CHAPTER FOUR: HISTORY OF THE NEW ORLEANS FLOOD PROTECTION SYSTEM

J. David Rogers

4.1 Origins of lower New Orleans

New Orleans is a deep water port established in 1718 about 50 miles up the main stem of the Mississippi River, on the eastern flank of the Mississippi River Delta. New Orleans was established by the French in 1717-18 to guard the natural portage between the Mississippi River and Bayou St. John, leading to Lake Pontchartrain. The 1749 map of New Orleans by Francois Saucier noted the existence fresh water versus brackish water swamps along the southern shore of Lake Pontchartrain.

The original settlement was laid out as 14 city blocks by 1721-23, with drainage ditches around each block. The original town was surrounded by a defensive bastion in the classic French style. The first levee along the left bank of the Mississippi River was allegedly erected in 1718, but this has never been confirmed (it is not indicated on the 1723 map reproduced in Lemmon, Magill and Wiese, 2003). New Orleans early history was typified by natural catastrophes. More than 100,000 residents succumbed to yellow fever between 1718 and 1878. Most of the city burned to the ground in 1788, and again, in 1794, within sight of the largest river in North America. The settlement was also prone to periodic flooding by the Mississippi River (between April and August), and flooding and wind damage from hurricanes between June and October. Added to this was abysmally poor drainage, created by unfavorable topography, lying just a few feet above sea level on the deltaic plain of the Mississippi River, which is settling at a rate of between 2 and 10 feet (ft) per century.

The tendency to flooding during late spring and summer runoff came to characterize the settlement. The natural swamps north of the original city were referred to as “back swamps” in the oldest maps, and “cypress swamps” on maps made after 1816. During the steamboat era (post 1810), New Orleans emerged as the major trans-shipment center for river-borne to sea-born commerce, vice-versa, and as a major port of immigration. By 1875 it was the 9th largest American port, shipping 7,000 tons annually. In 1880, after completion of the Mississippi River jetties (in 1879), New Orleans experienced a 65-fold increase in seaborne commerce, shipping 450,000 tons, jumping it to the second largest port in America (New York then being the largest). New Orleans would retain its #2 position until well after the Second World War, when Los Angeles-Long Beach emerged as the largest port, largely on the strength of its container traffic from the Far East. New Orleans remains the nation’s busiest port for bulk goods, such as wheat, rice, corn, soy, and cement.

New Orleans has always been a high maintenance city for drainage. The city’s residential district did not stray much beyond the old Mississippi River levee mound until after 1895, when serious attempts to bolster the Lake Pontchartrain “back levee” and establish a meaningful system of drainage were undertaken by the city. Most of the lowland cypress swampland between Mid-Town and Lake Pontchartrain was subdivided between 1900-1914, after the City established and funded a Drainage Advisory Board to prepare ambitious plans for keeping New Orleans dry all the way to Lake Pontchartrain's shoreline. This real estate bonanza increased the City's urban acreage by 700% and their assessed property values by 80% during the same interim (Campanella, 2002). Most of these lots were developed after the First World War (1917-18). Another 1,800 acres was reclaimed from the south shore of Lake Pontchartrain in 1928-31, between the mouth of the 17^{th} Street Canal on the west and the Inner Harbor Navigation Canal (IHNC) on the east. The entire area was subsequently built-out following the Second World War, between 1945-70.

4.2 Mississippi River Floods

The Mississippi River drains 41% of the continental United States, with a watershed area of between 1,245,000 square miles (mi^2), according to the U.S. Army Corps of Engineers. This makes it the third largest watershed of any river in the world. Although its official length is 2,552 miles (if measured from Itasca State Park in Minnesota), when combined with the Missouri River (2,540 miles long), it is the longest river in North America, with a combined length of 3,895 miles. Prior to 1950, the sediment load (suspended and dissolved) transported by the Mississippi River averaged between 550 and 750 million tons per annum (Meade and Parker, 1985). Since 1950, the average annual suspended discharge of the river has decreased to 220 million tons/yr (Meade and Parker, 1985), because of the construction of dams and maintenance of the navigation channel (which includes dredging). The Mississippi River now ranks as the 6th largest silt load in the world.

The Mississippi's flood plain upstream of Baton Rouge is an alluvial valley that, prior to 1928, was periodically subject to inundation by flooding. Vast tracts of the flood plain were periodically inundated. 26,000 square miles of land (mi^2) was inundated during the 1927 flood; 20,312 mi^2 in the 1973 flood, and 15,600 mi^2 in the 1993 flood (which focused on the lower Missouri watershed). 75% of the sediment deposited on the North American continent is overbank flood plain silt, which spills onto the flood plain when floods spill over natural or man-made levees. At its widest point in the Yazoo Basin, the Mississippi flood plain is more than 80 miles wide.

4.2.1 Mississippi River is the high ground

The river is the high ground in the Mississippi Embayment (Figure 4.1). A vexing problem with a high silt load river is that it tends to build up its own bed, which prevents drainage of the adjoining flood plains. Sediment is deposited on the adjoining lowlands when the river spills up out of its channel during flood stage. Sediments are hydraulically sorted during this process, becoming increasingly fine-grained and soft with increasing distance from the river channel, as sketched in Figure 4.2. Millions of acres of flood plain swamps and marshlands in the Mississippi Embayment downstream of Gape Girardeau, MO were reclaimed by mechanically excavated drainage ditches, beginning around 1910, when large rail-mounted dragline excavators became available. This machinery was also employed for levee construction on the MR&T Project (after 1928) as well as drainage work for agricultural reclamation.

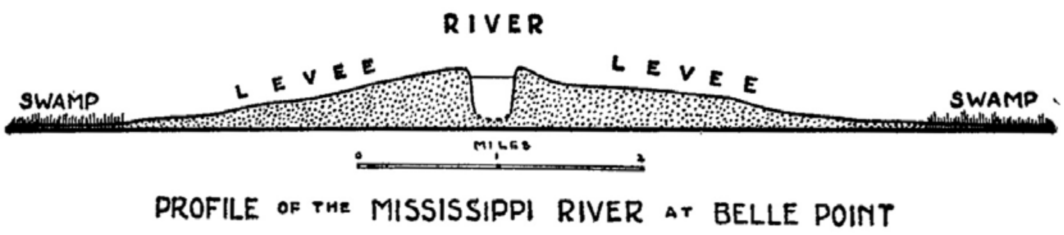

Figure 4.1: Typical cross section through the sandy bank levees of the Mississippi River, illustrating how the river's main channel lies above the surrounding flood plain, which were poorly drained swamp lands prior to reclamation in the post Civil War era (from Williams, 1928).

