



Geology and Hurricane- Protection Strategies in the Greater New Orleans Area

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Front cover: Canal Street, New Orleans, Louisiana, September 2005 by Rocky Beach.

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by:

Richard P. McCulloh, Paul V. Heinrich, and Bill Good

Baton Rouge

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Saffir-Simpson Hurricane Scale

Category	Winds (mph)	Winds (knots)	Winds (kn/h)	Pressure (millibars)	Storm surge (ft)
1	74-95	64-82	119-153	>980	4-5
2	96-110	83-95	154-177	965-979	6-8
3	111-130	96-113	178-209	945-964	9-12
4	131-155	114-135	210-249	920-944	13-18
5	>155	>135	>249	919	>18

Notes: from <http://www.nhc.noaa.gov/aboutsshs.shtml>. Millibars are a very small pressure unit; they are used to indicate atmospheric pressure. Normal atmospheric pressure at sea level is considered to be 1,013 millibars (which equals 14.7 pounds per square inch or 29.92 inches of mercury), so all categories of hurricane involve lower-than-average air pressures.

Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (statute) (mi)
kilometer per hour (km/h)	0.5400	mile (nautical) per hour (knot)
kilometer per hour (km/h)	0.6214	mile (statute) per hour (mph)
square kilometer (km ²)	0.3861	square mile (mi ²)
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (statute) (mi)	1.609	kilometer (km)
mile (statute) per hour (mph)	1.609	kilometer per hour (km/h)
mile (statute) per hour (mph)	0.869	mile (nautical) per hour (knot)
mile (nautical) per hour (knot)	1.15	mile (statute) per hour (mph)
mile (nautical) per hour (knot)	1.852	kilometer per hour (km/h)
square mile (mi ²)	2.590	square kilometer (km ²)

Geologic Setting and Settlement History—Major Influences on Hurricane-Damage Risk to Coastal-Plain Communities

New Orleans was founded on geologically young river deposits near the terminus of the North American continent's largest delta. This area is geologically active: deltas move over time, and much of the landscape is underlain by soils and sediment that are relatively unconsolidated, anaerobic, and organic. In addition, the Greater New Orleans area, like the rest of the Gulf Coast, historically has been susceptible to severe damage from hurricanes.

Levees completely surround the Greater New Orleans area. Those on the north side protect the area from storm-induced flooding by Lake Pontchartrain, and those on the south side, along the sinuous bank of the Mississippi River, prevent a repeat of the disastrous 1927 flood. This ring of levees, coupled with massive flood-control pumps, allowed vast former marshlands and swamplands to be drained to a level conducive to urban development, as has been done in other communities across America to provide more habitable land. The drainage projects caused a considerable lowering of the water table. In the process, the anaerobic, highly organic soils dried out, the organic material was oxidized, and the soils compacted in many areas by dramatic amounts. The net result was a growing urban population situated within a large bowl whose bottom is lower than the mean level of the Mississippi River and Lake Pontchartrain. Although perhaps unforeseeable at the outset, this flood-control levee and pump system resulted in a chain of events that contributed to the disastrous flooding that accompanied Hurricanes Katrina and Rita in 2005. Simply put, when the levees fail in any way, the surrounding water quickly pours into the bowl.

The river side of this ring levee system is one piece of the overall "Jadwin Plan," whereby the U.S. Army Corps of Engineers integrated the management of flood control and navigation on the Mississippi River after the 1927 flood. Among the unintended consequences of this plan is the well-documented loss of vast areas of deltaic wetlands along the Louisiana coast. The

loss of these wetlands has effectively reduced the distance between the Gulf of Mexico and New Orleans and thus exacerbates the consequences of hurricane storm surges (see the hurricane-history section "A Blast From the Past" for a summary of major U.S. hurricane landfalls from 1899 through 2005).

There will be those who propose that the levees be made bigger and higher so that a catastrophe such as Katrina caused can never happen again. Obviously, an engineering strategy using levees and pumps provides protection up to some threshold. But after this threshold is surpassed, an even greater catastrophe may befall New Orleans unless the engineering strategy is combined with a greatly improved evacuation strategy (see, for example, the extraordinarily comprehensive and prophetic series of articles by J. McQuaid and M. Schleifstein published by *The Times-Picayune* of New Orleans in 2002, partially showcased on the inside back cover of this publication). Given the geologic processes, especially subsidence, that will continue into the foreseeable future to lower the area and its effective levee height, a strategy comprising better evacuation infrastructure and procedures is an essential accompaniment to a strategy involving an improved levee and pump system.

Since the 1700s, changes associated with increasing settlement of south Louisiana have led to interference with the natural processes that previously had built and maintained the coastal plain. Present-day activities in the area depend on artificial leveeing of the Mississippi River to prevent flooding and to allow navigation, but at the same time, also depend on large areas of wetlands to serve as a nursery for coastal fisheries and to buffer the area against the effects of severe storms. However, the catch is that the continuing existence of the wetlands depends on periodic flooding by the river. If the sediment-depositing, delta-building Mississippi floods cannot occur, the wetland areas will not be replenished to compensate ongoing subsidence, and eventually will become submerged beneath the waters of the gulf. Engineering

Both metric and English units are used for measurements of length, but the order of their listing depends on the circumstances of the measurement. We normally present a measurement in metric units followed by the English-unit equivalent, because all of science formally uses the metric system for its measurements. In instances where the source measurements were in English units, however, we present the measurement in English units followed by the metric-unit equivalent. Geologists in the United States primarily encounter two kinds of measurements that were made in the English system: (1) elevation values on most U.S. Geological Survey 7.5-minute topographic quadrangle maps, which give elevations in feet, and (2) measurements derived from operations in which the English system is firmly established, especially the drilling and logging of wells by the petroleum industry. A conversion table for the units used in this publication is presented on page 6.

projects to restrict water influx into, and drain water from, the wetlands as well as urban development activities in and near them collectively accelerate subsidence that heightens the risk of storm damage and fatalities in coastal communities. The stepped-up rates of subsidence also have severe impacts on the region's natural ecosystems. These impacts threaten to take a huge economic toll—for example, the loss of vast areas of healthy coastal marsh ultimately could result in dramatically reduced revenue from commercial fisheries.

A recent white paper drafted by a group of scientists and engineers in response to the effects of Hurricanes Katrina and Rita in 2005 (Working Group for Post-Hurricane Planning for the Louisiana Coast, 2006) examines the entire complex of issues facing this region. These scientists and engineers conclude that during the rest of the twenty-first century, hurricane vulnerability in New Orleans and other communities in coastal south Louisiana can only be decreased by a combination of engineering measures and sustainable management of the natural landscape on which the communities lie—that sustainability entails not only storm-damage reduction, but also maintenance and preservation of the natural landscape for its renewable resources and “ecosystem services.” The authors of the white paper call for a new framework integrating the previously disparate infrastructure and policymaking sectors that often have pursued single-purpose objectives with sometimes contradictory results. The new framework would have the task of achieving multiple, coordinated objectives. The paper's authors also argue for explicit recognition of the coastal plain's inherently dynamic aspect instead of viewing its existence as basically static. In order to fulfill their vision, the proposed framework would incorporate a program of coordinated, science-based planning, administration and regulation, and investment.

The Geological Society of America and the Pontchartrain Institute of Environmental Studies at the University of New Orleans have also produced a white paper (Kulp and others, 2006) on the lessons to be learned from hurricanes Katrina and Rita and the options for mitigating damage from future hurricanes. More a brief, conceptual synopsis and statement than a detailed exposition, the paper out-

lines the natural geologic processes of the Louisiana coastal plain and the historical modification of their effects by structural measures originally designed to facilitate surface drainage, permit navigation, and prevent floods. Further, this paper presents options for mitigation of storm damage and other hazards related to issues of subsidence and coastal land loss and focuses on the value of input from the geological sciences to these hazard-mitigation efforts.

In another recent publication, T. Waltham (2005) has comprehensively surveyed aspects of the geologic setting of New Orleans in the historical context of its settlement and has reviewed their consequences for hurricane-damage risk, as exemplified by Hurricane Katrina's effects on the city's structures and neighborhoods. Waltham expressed confidence that this city, with its rich culture, history, and sense of place, undoubtedly will be rebuilt, but he concluded that the city almost as certainly will be considerably reconfigured. His discussion of the issues facing New Orleans conveys the impression that, according to any of the long-term scenarios under contemplation, reestablishment of the city with improved hurricane-protection measures will demand many difficult choices, a staggering dollar cost, and decades to reach completion, during which time the city likely will be struck again by one or more major hurricanes.

Background for This Public Information Document

This public information document focuses on the geological foundation that has led to different types of subsidence effects in the New Orleans area. These include effects that are thoroughly natural, some that are accelerated by activities that have become commonplace in inhabited areas of coastal south Louisiana, and some that are entirely human induced. We also reflect on the consequences of subsidence for continued habitation of south Louisiana, particularly the related increased vulnerability to storm damage. A hurricane-history section details Louisiana's and the wider Gulf Coast's experiences with hurricanes since the 1700s.

Geologic Context of Subsidence Affecting the New Orleans Area

Subsidence in the area encompassing New Orleans takes place on at least three scales (Figures 1, 2). Subsidence at all scales would be exacerbated by any future sea-level rise.

Regional Scale. Two large-scale processes generate subsidence across southern Louisiana: (1) Subsidence of the entire southern Louisiana landscape is taking place south of a hinge zone (shown in Figure 1) created in the recent geologic past when deposition of enormous volumes of deltaic and coastal sediments depressed the crust

underlying the coastal plain. The sediment accumulated to greatest thicknesses south of the hinge zone, whereas north of it, the sedimentary layers of the same age as the deltaic sequences are thinner and the older layers have been tilted upward. In prehistoric time, as deposition progressed and led to the normal development of the delta, the coastline advanced, the Gulf of Mexico retreated, and the increasing accumulation of sediment moved the hinge zone of the associated downward flexure of the crust southward in a broad wave. Today, the same processes continue to operate. Although the hinge zone represents the leading edge of this wave, and subsiding

