Parish at the Sauvé Plantation (www.wikipedia.org, article of Abdiel Crossman). Compare the flooding extent on this map to the elevation map for present-day New Orleans in Figure x. Map courtesy of the University of Texas Library (http://www.lib.utexas.edu/maps/historical/new_orleans_1849.jpg).

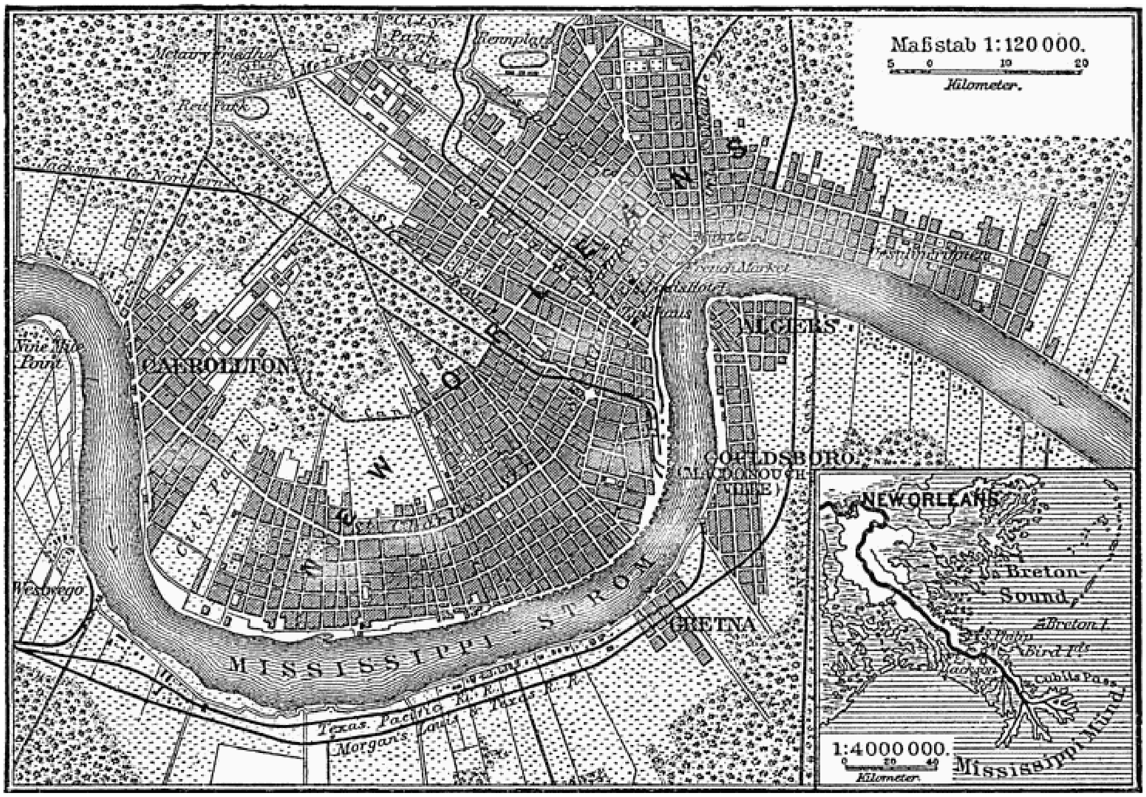

Figure A7: In 1888, development around the Mid-City/Broadmoor area was still noticeably absent. Although streets and canals traversed the area, there was little in the way of structure development. Map courtesy of Wikipedia (http://upload.wikimedia.org/wikipedia/en/f/f7/Karte_New_Orleans_MKL1888.png).