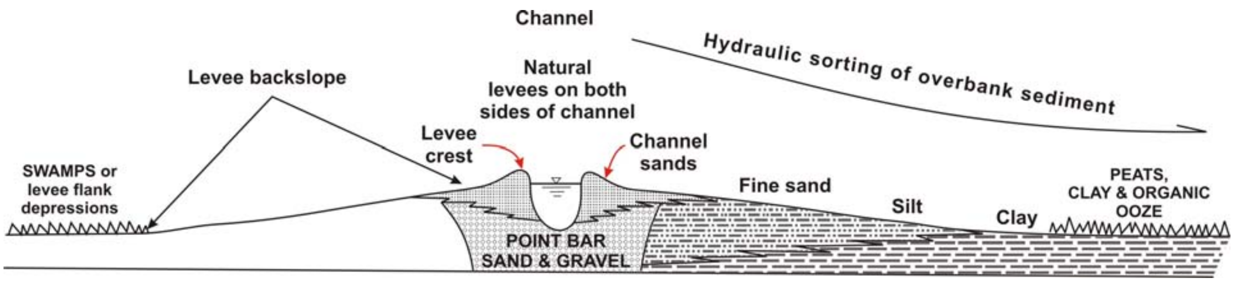

Figure 4.2: Same typical cross section, showing the hydraulic sorting of sediments moving away from the Mississippi River channel. The levee backslope zone lies between the elevated levees and the poorly drained swamps. In New Orleans, the Carrollton, Uptown, French Quarter, and Central Business Districts are situated on the natural levee and its backslope, while the Mid-City area was built on a levee flank depression between the Mississippi and Metairie levees. The Lakeview, Gentilly, and Ninth Ward areas occupy the old cypress swamps.

4.2.2 Flooding from the Mississippi River

A great number of floods have occurred in the lower Mississippi Valley during historic time, including: 1718, 1735, 1770, 1782, 1785, 1971, 1796, 1799, 1809, 1811, 1813, 1815, 1816, 1823, 1824, 1828, 1844, 1849, 1850, 1851, 1858, 1859, 1882, 1892, 1893, 1903, 1907, 1908, 1912, 1913, 1916, 1920, 1922, 1923, 1927, 1929, 1932, 1936, 1937, 1945, 1950, 1957, 1958, 1973, 1974, 1975, 1979, 1983, 1984, 1993, and 1997.

The most damaging to New Orleans were those in: 1816, 1826?, 1833?, 1849, 1857?, 1867, 1871, 1874, 1882, 1884, 1890, 1892, 1893, 1897, 1903, 1912, 1913, 1922, 1927, 1937, 1947, 1965, 1973, 1979, 1993, and 2005. But, the last flood of any consequence to affect the City of New Orleans emanating from the Mississippi River was in 1859!

New Orleans was founded in 1718. In April 1719 the town's founder Jean Baptiste le Moyne, Sieur de Bienville, reported that water from the Mississippi River was regularly inundating the new settlement with half a foot of water. He suggested constructing levees and drainage canals, and soon required such drainage work of all the landowners. In 1734-35 the

Mississippi River remained high from December to June, breaking levees and inundating the settlement.

Flood protection from the Mississippi River was originally afforded by heightening of the river's natural bank overflow levees (Hewson, 1870), like those shown in Figure 4.3. Crevasses, or crevasse-splays, (Figure 3.8) are radiating tensile cracks that form in the bank of a river, natural levee, man-made levee, or drainage canal. Crevasse-splays are often triggered by underseepage along preferential flow conduits, such as old sand-filled channels or the radiating distributaries of previous channel breaks. For these reasons, crevasse-splays often occur at the same locations repeatedly.

On May 5, 1816 the Mississippi levee protecting New Orleans gave way at the McCarty Plantation, in present-day Carrollton, and within a few day water filled the back portion of the city, extending from St. Charles Avenue to Canal and Decatur Streets, flooding the French Quarter. The water was only drained after a new drainage trench was excavated through Metairie Ridge and channels connecting to Bayou St. John.

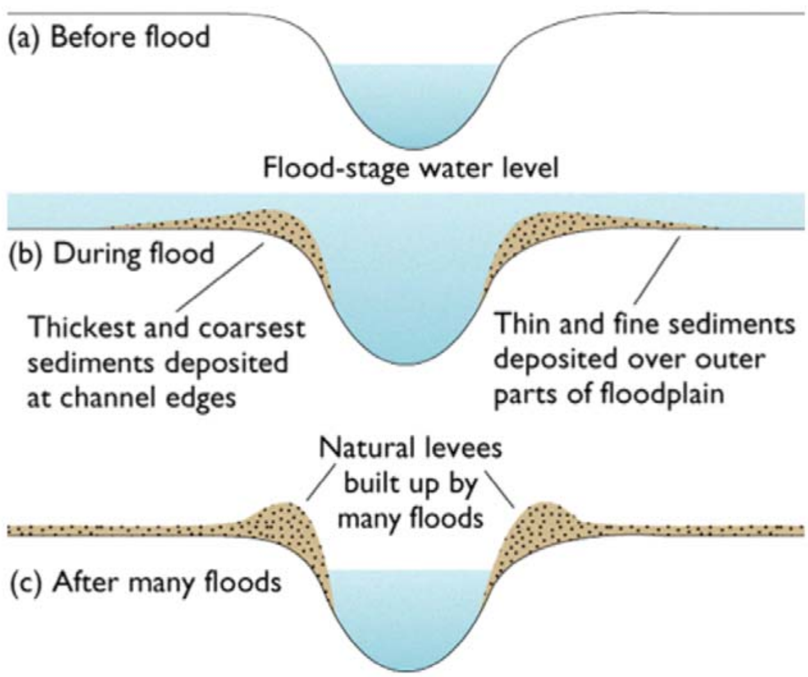

Figure 4.3: Natural levees exist along most perennial channels subject to periodic overbank flooding emanating from a prominent low flow channel, as sketched above. Man-made levees originated by piling up additional earthen fill on top of these natural levees (from Press and Siever, 1997).