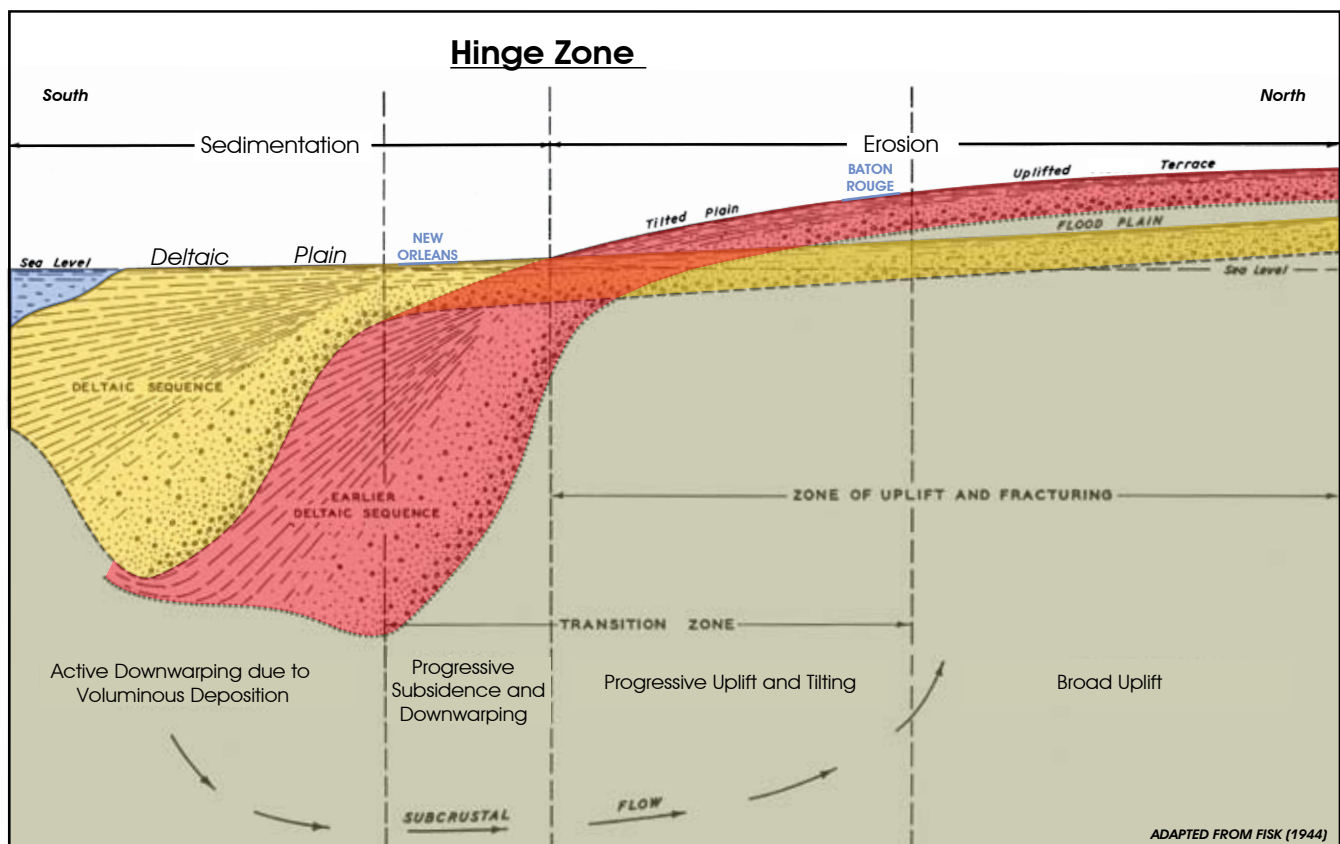


Figure 1. Schematic cross section depicting regional-scale subsidence and uplift near the Mississippi River Delta (adapted from Fisk, 1944). The diagram represents a single line of section oriented from the Gulf of Mexico on the left to upstream along the Mississippi River on the right. This coastal-plain region is characterized by complexly interrelated depositional and structural processes that under natural conditions lead to the southward growth of the coastline via deltaic deposition through time. These processes operate at a variety of scales. The largest effect portrayed is the creation of a hinge zone that, over the time frame of several thousand years, gradually migrates toward the Gulf of Mexico because of the voluminous deposition of the deltaic sequences. The diagram is simplified to show only two deltaic sequences of sediment; these deposits resulted from two episodes of deltaic sedimentation (that is, sedimentation accompanying the formation of two delta lobes). The earlier episode deposited the deltaic sequence shown in red, and the more recent episode deposited the deltaic sequence shown in yellow. A single “depocenter” could contain multiple delta lobes, and the coastal zone as a whole encompasses multiple depocenters of different ages. Both depocenters and delta lobes vary in position laterally as well as from north to south. South of the hinge zone in the cross section, the younger sequence is pressing down the older sequence, and their combined weight causes them to subside and makes the subcrustal material flow northward and upward, which raises the land on the north side of the hinge zone. North of the hinge zone, the Mississippi River has eroded down through the uplifted, older (red) deltaic sequence and is now depositing sediment into the younger (yellow) deltaic sequence.

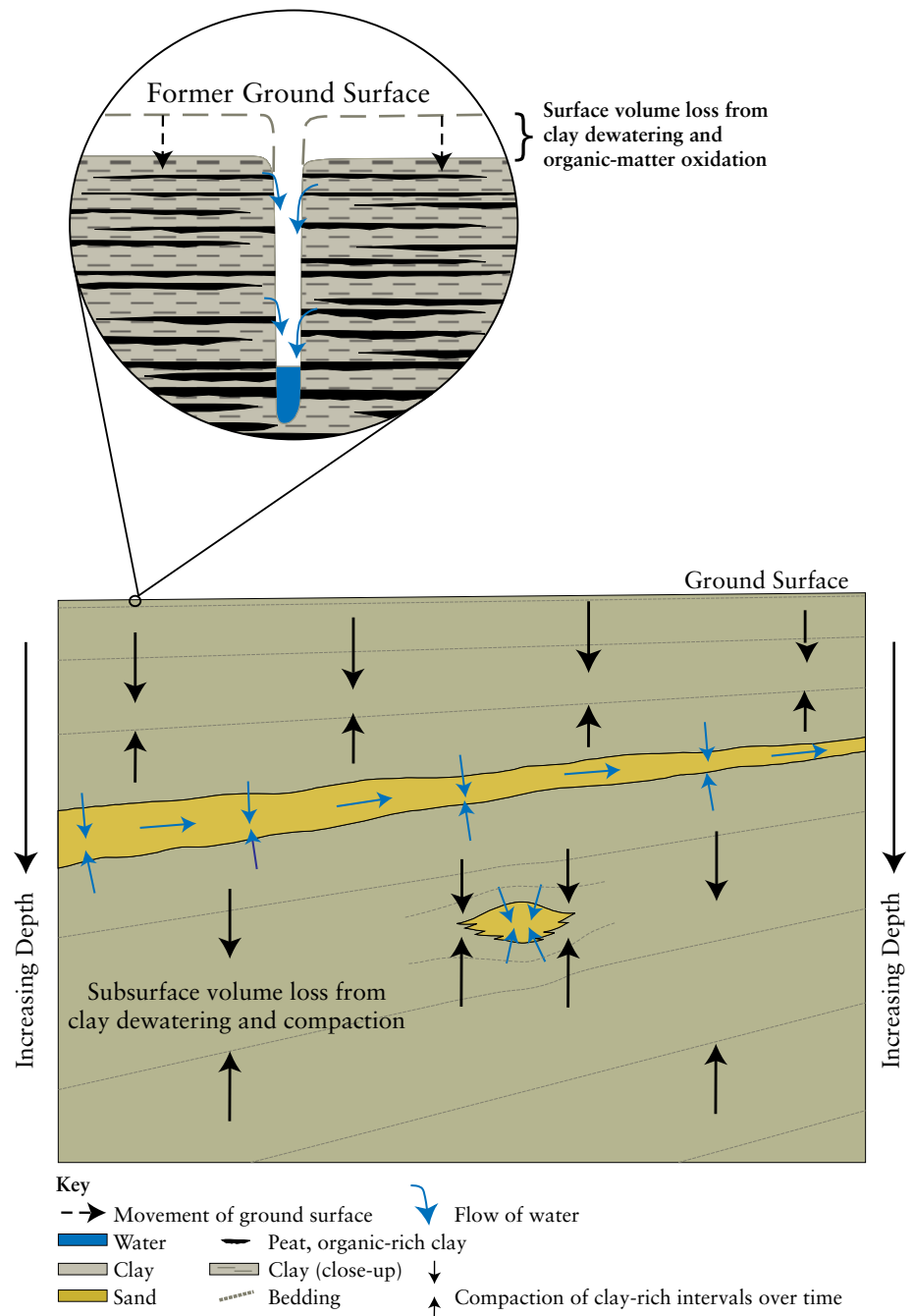


Figure 2. Schematic cross-sectional diagrams depicting subsidence at subregional and surficial scales in the New Orleans area. As shown in the cross section at the bottom, thick clay-rich layers in the subsurface compact more than sand layers and discrete sand bodies; the clay-rich layers expel water into the more permeable sands over time and further compact by concurrent mechanical rearrangement of the clay particles. In the New Orleans area, the resulting subsidence from this natural process has been accelerated by groundwater pumping that removes water from the sands, which are replenished with water expelled from the clay-rich layers. At and near the surface (shown magnified in the inset diagram), human-induced alterations of the land greatly accelerate drainage of the upper part of the soil column. When the soil is drained, it and its contained organic matter (peat and organic-rich clay, depicted as black lenses in the inset diagram) lose a substantial percentage of their original volume and are exposed to atmospheric oxygen. This process may result in a dramatic volume reduction of the organic matter in a short time, which at the surface appears as sinking of the ground. (In the main cross section, black arrows represent a decrease in the thickness of the sedimentary section over time, preferentially in the clay-rich layers. In the inset diagram, blue arrows represent the seepage and flow of water into a manmade excavation—in this case, a drainage canal—and black, dashed arrows represent the downward movement of the ground surface over time from volume loss caused by drainage and oxidation of organic-rich wetland soils.)

areas immediately in front of it ultimately will become uplifted, much of the coastal Louisiana landscape is on the subsiding side of the hinge zone. (2) Movement along faults can also lead to subsidence. In a recent paper, Dokka (2006) inferred from geodetic measurements that regional subsidence affecting the New Orleans area reflected movement of the downthrown block south of a particular subsurface fault zone that underlies the city. Dokka interpreted that this movement probably is driven by the same depositional loading of the crust that generates downwarping along the hinge zone. By both these regional-scale mechanisms, New Orleans will continue to subside for the indefinite future.

Subregional Scale. Dewatering and compaction of thick layers of fine-grained, clay-rich sediment in the subsurface result in subsidence effects at the surface. Water trapped in this fine-grained sediment is expelled as the clay particles become more tightly arranged. Because sand particles do not trap as much water as clay particles, the clay layers compact more than sediments composed of sand (Figure 2). In the New Orleans area, this type of subregional-scale, differential subsidence has been accelerated by pumping groundwater from subsurface, water-bearing sands termed *aquifers* (Kazmann and Heath, 1968). Elsewhere in the south Louisiana coastal plain, subregional-scale subsidence may have been accelerated by hydrocarbon withdrawal from subsurface sand-rich sediment (Morton and others, 2002).

Surficial Scale. Subsidence effects at the surface scale can be likened to shrinkage of the outer “skin” of the ground surface (Figure 2, inset). Surficial subsidence is a direct consequence of certain engineering measures, such as the cutting of canals to drain the wetland-dominated landscape. Most such alterations have the effect of simultaneously draining water from the ground (lowering the water table) and exposing the soil to atmospheric oxygen at progressively greater depths below the surface. These changes to the natural landscape can result in a substantial and comparatively rapid volume reduction in the upper part of the soil column in places. The resulting surficial-scale subsidence is due to dewatering and consolidation of clay layers and, more particularly, to dewatering, compaction, and oxidation of the abundant

organic matter in wetland soils (Saucier and Snowden, 1995; Kolb and Saucier, 1982; Snowden and others, 1980; Region VI Interagency Hazard Mitigation Team, 1991). Figure 3 shows typical examples of such surficial effects on some homes in the New Orleans area.