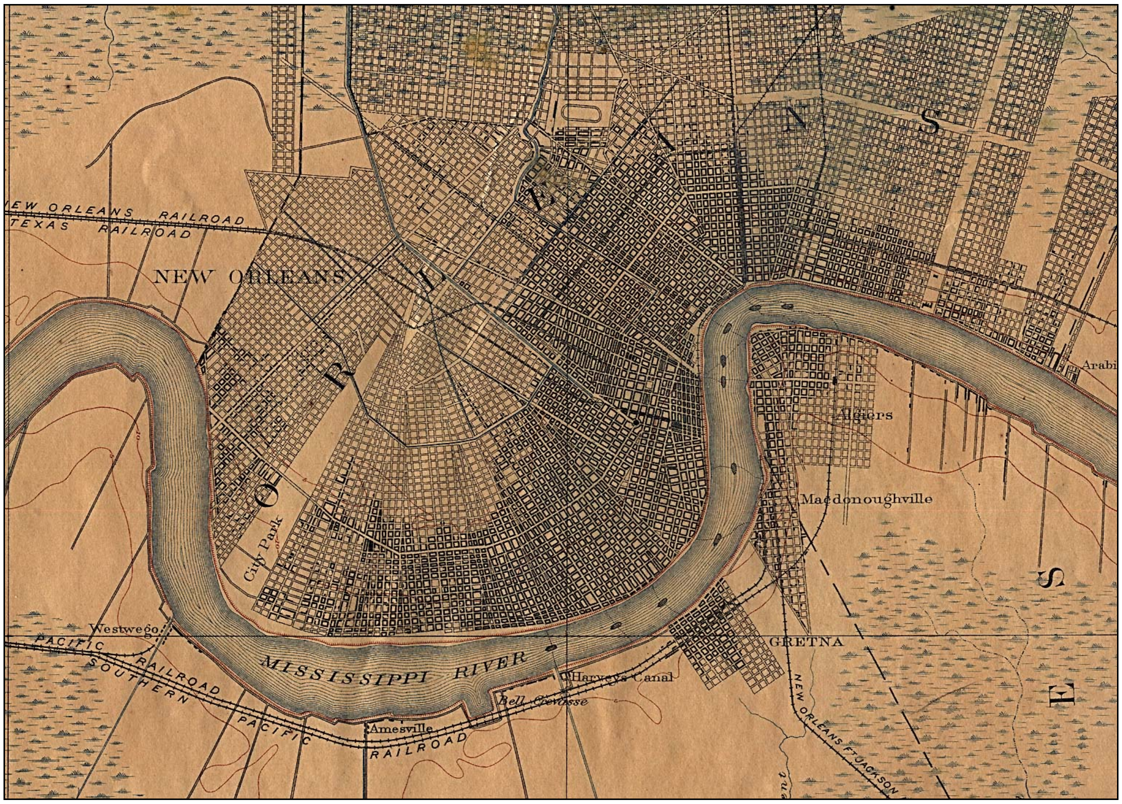

Figure A8: By 1891, just two years after Figure A4 was produced, the city drained and developed the Mid-City/Broadmoor area and continued expansion north towards Lake Pontchartrain. Note the neighborhoods to the north of the city are indicated as wetland, yet have still been developed. Map courtesy of the University of Texas Library (http://www.lib.utexas.edu/maps/historical/new_orleans_1891.jpg).

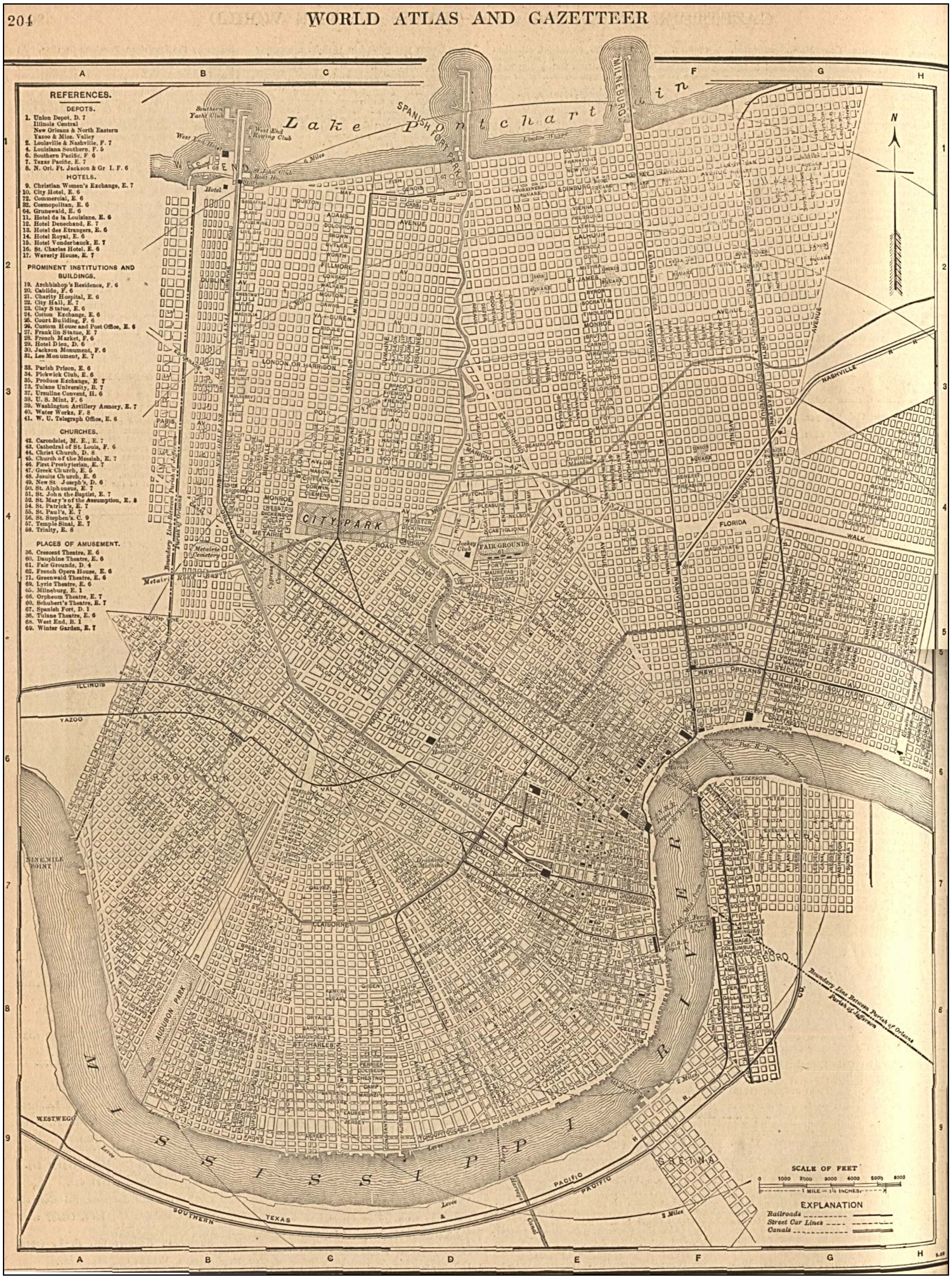

Figure A9: By 1908, the remaining back swamp areas between the Mississippi River and the Lake Pontchartrain shoreline had been drained and developed. Map from McNabb and Madére (2003).

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