On May 4, 1849 the Mississippi River broke the levee at the Suavé Plantation at River Ridge, 15 miles upstream of New Orleans. Within four days this water reached the New Basin Canal, and within 17 days was flooding the French Quarter in New Orleans proper, flooding the area downslope (north of) of Bienville and Dauphine Streets. The 1849 flood waters rose at an average rate of one foot every 36 hours, which allowed residents ample time to evacuate. Uptown residents thought about severing the levee along the New Basin Canal to prevent water levels building up on their side, but those living on the opposite side of the canal threatened to prevent such measures using armed force. Shortly thereafter the New Basin upper levee collapsed, diverting flood waters to Bayou St. John and thence, into Lake Pontchartrain. A nine foot deep lake developed in what is now the City's Broadmoor area, flooding 220 city blocks and necessitating the evacuation of 12,000 residents.

The 1849 crevasse at Suavé Plantation was eventually plugged by driving a line of timber piles and piling up thousands of sand bags against these on the land-side of the pile wall. This work was of unprecedented proportions until that time and took six weeks to complete before the river's waters were once again confined to their natural channel. Drainage trenches were then excavated through Metairie [distributary] Ridge to channel ponded water out to Lake Pontchartrain. By mid-June 1849 the water was finally receding and residents began re-entering their flooded homes, spreading lime to combat mold, mildew, and impurities.

Between 1849 and 1882, four major crevasse-splays occurred at Bonnet Carré, on the eastern bank of the Mississippi River, about 33 river miles upstream of New Orleans. The Bonnet Carré crevasses left a large fan-shaped imprint on the landscape. In fact, during the flood of 1849, a 7,000-foot-wide crevasse developed at Bonnet Carré which diverted flow from the Mississippi into Lake Pontchartrain for more than six months. This breach had to be filled so sufficient discharge could flow down the main channel to allow ocean going vessels to reach New Orleans.

The 1849 floods were the last time that the eastern bank of the Mississippi River was breached affecting New Orleans proper. In 1858 high water lapped over the east bank levee, but this was followed a few days later by a break on the west bank of the river (at Bell Plantation), which drew down the high water threatening New Orleans. The Bell Plantation crevasse remained open for six months. In 1859 the rear portion of New Orleans again flooded, between Carrollton and Esplanade Avenues, flooding one-third of the City between January and March.

The City of New Orleans and the Mississippi River became important battlegrounds during the American Civil War between 1861-65. Early in the conflict a principal goal of the Union forces west of the Appalachian Mountains was to sever the Confederacy along the Mississippi River. Union forces had a distinct advantage insofar as they retained most of their naval power, allowing them to blockade Confederate ports. General Ulysses Grant achieved considerable notoriety for his early campaigns up the Cumberland and Tennessee Rivers, and later, in the successful siege of Vicksburg, which gave northern forces control of the Mississippi, isolating 40,000 Confederate troops west of the river, where they played no further significant role in the conflict. Grant recognized the pivotal military role of the great river, because it was his Army's vital supply line. Grant turned to his engineers on numerous occasions and ordered the construction of cutoffs (Figure 4.4), some of which were successful, while others, such as that a short distance downstream of Vicksburg, were not.

The success or failure of the man-made cutoffs depended on a number of factors, such as time of year, severity of the spring flood, and ability to meter flows into the cutoffs trying to control the erosion caused by dropping the water over oversteepened gradients. These experiences were drawn upon soon after the war (Hewson, 1870) to create an inland empire through drainage of low lying swamps and construction of thousands of miles of privately constructed levees to keep the river from flooding reclaimed tracts.

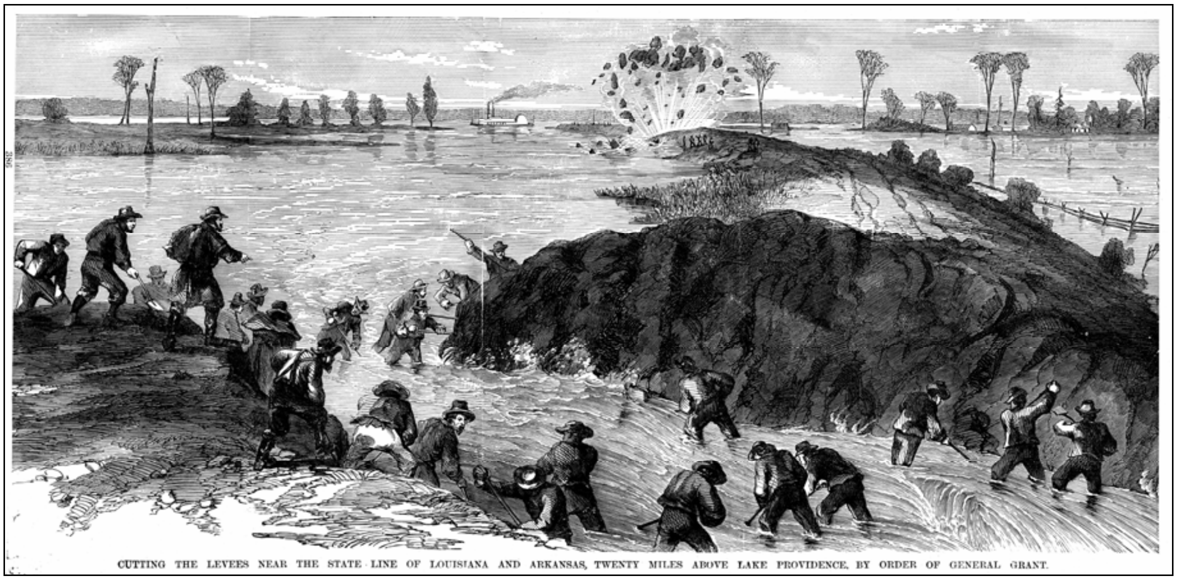

Figure 4.4: Union forces under General Grant cutting the levee near the state line of Louisiana and Arkansas, 20 miles above Lake Providence (from Moat and Leslie, 1896). In describing this activity, Moat and Leslie (1896) noted: *"The soil is very tough, and will not wash away. The levees consequently have to be blown up with gunpowder. The soil is then loosened with spades."* Levees constructed of cohesive clay were found to be the most resilient, but those constructed of other materials, such as overbank silt, peat, or organic ooze were easily eroded.