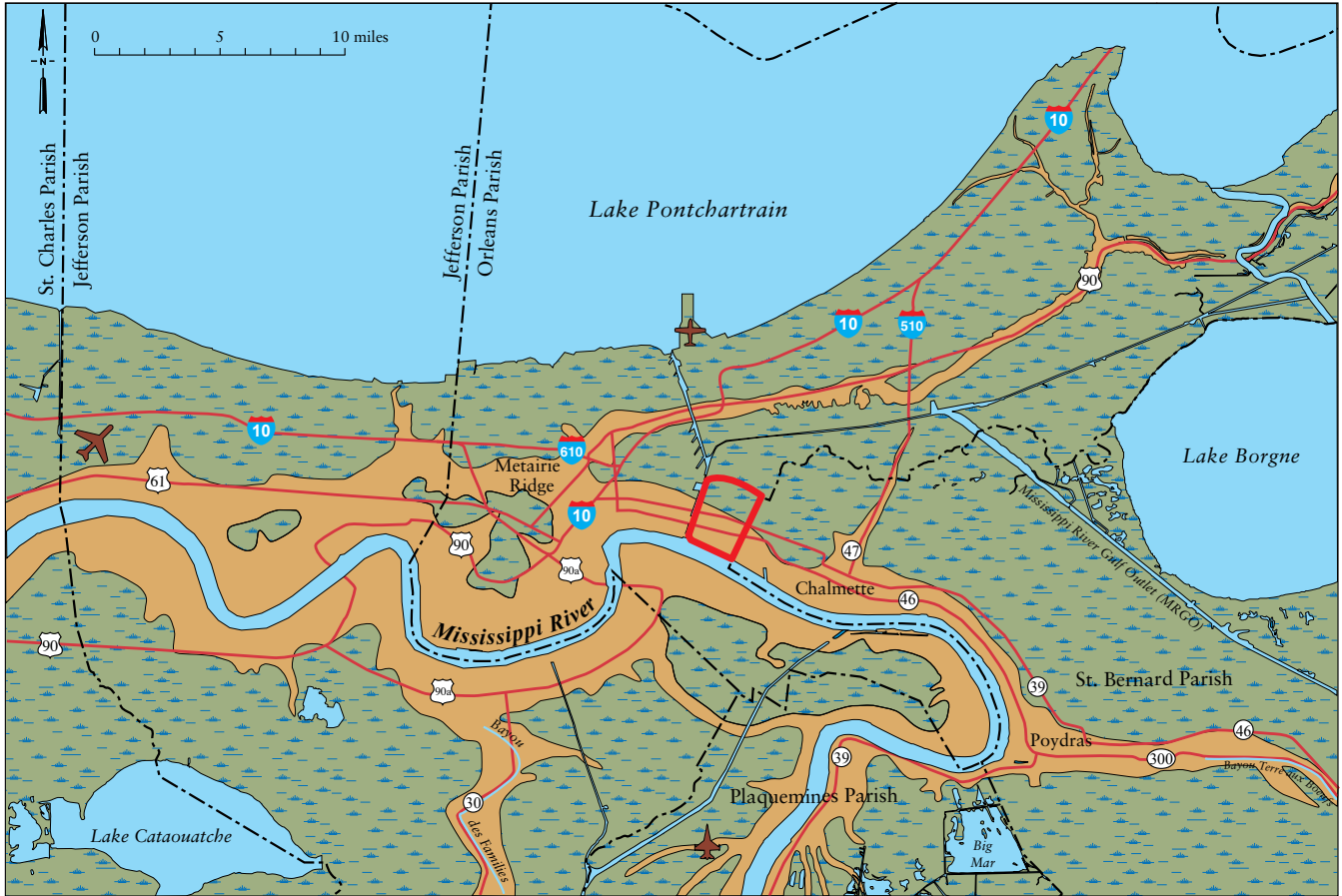
The subsidence processes at the regional, subregional, and surficial scales are additive in their effect of lowering the elevation of the Greater New Orleans area (see Figure 7 of Waltham, 2005, for a graphical representation). Since the onset of European settlement, leveeing of the river—which is now completely contained in levees—has served the dual purpose of flood control and maintenance of the river as a navigable waterway. However, maintenance of the land’s elevation by new overlays of sediment that would have been deposited via periodic flooding has also been prevented by leveeing. The coastal wetlands are starved of freshwater and sediment influxes, and salt-intolerant vegetation on the remaining wetlands is progressively killed by saltwater encroachment into the sinking landscape. Without the binding effect of the vegetation’s roots, the marsh soil is subject to increased erosion by waves, further lowering areas that were wetlands in the recent historic past. Therefore, land subsidence and coastal erosion are unavoidable longer-term side effects or “hidden” costs of the policy choice to confine the river’s flow.

Geologic Foundation of the New Orleans Landscape

Jefferson, Orleans, St. Bernard, and Plaquemines parishes all lie within the *delta plain* of the Mississippi River (Figure 4). One of the major characteristics of river deltas is their network of *distributaries*. These are streams that fork from the main river channel and distribute the water through a larger and larger area of the delta plain as the river approaches its mouth. Branching off from the modern and abandoned channels of the Mississippi are numerous distributaries, for example, Bayou La Loutre–Bayou Terre aux Boeuf. During a flood, the active deltaic distributaries carry sediment-bearing floodwaters away from the river and out onto the surrounding delta plain (Figure 4). Thus the distributaries, when unencumbered by artificial levees, play a significant role in maintaining the wetlands. These channels



Figure 3. New Orleans area homes showing surficial subsidence effects ultimately resulting from the fact that the homes were built in an area of wetland soils. Alterations of the ground and its surface drainage have led to dewatering of clay and peat layers and oxidation of organic matter in the soil, the volume of which has shrunk dramatically over a period of just a few decades. The homes are on slabs atop pilings; the homes therefore do not sink as much as the surrounding ground. (Photo credits: A, J. O. Snowden, Southeast Missouri State University; B–D, Don Davis, Louisiana Oil Spill Coordinator’s Office.)



- Key**
- Natural levees
 - Interdistributary basin
 - Lower Ninth Ward
 - New Orleans Lakefront Airport
 - Belle Chase Naval Air Station
 - Louis Armstrong New Orleans International Airport

Figure 4. Geologic map of New Orleans. Mapped by using soil surveys, 1:24,000-scale topographic maps, and Light Detection And Ranging (LIDAR) digital elevation models (DEMs). (Interpretation by P. V. Heinrich, adapted from Heinrich and others, 2004.)

radiate outward, in a fan-like network, from the main channel of the Mississippi River (Frazier and Osanik, 1969; Kolb and Saucier, 1982; Kolb and Van Lopik, 1958; Snowden and others, 1980).

The natural and man-made topographic relief of the Mississippi delta plain exhibits significant variations (Figure 5), although they are quite small relative to other parts of Louisiana. Detailed elevation maps of this area are reproduced in Figures 6 and 7, and the association of elevation values to particular depositional environments and landforms is summarized in Table 1.

The delta plain, which contains the New Orleans metropolitan area and Plaquemines Parish, consists of low-lying, mainly flat land visually dominated by two contrasting landscapes. The prominent sinuous, narrow ridges are *natural levees* created by the river as it flowed in its present as well as earlier channels. These ridges bound broad expanses of marshes and swamps situated in low-lying areas termed *interdistributary basins*.

The sediments in the subsurface below the Greater New Orleans area are not uniform, and their variations, if they are sufficiently shallow, also may affect the stability of levees and other engineered structures. The largest subsurface feature that affects the stability of engineered structures is a buried *barrier island chain*. It consists of a

ridge of sand and silty sand that lies buried beneath deltaic sediments along the southeast shoreline of Lake Pontchartrain and parts of East New Orleans.

Natural Levees

The most prominent landforms of the New Orleans area and the rest of southern Louisiana are the natural levees. They are the ridges flanking both sides of the channels of the Mississippi River, the trunk channels of abandoned delta lobes, and the distributaries that branch off of them. Natural levees are highest adjacent to the banks of their associated channel and slope downward away from it to eventually merge with the surrounding wetlands. Because of their elevation, the natural levees are the site of nearly all of the major inhabited and cultivated areas within the Mississippi River Delta. The lack of space on the narrow natural levees, however, has prompted the draining of adjacent marshes and swamps and the expansion of urban development into the former wetlands (Kolb and Saucier, 1982; Saucier, 1994; Snowden and others, 1980).

Within the New Orleans region, the most prominent landform is Metairie Ridge. It extends eastward from the junction of Little Farms Avenue and 3rd Street in Kenner through Jefferson and Orleans parishes and northeastward along parts of

Table 1. Elevations and Land Types in the New Orleans Area

Highest elevations (above sea level)	Lowest elevations (below sea level)
<p>Orleans and northern Jefferson Parishes</p> <p>+12 ft (+3.7 m): Natural levees bordering banks of Mississippi River</p> <p>+40 to +50 ft (+12 to +15m): Artificial mounds in the southwest corner of Avondale</p>	<p>0 to -5 ft (0 to -1.5 m): Swampland and marshland that have been leveed and drained for urban development, including large parts of Kenner, Metairie, Lakeview, East New Orleans, and southern parts of the West Bank</p> <p>-5 to -10 ft (-1.5 to -3 m): Some parts of Lakeview and East New Orleans</p>
<p>St. Bernard Parish</p> <p>+12 ft (+3.7 m): Natural levees of the Mississippi River</p> <p>+35 ft (+11 m): Artificial pile near Arabi, in northern St. Bernard Parish</p>	<p>-6 ft (-1.8 m): Marshland and swampland that have been drained and protected by levees</p>
<p>Plaquemines Parish</p> <p>+5 ft (+1.5 m): Short, discontinuous segments of Mississippi's natural levees between its northern border and Nairn</p>	<p>-5 to -10 ft (-1.5 to -3m): Marshland and swampland that have been drained and protected by levees</p>

Notes: The natural levees of the Mississippi River are the highest natural features in the area. The lowest natural elevations in the area are in the interdistributary basins between the natural levees.

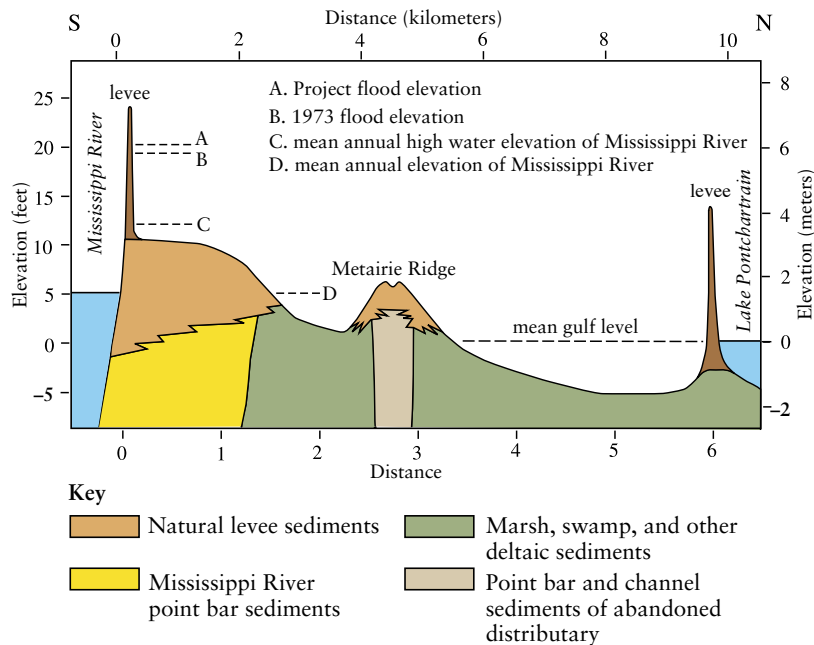


Figure 5. South to north cross section across New Orleans, Louisiana, showing topography, relief, and types of underlying deltaic sediments (redrawn and adapted from Saucier and Snowden, 1995, their Figure 6).

Chef Menteur Highway (U.S. Highway 90). As seen in Figure 4, Metairie Ridge is an ancient natural levee that forms a distinct ridge of land lying more than 5 ft (1.5 m) above sea level and surrounded by below-sea-level interdistributary basins (Kolb and Saucier, 1982; Kolb and Van Lopik, 1958; Snowden and others, 1980).

A prominent distributary is Bayou des Familles, which extends southward from the Mississippi River through the West Bank of Jefferson Parish. The natural levees flanking Bayou des Familles at its northern end are a little more than 5 to 6 ft (1.5 to 1.8 m) above sea level and decrease in elevation southward away from the Mississippi River (Figure 4).

In St. Bernard Parish, Poydras and Chalmette (Figure 7) occupy “high” ground at the junction of the modern Mississippi River with the natural levees along ancient, now-abandoned deltaic distributaries as well as a former Mississippi River channel. At Poydras, the Mississippi River intersects that former channel. The channel, which fed a now-abandoned and partially sunken delta lobe, now contains bayous Terre aux Boeuf and La Loutre. The natural-levee ridges bordering this bayou are narrow and have an elevation largely ranging between sea level and more than 5 ft (1.5 m) above sea level. The Mississippi River intersects a smaller and relatively insignificant deltaic distributary at Chalmette. The junction of

the natural-levee deposits along this deltaic distributary with those of the Mississippi River has widened a short segment of the east bank levee that rises to a little more than 10 ft (3 m) above sea level.

The natural levees within the New Orleans and St. Bernard Parish areas mainly consist of sandy silt, silt, clayey silt, and silty clay. The sandier and siltier sediments characterize the parts of natural levees adjacent to the banks of the Mississippi River. Away from the channel and down slope from the crests of the natural levees, the sediments composing them become progressively more clayey and eventually grade into the clay and organic-rich sediments of the interdistributary basins. The natural levees of the distributaries and the southernmost natural levees of the Mississippi River within Plaquemines Parish also predominantly consist of clayey silt, silty clay, and clay with minor silt. The thickness of these deposits varies from 20 to 30 ft (6 to 9 m) along the Mississippi River and its former channel to less than 3 to 6 ft (1 to 2 m) along distributaries (Kolb and Van Lopik, 1958; Kolb and Saucier, 1982; Saucier, 1994).

Prior to the construction of artificial levees, the Mississippi River and its distributaries constructed natural levees via overbank deposition in repeated episodes of flooding. During major floods, waters overflowed channel banks and poured out into the adjacent interdistributary basins. As the floodwaters left the channels of either the Mississippi River or its distributaries, the expansion of flow from unconfined channels and the baffling effect of the marsh or swamp vegetation caused an abrupt drop in the floodwater velocity. As a result of this decrease in velocity, the sand and silt being carried by the floodwaters settled out adjacent to the channel margins, causing the construction of natural levees along them. These floodwaters carried the finer-grained sediments, mainly clay particles, beyond the natural levees and out into the interdistributary basins where they preferentially accumulated (Saucier, 1994). The construction of artificial levees along the Mississippi River has prevented these distributaries from spreading sediment-bearing floodwaters across the delta plain (Frazier and Osanik, 1969; Kolb and Saucier, 1982; Kolb and Van Lopik, 1958; Snowden and others, 1980).

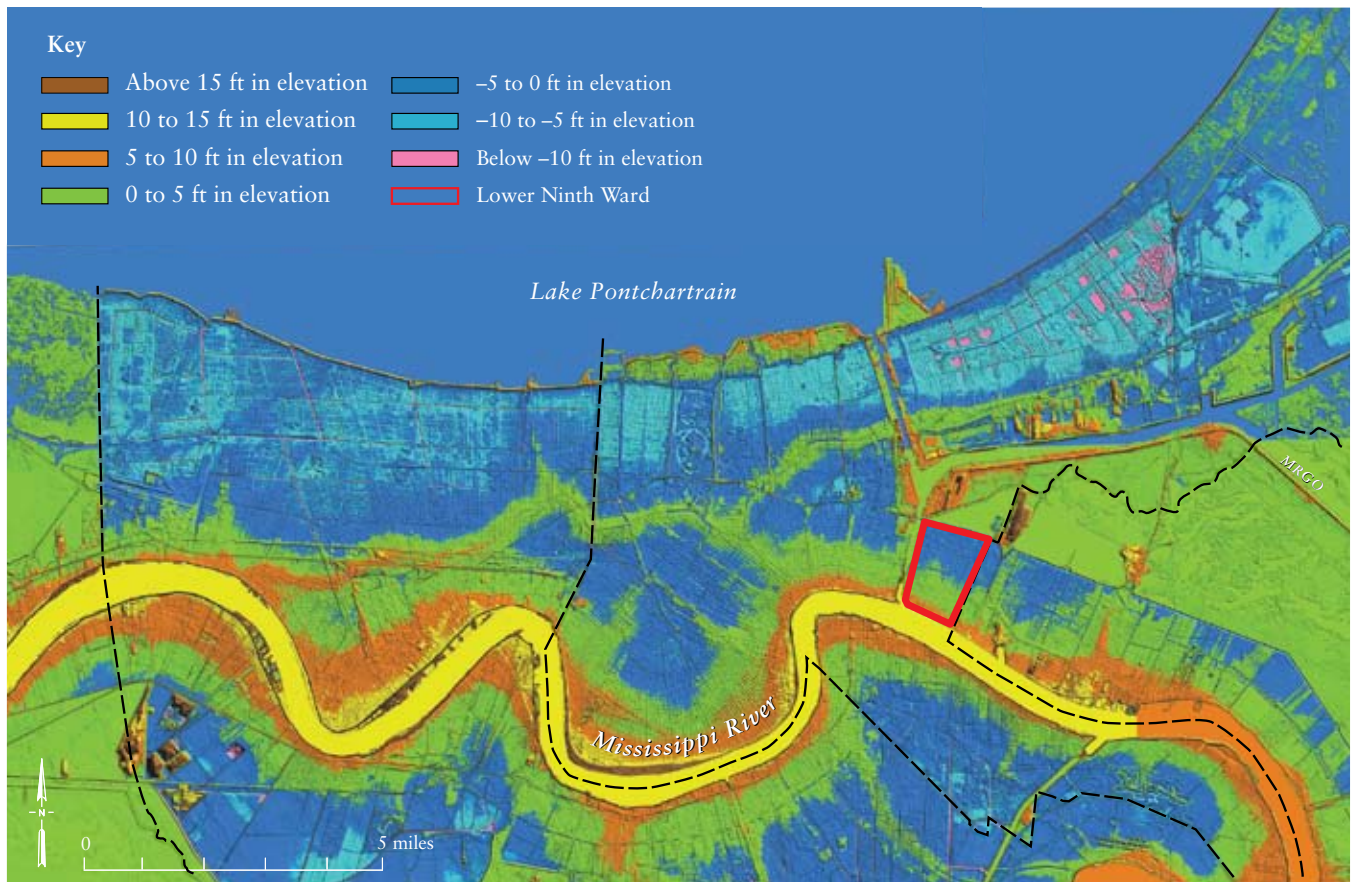


Figure 6. Relief map of New Orleans metropolitan area. In general, the areas colored light and dark blue and magenta were flooded as a result of Katrina. Produced from LIDAR data available from “Atlas: The Louisiana Statewide GIS” (geographic information system) at <http://atlas.lsu.edu/> by using Global Mapper 6.0. Abbreviation: MRGO, Mississippi River Gulf Outlet.

The channels of some segments of Bayou La Loutre, Bayou des Families, and the modern Mississippi River meandered in a limited manner during the past. While the channel migrated, narrow deposits called *point bars* were created by the accretion of sand, silty sand, sandy silt, and silt. The later construction of natural levees buried these point bars (seen in cross section in Figure 5). As a result, narrow, but thick, deposits of sand and silt underlie the natural levees along stretches of Bayou La Loutre, Bayou des Families, and the modern Mississippi River (Kolb and Van Lopik, 1958; Saucier, 1994, 1963).

Interdistributary Basins

Lying between the Mississippi's natural levees and the Gulf of Mexico shoreline are flat, low-lying marshes and swamps containing numerous shallow lakes, bayous, and tidal channels (Kolb and Saucier, 1982; Saucier, 1994; Snowden and others, 1980; Saucier and Snowden, 1995). The low-lying land marks the interdistributary basins of the delta plain occupied by Jefferson, Orleans, Plaquemines, and St. Bernard parishes. This land is actually the tops of the St. Bernard and Plaquemines delta lobes created by the Mississippi

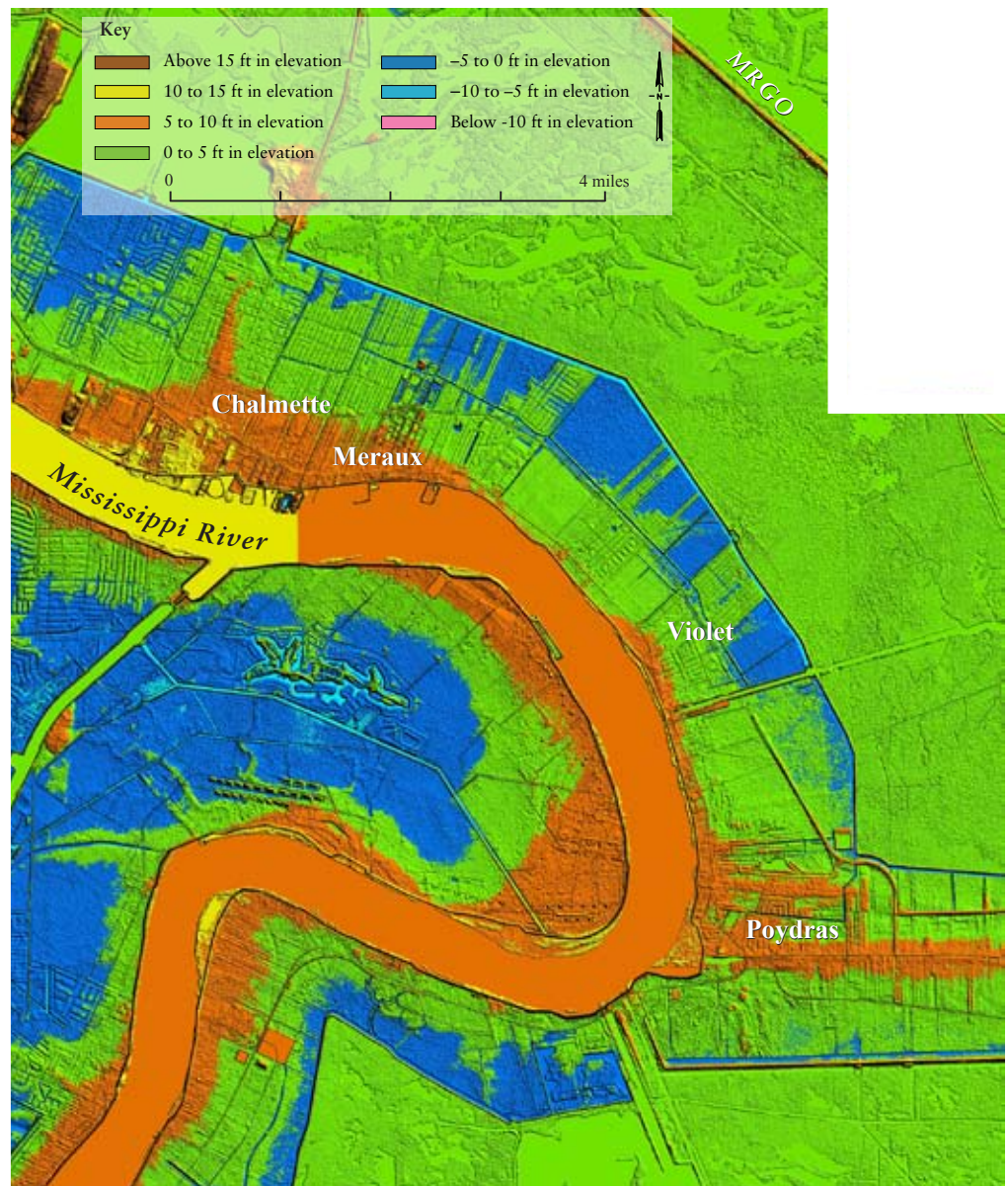


Figure 7. Relief map of northeastern St. Bernard Parish. Produced from LIDAR data available from "Atlas: The Louisiana Statewide GIS" at <http://atlas.lsu.edu/> by using Global Mapper 6.0. Elevation colors are same as in Figure 6. Abbreviation: MRGO, Mississippi River Gulf Outlet.

River over the past 5,000 years (Figure 8). The development of the present delta plain started about 7,000 years ago when the postglacial rate of sea-level rise slowed (Frazier, 1967). In prehistoric times, the ongoing natural process of hinge-zone subsidence of the delta plain (Figure 1) was compensated by regular deposition of fresh overlays of sediment during floods, which sustained large areas of wetlands along the coast and within the inter-distributary basins.

The natural levees of the Mississippi River and its distributaries and ancient, now-unused channels cross the delta plain. Before the marshes and swamps were drained for urban expansion and altered by wetland loss, the natural levees of the Mississippi River, Bayou La Loutre, and Bayou des Familles were bordered by a narrow strip of freshwater cypress swamp. Along the Mississippi River, the cypress swamps

extended as far south as Bertrandville. Farther away from the natural levees and south of Bertrandville along the Mississippi River, the delta plain consists entirely of brackish, intermediate, and saline inter-distributary marshland (Kolb and Saucier, 1982; Kolb and Van Lopik, 1958; Saucier, 1994, 1963).

In the New Orleans region, thick deposits of clayey, commonly organic-rich, sediments and peat underlie the lower-elevation interdistributary basins between the higher-elevation natural levee deposits of the distributaries. These sediments typically consist of soft to very soft gray clays with thin layers of silt and silty sand. Beds of black peat and thin layers of organic debris are interlayered within these clay deposits. The deposits underlying the interdistributary basins consist primarily of fine-grained sediment, which was washed into them by floodwaters. The peat and

Continued on page 23



Key

Delta complexes

Pdc-Plaquemines	1,350 - 0 BP	Ldc-Lafourche	1,500 - 0 BP
Sdc-St. Bernard	4,800 - 1,800 BP	Tdc-Teche	5,800 - 3,900 BP
Mdc-Maringouin	9,000 - 6,500 BP	Older coastal terraces	

Figure 8. Geologically young delta complexes of the Mississippi River Delta. Redrawn and adapted from Saucier (1994). The ages are given in years before present (yr BP).