During the post Civil War boom that witnessed significant reclamation of flood-prone tracts in the Mississippi flood plain, a pattern of protection emerged as the established cities like New Orleans battled the Mississippi: that being of adjacent breaks, upstream at Bonnet Carré and downstream, in Plaquemines Parish, often providing "safety valves" that reduced high water in the river along the New Orleans waterfront. The western bank would breach again in 1893, at the Ames Plantation in Marrero. Breaks in adjoining areas gradually give rise to rumors about levees being purposefully undermined to save the more valuable property within the city, which reached epic proportions during the record flood of 1927, when the levees adjoining Plaquemines Parish were dynamited no less than seven times, by City officials worried that their own protective works would crumble and give ay (Barry, 1997).

Army Engineer A.A. Humphreys and civilian engineer Charles Ellet were funded by Congress in separate contracts to make a scientific examination of the Mississippi River in 1850. Ellet completed his work in 1851, but Humphries did not completing his report until 1861, after suffering a nervous breakdown (Barry, 1997). Humphreys controlled the Mississippi River as Chief of the Corps of Engineers between 1866-1879. He was the father of the Corps' flawed "levees only policy" of flood control, which remained in effect till the wake of the 1927 flood ushered in the adoption of the Jadwin Plan, embodied in the Federal Flood Control Act of 1928 (Morgan, 1971; Shallat, 1994). The "levees only policy" maintained that the Mississippi River could be constrained within its natural low flow channel by extending its natural levees upward, assuming the channel would downcut its bed vertically during high flows, thus remaining in an artificially confined channel. This logic was hopelessly flawed in that it ignored the river's serpentine curvature, which causes it to loop on itself in an endless seemingly series of "meander belts" across the floodplain. Because of this curvature, the channel is seldom symmetrical (like Figure 4.2), but generally exhibits marked asymmetry, like that shown in Figure 4.5.

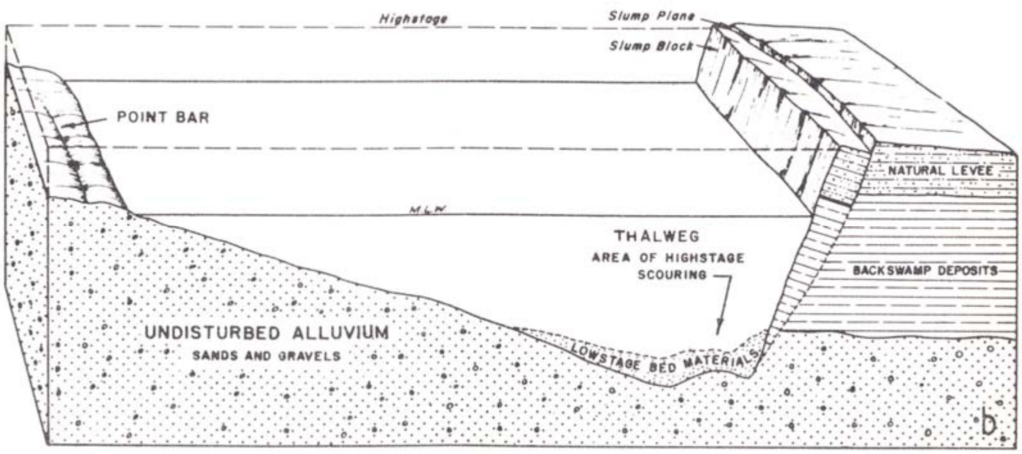

Figure 4.5: Asymmetric channel cross section typical of the Mississippi River, showing slumping of the oversteepened banks on the outside of its turns and the relative position of the river's thalweg, the line connecting the lowest points along the bed of the river. River mileage is measured along the thalweg, not along the river centerline, because this line more accurately describes the actual flow path (from Fisk, 1952).

In 1871 the Mississippi River once again spilled its eastern bank at Bonnet Carré, 33 miles upstream of New Orleans. The massive break diverted much of the river's flow into Lake Pontchartrain, raising its level. A strong north wind pushed lake water up into the Metairie and Gentilly ridges, filling the then-existing system of drainage canals. A levee on the Hagan Avenue (now the Jefferson Davis Parkway) drainage canal gave way, flooding the back side of New Orleans, including the Charity Hospital, a town landmark.

The 1927 flood was the largest ever recorded on the lower Mississippi Valley (Figure 4.6). The deluge was preceded by a record 18 inches of rain falling on New Orleans in a 48 hour period in late March 1927, which was followed by six months of flooding. The levees that were supposed to protect the valley broke in 246 places, inundating 27,000 square miles of bottom land; displacing 700,000 people, killing 1,000 more (246 in the New Orleans area), and damaging or destroying 137,000 structures.

There was an enormous public outcry for the government to do something more substantive about flood control. Fearing the worst, the political leadership of New Orleans sought relief by dynamiting the Mississippi levee in Plaquemines Parish, downstream of New Orleans. By the time promises were made regarding damage compensation and the necessary permission was granted, the flood had crested and begun to subside. No less than seven sequences of dynamiting ensued, all promoted by fear. The initial dynamiting of the Caernarvon levee below New Orleans with 30 tons of dynamite devastated much of St, Bernard and Plaquemines Parishes, and their residents were never remunerated in any meaningful way for their damages. The saddest aspect of the dynamiting was that it was unnecessary, as several levees gave way upstream of New Orleans, one the very afternoon of the dynamiting and the river level at New Orleans never regained its maximum crest the remainder of that record year (Barry, 1997).