Major Historical U.S. Hurricane Landfalls

Sources: National Oceanic and Atmospheric Administration

(<http://www.ncdc.noaa.gov/img/climate/severeweather/2hur9996.gif> and

<http://www.ncdc.noaa.gov/img/climate/severeweather/hur5005.jpg>);

Unisys Corporation

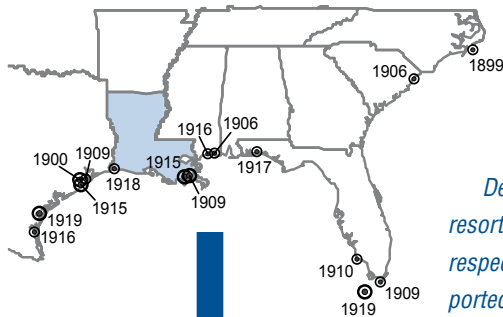
(<http://weather.unisys.com/hurricane/atlantic/2005/index.html>); and

Southern Regional Climate Center

(<http://www.srcc.lsu.edu/tropical/pastTrk>)

Category

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A Blast from the Past—Louisiana’s Historical Hurricanes

A Cautionary Tale

Coastal Louisiana spreads loosely across America’s great delta plain like a vast green shrimp net. Here the once-vibrant marshes are unraveling. The ancient struggle between the river and the sea is rapidly turning in the sea’s favor. Much of the marshland built by the river in the past 5,000 to 6,000 years has drowned in the Gulf of Mexico, and more is sure to follow. Yet the people here celebrate life in their own special way. Perhaps this is due in part to an understanding of the paradox that while the land and the sea are bountiful, the powers of one storm, in a single day, can take it all away.

The earliest noted Louisiana community that was destroyed outright by a hurricane was the community at Last Island or Isle Derniere, in lower Terrebonne Parish. It is now called Isles

Dernieres (plural) because the former single island has eroded into several smaller islands. Isle

Dernier was known as a resort island, similar in many respects to Grand Isle. It supported a thriving community and had numerous permanent structures including the luxury

Trade Wind Hotel. However, on August 10, 1856, a powerful hurricane blew ashore that destroyed most of the structures on the island and resulted in the deaths of at least 200 people. The storm’s track toward the northwest then brought it to the town of Abbeville in Vermilion Parish, where it is said to have leveled every house.

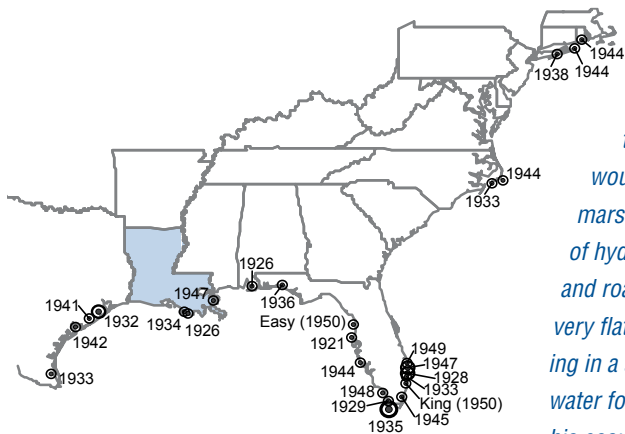
Balise (French for “beacon”) was once an important nautical community at the mouth of the Mississippi River on Southeast Pass. It had been established as a strategic gateway to the river by Adrien Pauger, Bienville’s engineer, in 1723. The small community—that once had a fort, light-house, and taverns—subsided underwater by the middle eighteenth century. But even before that it was abandoned because the Eads Jetties and other navigation aids made the remote station obsolete.

Prior to its abandonment, however, it was at one time known as “the wickedest spot in Louisiana.” It became so notorious that official attempts were made to clean it up and were reportedly successful. Goodness notwithstanding, in 1865 Balise lost 300 to 350 people because of a violent hurricane (Leeper, 1976).

The greatest recorded loss of life in Louisiana from a single event occurred when a deadly storm struck Louisiana’s barrier islands during the night of Sunday, October 1, 1893. It destroyed the community of Cheniere Caminada, which was one of the most heavily populated areas of Louisiana’s Gulf Coast at the time. It has been estimated that half of the 1,700 residents of Cheniere Caminada were killed by the storm, with nearly 2,000 fatalities coast-wide. Many of the survivors moved inland and established the town of Golden Meadow. Although Grand Isle was also impacted by the storm of 1893, only 21 lives were lost there.

On September 20, 1909, a Category 4 hurricane made landfall at Berwick and moved eastward, pushing a 15-ft-high (4.6-m-high) storm surge ashore that flooded much of southeastern Louisiana. Although 350 people were killed on Grand Isle, the community eventually rebounded from the storm. Some people attribute Grand Isle’s resiliency to the fact that it is linked to the mainland by a road; however, there was no road to Grand Isle until 1934. For many years a steamer connected the denizens of New Orleans with those of Grand Isle via the Mississippi River, Harvey Locks, the Harvey Canal, and Bayou Barataria.

In September 1915, another Category 4 hurricane struck New Orleans, claiming 275 lives. This same storm destroyed St. Malo, a remote fishing village east of New Orleans in the marshes fringing Lake Borgne in St. Bernard Parish. St. Malo was a decidedly unusual village that was composed almost exclusively of men who were mainly of Filipino origin. They reportedly jumped ship from Spanish galleons that sailed between the west coast of Mexico and the Philippines. They somehow managed to reach Vera Cruz and from there made the arduous journey to this remote location. They earned their livelihoods through a combination of fishing and alligator trapping. Their unique community was originally described in

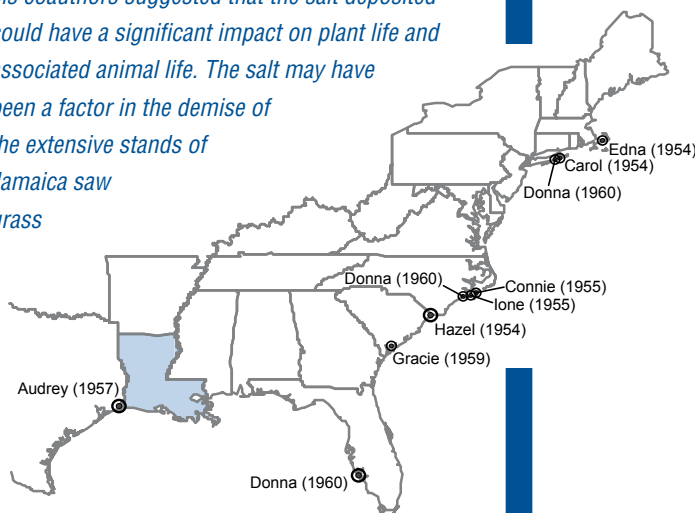


1883 by Lafcadio Hearn in a very interesting article that is now available on the Internet (the Web link is in the bibliography).

In 1947, a significant hurricane struck New Orleans, although it has been nearly forgotten today. A Category 5 hurricane had approached Florida from the east and crossed that state as a Category 4 hurricane. Fortunately, it weakened substantially before reaching the Louisiana coast. The storm crossed the Chandeleur Islands on September 19 and proceeded along a similar course as the present Mississippi River Gulf Outlet. It crossed the Louisiana mainland just north of New Orleans over Lake Pontchartrain. Fortunately, the Mississippi River Gulf Outlet had not yet been constructed. Wind gusts of 112 mph (180 km/h or 97 knots) were measured at Moisant International Airport (now renamed for Louis Armstrong). Water poured into Orleans and Jefferson parishes from the lake. Although it was downgraded to a Category 1 hurricane in Louisiana, it caused an estimated \$100 million in damages in New Orleans and resulted in 51 fatalities. This storm provided the impetus for the levee system along the south shore of Lake Pontchartrain.

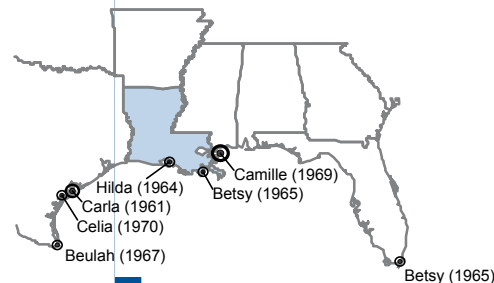
The worst hurricane to strike southwestern Louisiana in living memory, prior to Hurricane Rita in 2005, was Hurricane Audrey, which came ashore as a Category 4 storm during the morning of June 27, 1957. The loss of life in Louisiana was in excess of 500. Thousands of cattle were drowned or starved as a result of the storm, and 90 to 95 percent of the buildings in the town of Cameron were destroyed. The parishes of Cameron and Vermilion were inundated by salt water across an area as far as 30 mi (48 km) inland. Maximum flooding depths exceeded 12 ft (3.7 m). Morgan and others (1958) made an interesting

observation regarding the drainage of the floodwaters after the storm. Under natural landscape conditions, the rainfall associated with the hurricane would assist in flushing the seawater from the marsh back into the gulf. However, as a result of hydrological barriers created by spoil banks and roads, the gradual drainage patterns of this very flat area had been completely altered, resulting in a substantial degree of retention of saline water for an extended period of time. Morgan and his coauthors suggested that the salt deposited could have a significant impact on plant life and associated animal life. The salt may have been a factor in the demise of the extensive stands of Jamaica saw grass

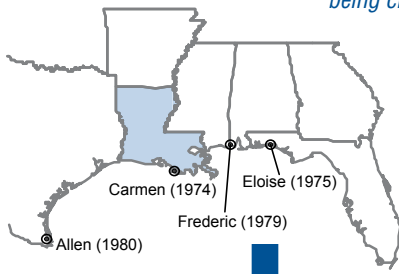


that were historically characteristic of the area. Hurricane Hilda, a Category 3 storm, struck the Louisiana coast on the morning of October 3, 1964. Winds were recorded as high as 135 mph (217 km/h or 117 knots), and the storm produced a number of tornadoes that caused a large amount of structural damage and accounted for several of the state's 38 hurricane-related deaths. In fact, a single tornado at Larose resulted in 22 deaths. Considering the intensity of the storm, it has been recognized that a thorough but voluntary evacuation of the coast was responsible for there not being a much higher casualty rate.

On September 9, 1965, Hurricane Betsy, another Category 3 storm, impacted the Bahamas, the Florida Keys, and Louisiana, killing 75 people, mainly in Louisiana, in the process. Eastern Louisiana saw a storm surge 8 to 10 ft (2.5 to 3 m) high. Nearly every building in Grand Isle was destroyed as gusts of wind up to 160 mph (257 km/h or 139 knots) assaulted the island community. By the time the

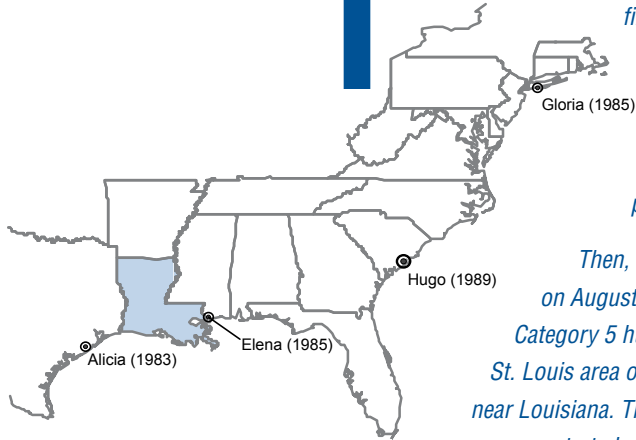


storm hit the New Orleans area, gusts were still being clocked in the 125 mph (201 km/h or 109 knots) range. The hurricane pushed a storm surge into Lake Pontchartrain, which overtopped the levees surrounding the lake. The flooding in the city was catastrophic. The outlying areas were also devastated. Manila Village, 14 mi (23 km) south of the current village of Lafitte, on Barataria Bay, having been pummeled by several previous hurricanes, was finally abandoned after Hurricane Betsy in 1965.