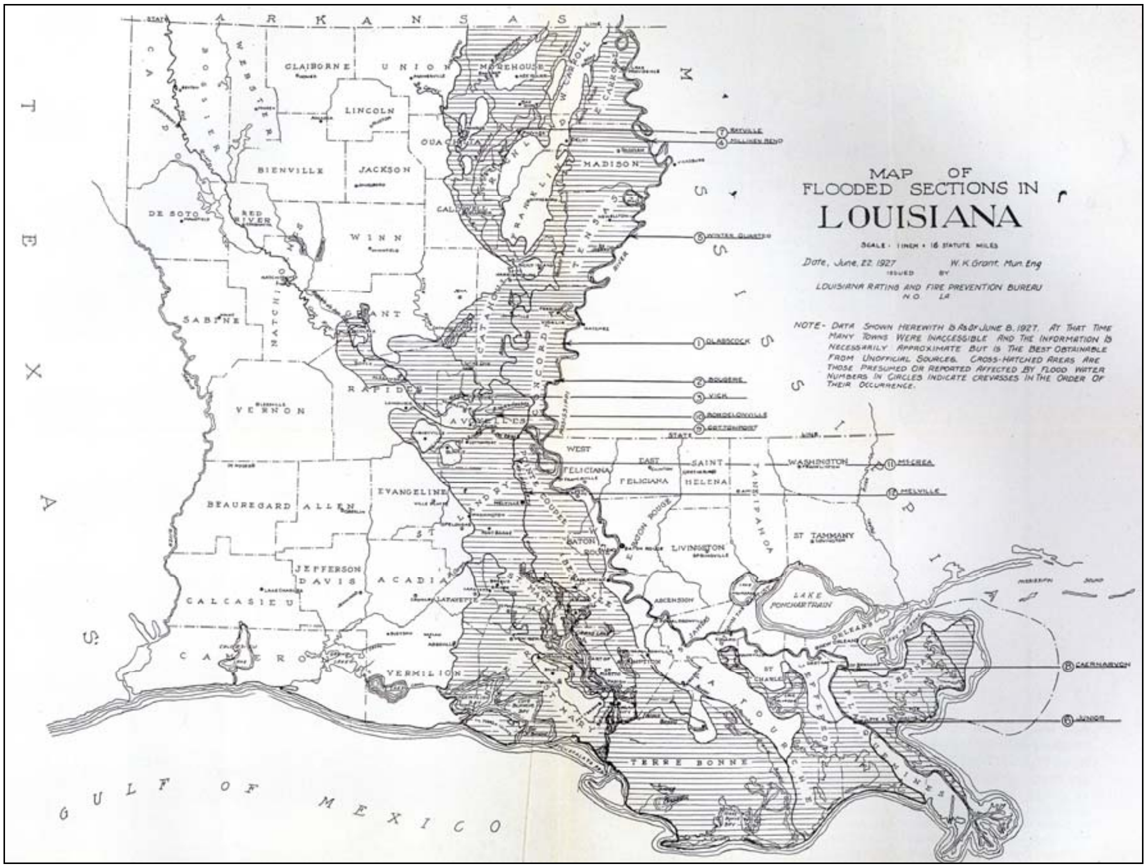

Figure 4.6: Map showing the lands inundated in Louisiana during the height of the great Mississippi River Flood of 1927 (from the Historic New Orleans Collection). Concerns over long term safety from flooding caused many businesses and financial institutions to depart New Orleans to seemingly safer havens, such as Houston, TX (Barry, 1997).

4.3 The Mississippi River and Tributaries Project 1931-1972

The Corps of Engineers Mississippi River & Tributaries (MR&T) Project was authorized by Congress in the Flood Control Act of 1928, which emanated from the Great Flood of 1927 on the lower Mississippi River. At the time of its introduction it was referred to as The "Jadwin Plan," because Major General Edgar Jadwin was the Army's Chief of Engineers at the time it was issued, on December 1, 1927 (Jadwin, 1928). It was incorporated into the Federal Flood Control Act of May 15, 1928, which authorized $325 million to the Mississippi River Commission (created in 1879) controlled by the Corps of Engineers to provide for flood protection along the Mississippi River between Cape Girardeau, MO and Head-of-Passes, LA. In essence the Mississippi River Commission adopted the Mississippi River & Tributaries Project, and the commission's responsibilities, annual budget, expenditures and importance increased by an order of magnitude, where it remains more-or-less today. Actual construction did not begin until 1931, when the authorized funds were finally appropriated by Congress.

The original flood control plan selected a project flood of 2,360,000 cubic feet per second (cfs) at the mouth of the Arkansas River and 3,030,000 cfs at the mouth of the Red River. These figures were about 11% greater than the record 1927 flood at the junction of the Mississippi and Arkansas Rivers and 29% greater than 1927 flood at the junction of the Mississippi and Red Rivers, 60 miles downstream of Natchez, MS.

The Jadwin Plan proposed four major elements to control the flow of the Mississippi River. These were: 1) levees to contain flood flows wherever practicable, or necessary to avoid razing large sections of existing cities and transportation infrastructure; 2) bypass floodways to accept excess flows of the river, passing these into relatively undeveloped agricultural basins or lakes; 3) channel improvements intended to stabilize river banks, to enhance slope stability and commercial navigation; and 4) improvements to tributary basins, wherever possible. This category included dams for flood storage reservoirs, pumping plants, and auxiliary channels.

The main stem levees (Figure 4.7) were intended to protect the Mississippi alluvial valley against flooding by confining the river to its low flow channel. The main stem, or so-called "federal levees," extend 1,607 miles along the Mississippi River, with another 600 miles along the banks of the lower Arkansas, Red, and Atchafalaya Rivers.

A vexing problem with maintaining 1,552 miles of flood control levees in the lower Mississippi Valley has been the complex and ever-changing foundations upon which they are founded (Figure 4.7). In addition, channel curvature promotes undercutting the outboard banks of bends, often depositing these materials in semi-linear stretches of channel a short distance downstream, because of lower gradients. This sediment reduces freeboard and raises flow levels, often beyond design assumptions. Crevasses are often sand-filled distributary channels that form preferred seepage paths beneath the flood plain during high flow. These high permeability corridors lie beneath earthen levees like ticking time bombs, waiting to explode (areas indicated by red arrows on Figure 4.8).

The 1928 Jadwin Plan also sought to emplace storage facilities wherever practicable in the four principal watersheds bordering the lower Mississippi Valley: the St. Francis Basin in southeastern Missouri and northeastern Arkansas; the Yazoo Basin in northwestern Mississippi; the Tensas Basin in northeastern Louisiana; and the Atchafalaya Basin in southern Louisiana. Five flood control reservoirs were constructed in these basins as part of the MR&T Project: Wappapello Dam and Reservoir in the St. Francis Basin; and four dams in the Yazoo Basin: Arkabutla, Sardis, Enid, and Grenada.

Bypass floodways were constructed by the Corps of Engineers. These included: 1) the Birds Point-New Madrid Floodway between Cairo, IL and New Madrid, MO (which depends on a fuse plug levee in lieu of a spillway; only used once, in 1937); 2) The Old River or Red River Landing Diversion structure, intended to divert half the project flood (1,500,000 cfs) from the main channel into the Atchafalaya River through the Morganza and West Atchafalaya floodways; 3) The Bonnet Carré bypass and floodway, a concrete spillway capable of diverting 250,000 cfs into Lake Pontchartrain during periods of high flow, about

30 miles upstream of New Orleans. The locations of MR&T structures in proximity of New Orleans are shown on Figure 4.9.

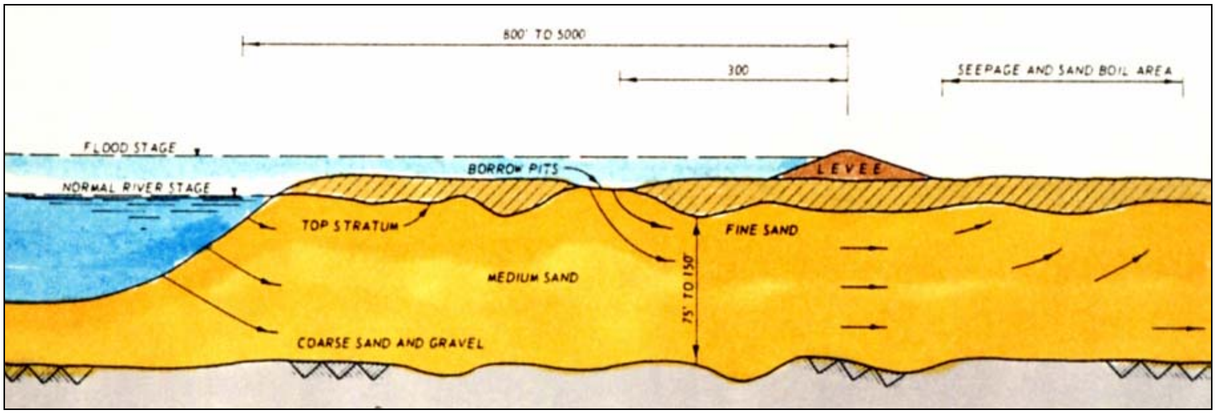

Figure 4.7: Cross section through a typical Corps of Engineers levee in an alluvial valley (from Mansur and Kaufman, 1956). Analyses of levee stability depend in large measure on various assumptions made about seepage conditions beneath and adjacent to such structures. For instance, the coarse sand and gravel shown here may be 1000x more permeable than the overlying medium sand.

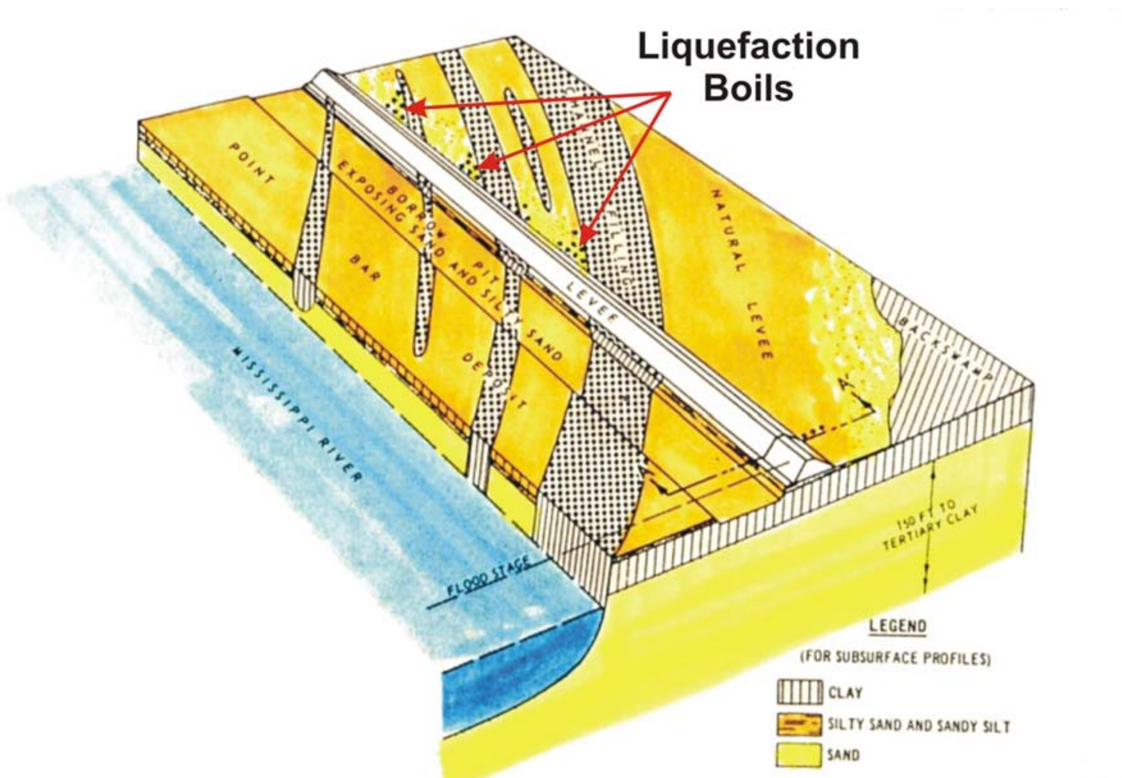

Figure 4.8: A major problem with man-made levees constructed during the MR&T Project is that they are necessarily constructed upon highly heterogeneous foundations, as portrayed here (taken from Kolb, 1976). The sharp contrast between highly organic channel fills (stippled zones) and natural levee sands and gravelly point bars promotes dangerous concentrations of seepage and differential settlement.