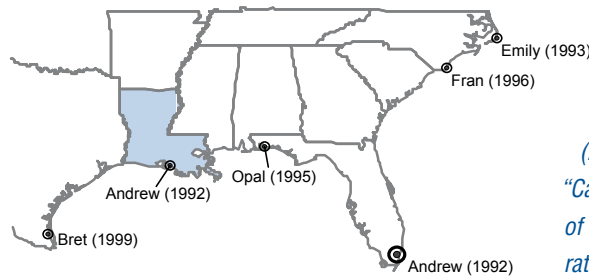


Its primary historical role had been as a major shrimp-drying platform.

Then, in 1969, near midnight on August 17, Hurricane Camille, a Category 5 hurricane, struck the Bay St. Louis area of the Mississippi coast near Louisiana. The damage to Louisiana was concentrated mainly in Plaquemines and St. Bernard parishes and was much less than the devastation experienced in Mississippi. This monster hurricane had sustained winds of 190 mph (306 km/h or 165 knots) and gusts in the 210 to 220 mph (338 to 354 km/h or 182 to 191 knots) range and produced a storm surge of up to 25 ft (7.6 m). It was estimated that 255 people were killed, 8,500 people were injured, 6,000 homes were destroyed, and 14,000 were damaged by the storm—mainly in Mississippi.



Hurricane Andrew was among the most economically destructive storms to impact the United States. Originally the storm was classified as a Category 4 hurricane, but in 1992, the National Oceanic and Atmospheric Administration reclassified Andrew as a Category 5 storm when it hit Florida. The estimated total damage in the



United States was \$26.5 billion, of which \$1 billion occurred in Louisiana and the remainder in south Florida. The toll upon Louisiana was substantial, nonetheless. The storm struck Louisiana on August 26, 1992. In Berwick, sustained winds of 120 mph (193 km/h or 104 knots) were reported, with gusts up to 154 mph (248 km/h or 134 knots). Storm surges of at least 8 ft (2.5 m) were reported across a large area of southeastern Louisiana, and rainfall exceeded 10 inches (25 cm). Although various fatality statistics have been reported, the **Morbidity and Mortality Weekly Report** of the Centers for Disease Control and Prevention indicate that in Louisiana there were 17 fatalities and 445 injuries sustained as a result of the storm.

Between Andrew in 1992 and Katrina and Rita in 2005, Louisiana experienced several hurricanes. Fortunately none was as devastating as the 1893 Cheniere Caminada Hurricane, the 1909 Grand Isle Hurricane, the 1915 New Orleans hurricane, Audrey (1957), Betsy (1965), or Juan, which in 1985 managed to inflict damage worth over \$1.5 billion although it was only a Category 1 storm. In September of 1998, Hurricane Georges wandered about the Gulf of Mexico and pounded the Lesser Antilles, Cuba, and Key West. At one point the storm was south of Louisiana and was on a trajectory upriver toward New Orleans. Fortunately (for New Orleans), it veered eastward and made landfall near Biloxi on September 28 as a Category 2 storm. Gulf-wide, Georges caused over 600 deaths. Within a month, however, another storm would enter the gulf that would make Georges look small by comparison. Hurricane Mitch hit Central America with sustained winds of 180 mph (290 km/h or 156 knots) and torrential rains—keep in mind that any storm with winds greater than 155 mph (249 km/h or 135 knots) is designated as “Category 5.” It is instructive to note that most of the 18,200 fatalities resulted from flooding rather than wind effects, although the steep terrain led to deaths in rain-caused mudslides rather than wholesale floodwater influx as happened in New Orleans in the fall of 2005. After weakening, Mitch meandered across the Yucatan and Florida en route to the North Atlantic.

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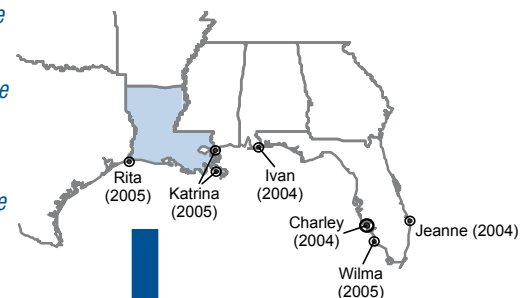
Then, in 2002, the Louisiana coast was in for back-to-back visits from two hurricanes. Tropical

storm Isidore made landfall along the Louisiana coast on September 26 with winds of about 65 mph (105 km/h or 56 knots), bringing with it heavy rains. Fortunately for New Orleans, it was only loosely organized by the time it arrived here, having spent the bulk of its fury over the Yucatan coast. Hurricane Lili hit Marsh Island on October 3, seven days later. Although neither storm was catastrophic, each had the potential to be much worse. Lili had degraded during the night before landfall from a Category 4 to a Category 2 storm. Apparently, the effects of Isidore from the week before had cooled the gulf waters sufficiently to sap some of Lili's energy. Nevertheless, winds were in the 75 mph (121 km/h or 65 knots) range with gusts up to 90 mph (145 km/h or 78 knots), the town of Montegut was flooded, and Grand Isle and other coastal communities suffered considerable flooding and wind damage.

Hurricane Katrina became infamous almost overnight as one of the worst natural catastrophes to affect the United States. According to the National Hurricane Center of the National Oceanic and Atmospheric Administration (Knabb and others, 2005), the storm came ashore in Louisiana on August 29 as a high Category 3 hurricane with estimated maximum sustained winds of 127 mph (204 km/h or 110 knots). (The initial intensity interpretation was Category 4; subsequent analysis indicated that Katrina actually made landfall near New Orleans as a high Category 3.) The hurricane continued to move to the north and made an additional landfall near the Louisiana-Mississippi border where the estimated maximum sustained winds were 121 mph (195 km/h or 105 knots), also category 3. The storm packed the punch of Camille, but was significantly larger. As the storm passed just east of New Orleans, wind speeds there gusted to over 100 mph (161 km/h or 87 knots). The combined storm surge and heavy winds and rains resulted in flooding through several failures in the levee protecting the city from flooding from Lake Pontchartrain and connecting waterways. By August 31, at least 80 percent of the city was flooded. Damage to other Gulf Coast cities was also severe, but nowhere was the devastation as profound as in New Orleans where thousands lost homes, jobs, and in some cases their lives. The total official death toll in Louisiana stands in excess of 1,000, and initial estimates of

damage to insured property in New Orleans was \$19 billion (Randolph, 2005). While overtopping of the flood-protection system was anticipated under conditions exceeding a Category 3 hurricane, structural failure of the floodwall was not (Carter, 2005). Consequently, an independent investigation was performed by the American Society of Civil Engineers. They presented their preliminary findings to Congress on November 2, 2005, in which they enumerated dozens of Hurricane Katrina-related failures of the floodwalls and levees (Nicholson, 2005).

Less than a month after Hurricane Katrina had left southeastern Louisiana and coastal Mississippi and Alabama in shambles, Hurricane Rita followed up with a devastating blow to southwestern Louisiana and southeastern Texas. Additionally, because Katrina had already weakened New Orleans' levee system, Rita generated sufficient storm surge and rainfall to overwhelm the levee system on September 23—a day before landfall. Consequently, many of the same areas flooded by Katrina were flooded once again. This hurricane, like Hurricane Katrina, had picked up an enormous amount of energy in the warm waters of the Gulf Loop Current and, while over the ocean, peaked well into the Category 5 level with sustained wind speeds at 175 mph (282 km/h or 152 knots). Fortunately, its wind speed reduced to 120 mph (193 km/h or 104 knots) (Category 3) as it slammed into the Louisiana/Texas coast on the afternoon of September 24, 2005. Nevertheless, the Louisiana communities of Hackberry, Holly Beach, Johnsons Bayou, and Cameron were virtually obliterated by high winds and a 20-ft-high (6-m-high) storm surge. In Texas, Beaumont, Orange, and Port Arthur were to the west of the eye and less severely damaged; nevertheless, damages there were enormous. According to an October 6 article in *The Advocate of Baton Rouge* (Sayre, 2005), Rita downed 38 percent of Entergy's transmission lines in southwestern Louisiana and 82 percent in Texas. The associated costs were estimated to be between \$400 and \$500 million, which was on top of the estimated \$750 million to \$1.1 billion for Katrina.



But what does the future hold for New Orleans and other similarly situated coastal communities?

There is no clear answer with respect to climate changes. Scientists debate the effects of the Atlantic Multidecadal Oscillation on the frequency and intensities of hurricanes (the oscillation supposedly corresponds to periods of a decade or longer when higher-than-average frequencies of hurricanes prevail) (for example, Landsea and others, 1999). The role of global warming is also discussed (for example, Trenberth, 2005). However, some risk factors are clear. Since the 1930s, the coast has experienced a loss of land mass of more than 1,900 square miles (4,900 square kilometers). Additionally, subsidence has lowered roads, levees, and other protective infrastructure by a considerable amount. Thus, New Orleans and other coastal communities are faced with an ongoing loss of protective distance both vertically and horizontally. Subsidence diminishes elevations while catastrophic wetland losses effectively bring the Gulf of Mexico closer to communities. Therefore, it is safe to say that future storms of a given intensity category will pose increasingly higher risks over time than did comparable past storms—especially with respect to storm surges. The recent publication by T. Waltham (2005) describes what the future may hold for New Orleans and presents some possible solutions that are among the many being considered.

So, what's the bottom line from the layperson's perspective? Take all hurricane warnings and official notices seriously; and, if there is a need to evacuate, evacuate early.

Continued from page 17

organic matter found in these deposits was produced in place by the marsh vegetation and preserved by the waterlogged nature of the interdistributary basins (Frazier and Osanik, 1969; Kolb and Saucier, 1982; Kolb and Van Lopik, 1958; Saucier, 1994).

Buried Barrier Island Complex

Underlying the southeast shoreline of Lake Pontchartrain and the north edge of East New Orleans, a barrier island chain, called the *New Orleans Barrier Island Complex*, lies buried under 3 to 30 ft (1 to 9 m) of delta sediments. It consists of a northeast-southwest-oriented, segmented ridge about 21 mi (34 km) long and 1.5 to 2.4 mi (2.4 to 3.9 km) wide. It is composed of sand and silty sand containing seashell material. Although buried, it affects the surface because it is composed of sediments that are not subject to consolidation and shrinkage to the same degree as the surrounding delta sediments (Saucier, 1963; Stapor and Stone, 2004). The thickness of the compressible, organic-rich deltaic sediments increases to the north and south of the axis of this buried barrier island. As a result, north-south-oriented structures, such as artificial levees, that cross it, are prone to differential subsidence that might significantly compromise their integrity. In addition, the porous sand composing this barrier is thick enough and lies close enough to the surface that it might readily serve as a conduit for the movement of water beneath artificial levees unless blocked by grout curtains, sheet piling, or some other measure.

New Orleans—Primed for Catastrophe

New Orleans has seen its share of hurricane-induced suffering. Most recently, Hurricane Katrina made landfall—and history—when it arrived on the morning of Monday, August 29, 2005. Its initially reported wind speed of 138 miles per hour (mph; 222 km/h or 120 knots) qualified it at that time as a mid Category 4 hurricane (see the explanation of hurricane intensities on the inside front cover). On the previous day the mayor had ordered a mandatory evacuation, the first in the history of New Orleans. Unfortunately, several thousand residents either would not or could not evacuate. By the following day, it was clear that 80 percent of the city had been flooded. The storm surge measured almost 9 ft (2.75 m) above sea level once it reached

Lake Pontchartrain. The flood-protection system failed along the 17th Street Canal, the London Avenue Canal, and the Industrial Canal (see the locations of these failures in the map on the inside back cover). Levees and floodwalls were either overtopped or breached, and several of the pumping stations did not operate. The floodwaters rose quickly over much of the city. To make matters worse, the levee of the Industrial Canal was overtopped and breached again on September 23 by Hurricane Rita (a Category 3 storm), reflooding the already-devastated Lower Ninth Ward. It was not until 43 days after Katrina's visit to the "Crescent City," on October 11, that the U.S. Army Corps of Engineers (2005) claimed victory in removing the foul-smelling floodwaters. The nation and much of the world were transfixed by the enormous scale of the suffering left in the wake of these two hurricanes.