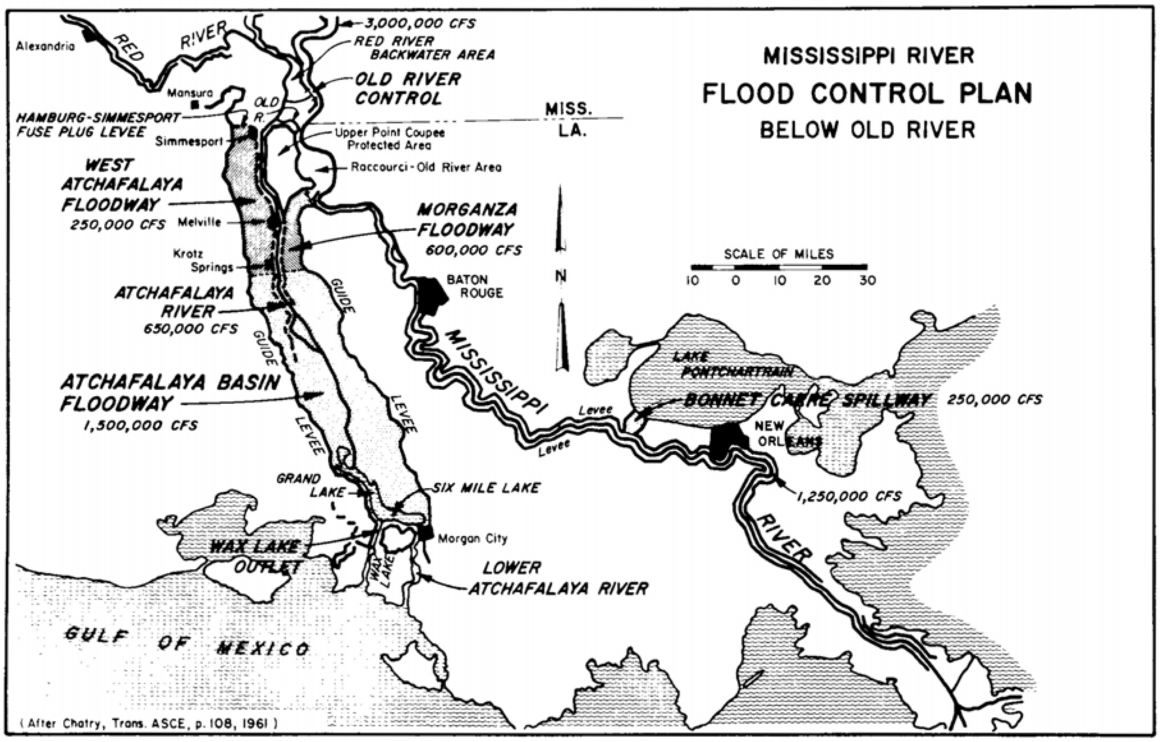

Figure 4.9: Map showing principal elements of the Mississippi River & Tributaries Project flood control for the lower Mississippi River Delta region (from Chatry, 1961). Note the much shorter flow channel to the Gulf of Mexico along the Atchafalaya River as opposed to the Mississippi River. The Mississippi River would have switched to this channel by 1975 if the Old River Control Structure had not been constructed in 1961-63.

This was followed numerous Channel improvement and stabilization measures have been implemented as needed along the entire course of the navigable river channel, to enhance river bank stability and commercial navigation. The Corps typically employs channel cutoffs to shorten the river channel and increase hydraulic grades, which reduces flood heights. They employ armored revetments to retard channel migration and meandering. Countless dikes have been employed to direct the river's flow, beneath the channel surface. Annual dredging is required to maintain navigable channels, as sediment is deposited by seasonal high flows. These activities have combined to reduce the annual sediment yield of the river by 60% (Kesel, 2003).

The Bonnet Carré bypass and Old River Control Structure (into the Atchafalaya Basin) are major elements of the MR&T Project that protect New Orleans from a Mississippi River flood by reducing the volume of flow that passes the city. The Bonnet Carré spillway was the first structural element of the MR&T Project to be constructed, in 1931, and initially used during the 1937 flood. It is opened up whenever the river level exceeds 19.0 to 19.6 ft in New Orleans and can draft off 25,000 cfs into Lake Pontchartrain.

The Old River Control Structure was not authorized by Congress until 1954. It was intended to draft off 600,000 cfs of the Mississippi's flow during an extreme flood event and prevent capture of the Mississippi River by the Atchafalaya River, which would have occurred naturally by 1975 (because the flow distance of the Atchafalaya to the Gulf of Mexico is only one-third the distance taken by the present channel of the Mississippi; see Fisk, 1952 and McPhee, 1989). The Corps constructed the Old River Control Structure and lock from 1961-63. The project was intended to divert 30% of the Mississippi River Project Flood into the Atchafalaya Basin. The Old River Control Structure has only been used once, during the Flood of 1973, when it nearly failed catastrophically (MRC, 1975; Noble, 1976). In the wake of this failure, the capacity was doubled with construction of an auxiliary structure, completed by the Corps of Engineers in 1986, doubling the bypass capacity at Old River into the Atchafalaya-Morganza Basin to 1,220,000 cfs.