The "Greater New Orleans area" includes the developed parts of Orleans and Jefferson parishes between Lake Pontchartrain and the Mississippi River. Greater New Orleans is somewhat unusual because roughly 80 percent of its area is below sea level. This was not always the case, though even in a completely natural state these areas were never much above sea level. It is ironic that the sinking of much of the area was caused by flood-protection levees and pumps, which, by lowering groundwater levels, caused the highly organic soils to dewater, oxidize, and shrink. The loss in soil volume is expressed as a lowering of the surface of the soil and represents the "surficial" component of subsidence diagrammed schematically in Figure 2. Thus, the strategy employed to keep New Orleans dry—to provide flood protection and to drain many of the swamps and marshes—set up a situation that ultimately contributed to a catastrophic flood.

Originally the city was restricted to the natural levee of the Mississippi River and the few natural ridges along ancient distributaries and atop former barrier islands (Snowden and others, 1980). The French began leveeing the river side of the city almost immediately upon its founding in 1718. These initial artificial levees were enlarged sporadically as the city grew. In 1927, a massive flood on the Mississippi River led to the development of the present-day, continuous Mississippi

River levee system. The city's current footprint extends from the Mississippi River on the south all the way to Lake Pontchartrain on the north.

A map comparison published on the front page of *The Times-Picayune* (Russell, 2005) showed a striking correlation between areas not yet inhabited in 1878 and areas flooded by Katrina in 2005. In general, the areas colored blue and magenta in Figure 6 were flooded as a result of Katrina. Although early settlement in New Orleans was limited to the natural levee ridges that often did not flood and these higher areas remained above the floodwaters during and after hurricanes Katrina and Rita, many structures in the higher areas of "old" New Orleans nevertheless were damaged in 2005 by wind. The wind velocity was higher than it would have been if the former amount of wetlands to the south still remained to decrease the hurricane's strength.

In 1947 a Category 1 hurricane struck New Orleans. It made landfall at the Chandeleur Islands on September 19 and proceeded along a course similar to that of the present Mississippi River Gulf Outlet; then the hurricane crossed Lake Pontchartrain just north of New Orleans. Water poured into Orleans and Jefferson parishes from the lake. The storm caused 51 fatalities and an estimated \$100 million in damages. This storm provided the impetus for the initial hurricane-protection levee system along the south shore of Lake Pontchartrain (Penland and others, 2002).

Then, on September 9, 1965, Hurricane Betsy, a Category 3 storm, impacted the Bahamas, the Florida Keys, and Louisiana. Betsy killed 81 people, 58 in Louisiana. Eastern Louisiana saw an 8–10 ft (2.5–3 m) storm surge. By the time the storm hit the New Orleans area, gusts were still being clocked in the 125 mph (201 km/h or 109 knots) range. The storm surge in Lake Pontchartrain overtopped the levees surrounding the lake and caused catastrophic flooding (Penland and others, 2002). Reminiscent of the 1927 flood, the situation galvanized federal policy, and a massive levee system to protect the area along Lake Pontchartrain from hurricane damage was raised and strengthened in order to prevent the lake from flooding the city again. The system was designed to protect against a Category 3 storm. Hurricane Katrina was initially considered a Category

4 storm (several months later, scientists' interpretation of Katrina's intensity was downgraded to a high Category 3), and while it did not follow the worst-case trajectory, its path was close enough.

Setting the Stage for Disaster

An important technological advancement was made during the early twentieth century that played a critical role in setting up the conditions conducive to the recent flooding of New Orleans. Mr. Baldwin Wood, a mechanical engineer, invented very efficient low-maintenance pumps that were capable of moving huge volumes of water: the Wood Screw Pump in 1913 and the Wood Trash Pump in 1915. These pumps made feasible the growth of the city onto previously uninhabitable wetlands in the intertributary basins. By World War II, the water had been pumped out of the swamps east and west of the older parts of the city, and the new land had been annexed by the growing city. Coupled with a 350-mi-long (560-km-long) ring of levees and drainage canals, these pumps allowed for the draining and urban development of a large area of former marsh and swamp. Subsequent to the hurricane of 1947 and Hurricane Betsy in 1965 and the ensuing leveeing of the south side of Lake Pontchartrain, the marshes fringing the lake were pumped out and built upon. At that point, houses and businesses, supported on pilings because of the very fragile soils, began to spring up over vast areas of previously uninhabited land in New Orleans and Jefferson parishes (Snowden and others, 1980).

This lowering of the groundwater allowed oxidation of the previously anaerobic, organic-rich soil, which in many cases compacted as much as 5 ft (1.5 m) between 1935 and 1970 (Snowden and others, 1980). The net result was a substantial urban population situated within a large "bowl" whose bottom is lower than the mean level of the Mississippi River and Lake Pontchartrain (Kolb and Saucier, 1982). When the levees failed during hurricanes Katrina and Rita, the surrounding water quickly poured into the bowl. The 80 percent of the city built on drained former wetlands corresponds closely to the 80 percent that is below sea level and the 80 percent that flooded (Russell, 2005).

In addition, the taking of water from the principal aquifer underlying the city, called the “700-foot sand,” has contributed substantially to the area’s subsidence at the “subregional” scale (Kazmann and Heath, 1968). It was estimated that this groundwater pumpage resulted in a total land-surface elevation decrease of as much as 1.7 ft (0.5 m) between 1938 and 1964 and that every 50 ft (15 m) of water-level reduction within this aquifer resulted in surface subsidence of 1 ft (0.3 m) (Kazmann and Heath, 1968).

In 2002, *The Times-Picayune* published a comprehensive five-part series expressing concerns about New Orleans’ safety during an intense hurricane (McQuaid and Schleifstein, 2002). But at least a quarter century previously, the Hurricane Katrina scenario had been foretold in a geological report dealing with the interrelationships among development patterns in the Greater New Orleans area, subsidence due to lowering of the water table, and potential flooding. The following is a quote from that report:

“If a typical hurricane were to approach from the gulf along a certain critical path east of the city, winds would blow from the south and/or east resulting in high tides in Lake Borgne and Lake Pontchartrain. Once the eye of the hurricane moved past the city, winds would become northerly, pushing the lake water toward the southern shore. Lakefront levees [as illustrated on the inside back cover] would then be topped by waters and flooding would result” (Snowden and others, 1980, p. 23).

Rapid Shoreline Retreat Brings the Gulf Waters Inland

The landscape surrounding New Orleans is all part of the Mississippi delta plain. This land has been built up by the river’s delta processes during the past 5,000 to 6,000 years (Kolb and Van Lopik, 1958; Frazier, 1967; Penland and others, 1988). Over time, sediment carried in floodwaters from the river and its distributaries built and sustained a dynamic series of new delta lobes covered with wetlands while concurrently abandoning the older delta lobes. Natural flooding by distributaries thus helps to sustain a large area of wetlands. However,

many of the river’s distributaries have been closed off to reduce local flooding, as in the case of Bayou Lafourche, which was dammed off in 1904 upriver from New Orleans at Donaldsonville (located in Figure 8).

The current river management policy arose in large measure from the “Jadwin Plan” as formulated by Major (later Lieutenant) General Edgar Jadwin of the Army Corps of Engineers and articulated in the United States Flood Control Act of 1928, which was enacted in response to the “Great Flood” of 1927. The flood-control levees that are a major component of this management system prevent the normal flooding of fresh water into the adjacent wetlands. One significant consequence is that the natural accretion—that is, the addition of sediment to the wetlands—is greatly diminished, in most places to the point that accretion rates cannot keep up with the sea-level rise caused by the subsidence of the area south of the hinge line shown in Figure 1. Therefore the artificial levees’ disruption of natural flooding by the river

and its distributaries is causing the sinking wetlands to be drowned by seawater.

Another major feature of the current management strategy of the Mississippi River that greatly reduces available sediment for wetland maintenance on the delta is the jetty system at Southwest Pass. These jetties in fact bring the river’s main channel out to the edge of the continental shelf. As a result, millions of tons of sediment are annually discharged off of the continental shelf and into the deep ocean where they are unavailable for wetland-sustaining deposition.

Additionally, the system of locks and dams along the river upstream of the delta has

greatly reduced the river's sediment load that would be available for delta building and wetland maintenance. And dredging to maintain a navigable channel through the delta actually lowers the bottom of the river. Thus more energy is needed to lift water-borne sediment—much of which is carried deep in the river—onto the surface of the delta. However, except for the relatively small area affected by controlled diversion projects, the river is prevented from flooding onto the delta plain by the engineering structures, and this fact overrides both the decreased amount of sediment and the unlikelihood of its being raised out of the river and onto the delta plain. The bottom line is that the wetlands are starved of sediment and are not replenished to compensate the effects of subsidence.

Collectively, these management practices have contributed to Louisiana's loss of 1,900 square miles (4,900 square kilometers) of wetlands over the twentieth century. Another 700 square miles (1,800 square kilometers) are likely to be lost by 2050 (U.S. Geological Survey, 2003a, 2003b). This drowning of coastal wetlands by the waters of the gulf (Figure 9) ultimately threatens New Orleans by effectively bringing the Gulf of Mexico closer to the city (Table 2). The area of severe land loss to the south and east—and thus the area newly occupied by water from the gulf—already has to date been brought uncomfortably close to the original New Orleans settlement centered on the French Quarter area. The areas of land loss were wetlands before they became open water. Because these wetlands historically played an important

role in absorbing the energy and storing the storm-surge volumes associated with hurricanes, their demise has greatly increased the vulnerability of the city.

This increase in proximity of the gulf has happened in combination with the land subsidence operating at the different scales (surficial, subregional, and regional) outlined in the section on geologic context. Subsidence has lowered the ground, roads, bridges, levees, and infrastructure by a considerable amount. Although the exact figures vary from place to place, "regional" subsidence rates of 10 to 15 mm (0.4 to 0.6 in.) per year are common throughout coastal Louisiana (Shinkle and Dokka, 2004). A subsidence rate of 10 mm (0.4 in.) per year implies that, by 2056, subsidence will have lowered the surface by about 500 mm, or 20 inches. The results of such subsidence would be made worse by any future sea-level rise. The loss of elevation and the drowning of coastal wetlands to the south of the metropolitan area have made New Orleans much more vulnerable to the effects of hurricane-induced storm surges. The same would be true for and Louisiana's other coastal communities.

Alternative Strategies for Addressing Flooding Problems in New Orleans

Although the recent increase in hurricane frequency can be attributed to natural cycles in North Atlantic climate, the potential long-term effects of global warming—that is, greater than 50 years—must also be considered. Especially because of the ongoing sea-level rise and the increasing

Table 2. Development of New Bodies of Open Water near New Orleans

Direction from the French Quarter	Distance from area of original New Orleans settlement to currently closest sizable area of open water	Distance to historic gulf shoreline across former dry land or marshy areas that now are mainly areas of open water
To the east	12km (7.5 mi)	14 km (9 mi)
To the southeast	18 km (11 mi)	36 km (22 mi)
To the south	29 km (18 mi)	61 km (38 mi)
To the west	18 km (11 mi)*	

**This open water just south of the west end of Lake Pontchartrain is 27 km (17 mi) closer than Lac Des Allemands (Figure 9), which in the recent historic past constituted the nearest open water to the west of the French Quarter at a distance of 45 km (28 mi).*

coastal population, it has been suggested that this century may witness a significant increase in hurricane-related destruction to populated areas (Emanuel, 2005).

The devastation caused by hurricanes Katrina and Rita bears stark testimony to the potential dangers that this level of increased threat portends. Thus, the question concerning the best approach to provide future inhabitants of New Orleans with protection from yet another catastrophe has stimulated much debate. Some kind of structural strategy of raising and strengthening the levee system in order to provide an incremental increase in protection will be an essential part of any new plan for protection from flooding during hurricanes. Some suggest, however, that exclusively taking this engineering approach could overlook other crucial aspects of the total problem and thus could be dangerously one-sided, and a consideration of the issues examined in this document would seem to support that concern. For navigation as well as flood protection of the low areas in New Orleans, the levees at their present (or greater) heights and the operation of the various pump installations will continue to contribute to surficial subsidence effects and to depriving the wetlands of sediment.

As long as subsidence and coastal land loss continue into the foreseeable future, any static barrier system will continually lose elevation while sea level will rise relative to the local ground surface. New Orleans and its surroundings will become progressively lower and the Gulf of Mexico will become effectively ever closer; therefore, such an exclusively structural strategy may set the stage for an even greater catastrophe, unless a much improved evacuation strategy is also implemented.

Improved evacuation procedures and an enhanced and expanded emergency public transportation network can be planned and implemented concomitantly with development of future defensive engineering strategies. A sliding scale of response is the most effective approach. For lower-category hurricanes, people would be sheltered in place. However, when there is a reasonable threat of impact by a larger storm, then a mandatory evacuation seems the sensible course of action to preserve the lives of New Orleans residents.

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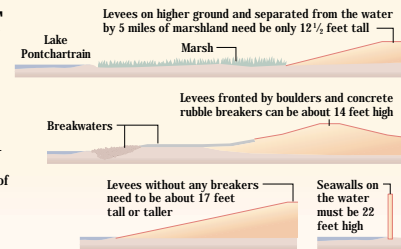
LAST LINE OF DEFENSE HOPING THE LEVEES HOLD

Army Corps of Engineers officials say hurricane levees in the New Orleans area will protect residents from a Category 3 hurricane moving rapidly over the area. But computer models indicate even weaker storms could find chinks in that armor.

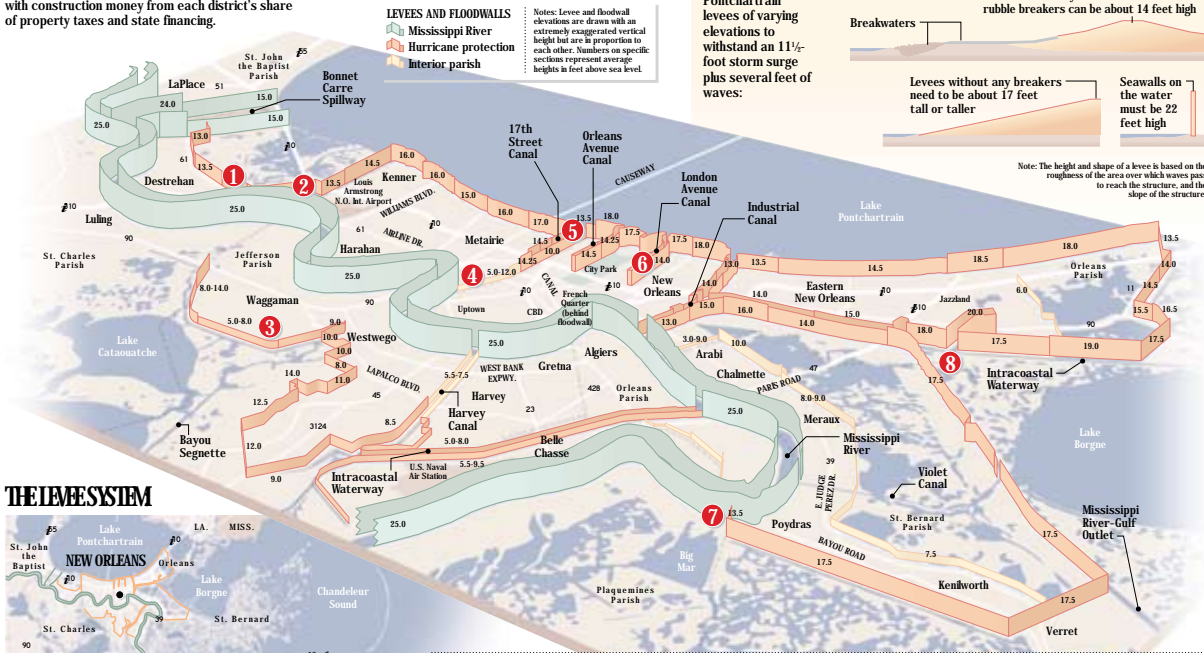
BARRIERS OF EARTH AND CONCRETE

Levees and floodwalls that protect against flooding from both the Mississippi River and hurricanes are built by the Army Corps of Engineers and are maintained by local levee districts. The corps and the local districts share the construction cost of hurricane levees, while the Mississippi River levees are a federal project. Local levee districts also build and maintain nonfederal, lower-elevation levees with construction money from each district's share of property taxes and state financing.

HEIGHTS NOT EVERYTHING
Different factors permit Lake Pontchartrain levees of varying elevations to withstand an 11 1/2-foot storm surge plus several feet of waves:



Note: The height and shape of a levee is based on the roughness of the area over which waves pass to reach the structure, and the slope of the structure.



THE LEVEE SYSTEM

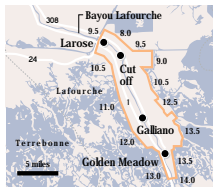


FARTHER SOUTH

Residents and businesses in developed areas along bayous and the Mississippi River have successfully argued that the benefits of building levees around their communities outweigh the costs of construction.

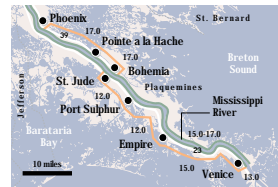
LARGE TO GOLDEN MEADOW LEVEE

This 40-mile ring levee encircles residential and commercial developments along Bayou Lafourche. Parts of the levee are being raised to counteract subsidence.



NEW ORLEANS TO VENICE LEVES

There are 37 miles of levees in this project on both sides of the Mississippi River between Phoenix and St. Jude to the north and Bohemia and Venice at the southern end of the river. Different pieces of the levee are 60 percent to 90 percent complete.



LEVEE HOT SPOTS AROUND NEW ORLEANS:

1 ST. CHARLES PARISH



Construction of a new drainage structure west of Louis Armstrong International Airport is part of an incomplete 10-mile levee from the Bonnet Carré Spillway to the parish line, five miles inland from Lake Pontchartrain. Computer models indicate storm surge from smaller hurricanes would flood populated areas toward the river through gaps.

2 ST. CHARLES-JEFFERSON PARISH LINE



This 5-foot to 10-foot wall of sandbags and sheet piling runs south of Airline Drive to the Mississippi River levee near the airport. Surge water from the lake could pool along the parish levee and pour over this barrier into Jefferson Parish and New Orleans, according to computer models.

3 WEST BANK



More than 60 miles of levees and floodwalls from east of the Harvey Canal to west of Lake Cataouatche - including this stretch of completed floodwall and yet-to-be-raised levee along Bayou Segnette State Park - are years from completion. Small hurricanes can push water from Timbalier and Barataria bays into West Bank neighborhoods.

4 JEFFERSON-ORLEANS PARISH LINE



Chesterfield Street passes through a low levee from Monticello Avenue in Jefferson Parish into New Orleans near the city's water plant. Computer models indicate this is the likely spot for floodwater to enter the city from St. Charles and Jefferson parishes during hurricanes.

5 JEFFERSON-ORLEANS PARISH LINE



The Hammond Highway bridge over the 17th Street Canal is being replaced with a new, hurricane-resistant structure. Huge sandbags are kept nearby to plug this hole in the hurricane protection for Jefferson and Orleans parishes.

6 NEW ORLEANS



The Filmore Avenue bridge over the London Avenue Canal is being replaced with a new span with floodwalls. Until its completion, only sandbags will stop hurricane surge from pouring into city neighborhoods.

7 ST. BERNARD-PLAQUEMINES PARISH LINE



A computer model indicates storm surge could overtop a V-shape area where levees meet at the parish line near the Caernarvon Freshwater Diversion Project along the east bank of the Mississippi River.

8 EASTERN/NEW ORLEANS AND ST. BERNARD PARISH

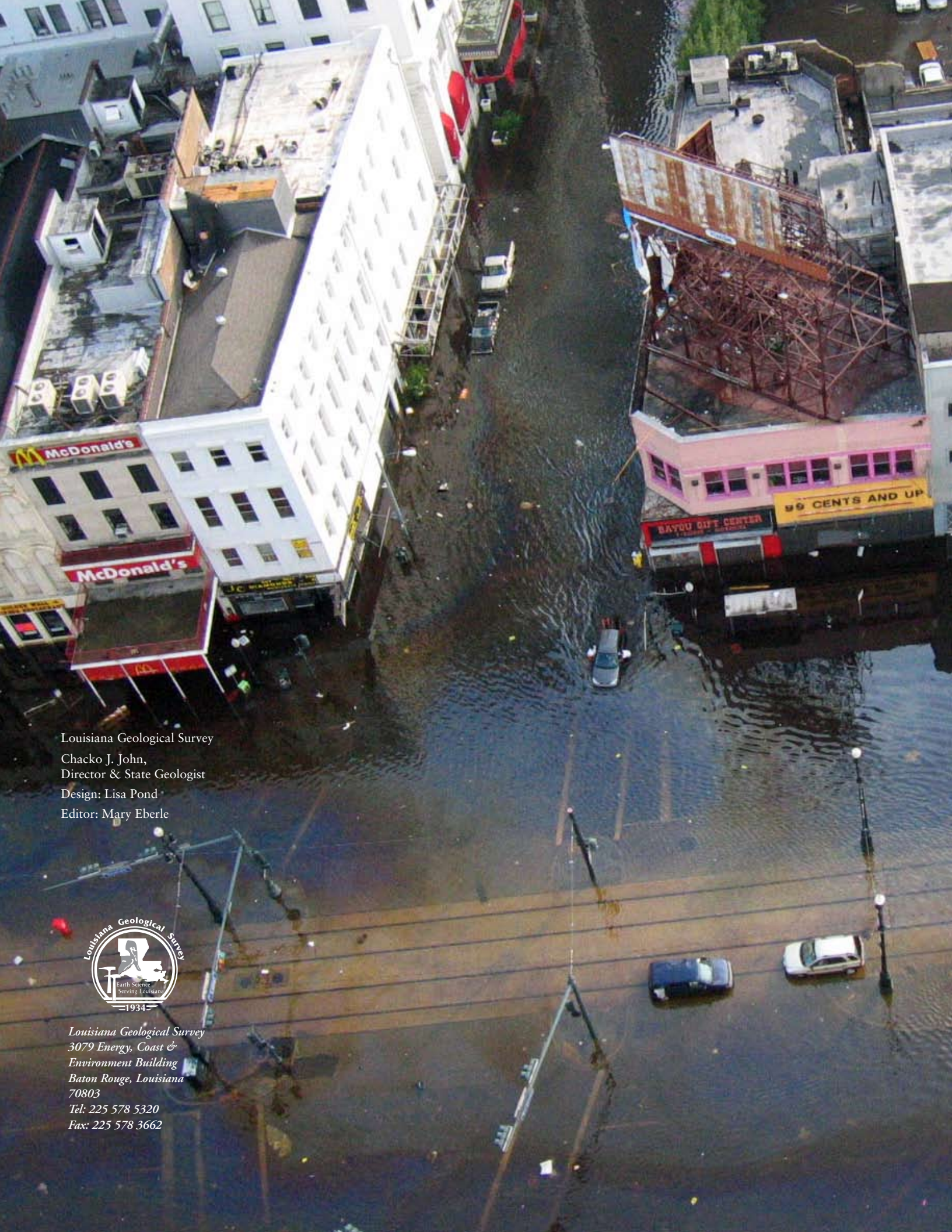


Computer models indicate surge from Lake Borgne might rise in the Mississippi River-Gulf Outlet and overtop New Orleans levees near the Paris Road bridge and a section of levee in St. Bernard during a hurricane.

Sources: Army Corps of Engineers, New Orleans District; Orleans Levee District; East Jefferson Levee District; West Jefferson Levee District; Lake Borgne Basin Levee District; Plaquemines Parish Levee District
Research: Emmett Mayer III and Mark Schleifstein

Staff graphic by Emmett Mayer III/emayer@timespicayune.com
STAFF PHOTOS BY ELLIS LUCIA, ALEX BRANDON AND DEVANSHI MARADEVA

New Orleans System of Artificial Levees
(graphic by Emmett Mayer III from Part 1 of McQuaid and Schleifstein, 2002)
Source: The Times-Picayune (used with permission)



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