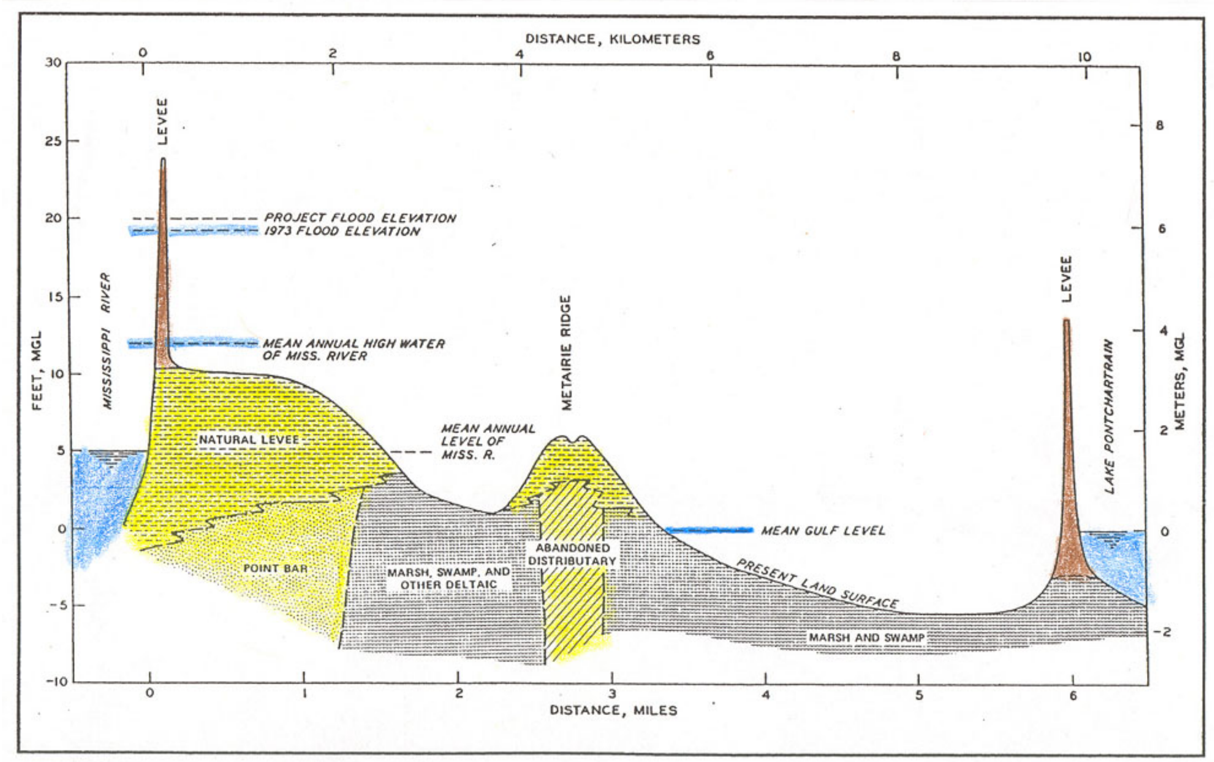

Figure 4.10: This cross section illustrates how much of New Orleans lies below mean gulf level, requiring every drop of rain water to be pumped out. The height of the Mississippi River levee is 24.5 ft while the Lake Pontchartrain levee crests at 13.5 ft (from Kolb and Saucier, 1982).

The average height of the MR&T levees above the natural levees in the Gulf Region is about 16 ft (Kolb and Saucier, 1982). The crest of the flood protection levee along the eastern bank of the Mississippi River is 24.5 feet MGL at Carrolton in New Orleans, as shown in Figure 4.10. The Lake Pontchartrain protection levee is 13.5 feet MGL, as shown in Figure 4.10. All of the neighborhoods north of Metairie Ridge lie below sea level. The worst flooding scenario for New Orleans would be a breach of the Mississippi River levee because of its elevated position, which would engender rapid erosion and high spill velocities, which could overwhelm the City's lowest neighborhoods before residents could affect an escape.

From its inception the 1928 Flood Control Act has been modified every few years by additional authorizations from Congress, usually based on modifications requested by the Corps of Engineers. These included expenditures for establishment of an emergency fund for maintenance and rescue work (1930) and acquisition of lands for floodways, etc. These early changes resulted in the Flood Control (Overton Act) Act of 1936, which established a national flood control policy to be administered by the Corps of Engineers, beyond the lower Mississippi Valley. Even with these sweeping changes, more acts followed in quick succession throughout the late 1930s and 1940s (for instance, a 1937 act authorized $52 million for strengthening of levees following the disastrous 1937 flood in the Ohio and Mississippi Valleys). This pattern of amended flood control acts and authorized expenditures continued throughout the 1940s, 50s, 60s, and 70s, usually following flood years.

Today, 3,714 miles of flood control levees have been authorized for construction under the Mississippi River & Tributaries Project. 3,410 miles of levees have been completed and 2,786 miles are in place to grade and section. On the main stem of the Mississippi River, 1,602 miles of levees have been completed. Work on the main stem levees of the Mississippi River is approximately 89 percent complete wand work on tributary levees is approximately 75 percent complete.

The breaches of August 29, 2005 during Hurricane Katrina occurred near the lowest possible elevations of the city, which retarded peak inflows to very low values, allowing residents to literally walk out of the neighborhoods, had they chosen to do so (most had already evacuated the city).

4.3.1 Dimensions of navigation channels maintained by the Corps of Engineers on the lower Mississippi River

Over the next 60 years Congress added new river borne transport projects, extending up the Mississippi drainage, and elsewhere, creating an intricate system of barge commerce that demands constant maintenance, clearing, patching, and dredging. In addition to insuring flood protection, the Corps of Engineers was also charged with maintaining year-round navigation for the Port of New Orleans, which was the nation’s second largest port facility when MR&T project work commenced in 1931.

After the mouths of the Mississippi River had been opened and maintained in a navigable state (the first jetty was completed in 1879), navigation interests lobbied Congress to establish and maintain "feeder" channels to the Mississippi River and deepen the main stem channel to accommodate more modern vessels, with deeper draft. In 1945 Congress authorized the development of a navigation channel for oceangoing traffic in the lower reaches of the Mississippi River. Over the past 60 years this system has been expanded greatly through a series of Congressional acts, until today it consists of 12,350 miles of navigable inland waterways. The depths and widths of the Mississippi River channel between Baton Rouge and the Gulf of Mexico have been established as:

- Baton Rouge to New Orleans - 40 by 500 feet
- Port of New Orleans - 35 by 1,500 feet, with portion 40 by 500 feet
- New Orleans to Head of Passes - 40 by 1,000 feet
- In Southwest Pass - 40 by 800 feet
- In Southwest Pass Bar Channel - 40 by 600 feet
- In South Pass - 30 by 450 feet
- In South Pass Bar Channel - 30 by 600 feet
- Mississippi River-Gulf Outlet - 36 by 500 feet
- Mississippi River-Gulf Outlet Bar Channel - 38 by 600 feet

4.4 Flooding of the New Orleans Area by Hurricanes

Hurricanes strike the Louisiana Coast with a mean frequency of two every three years (Kolb and Saucier, 1982). Since 1559, 172 hurricanes have struck southern Louisiana (Shallat, 2000). Of these, 38 have caused flooding in New Orleans, usually via Lake Pontchartrain. Some of the more notable events have included: 1812, 1831, 1860, 1893, 1915, 1940, 1947, 1965, 1969, and 2005.

In 1722 a hurricane destroyed most of embryonic New Orleans and raised the river by 8 feet. Had the river not been running low prior to the storm, the river might have overtopped its banks by as much as 15 feet. In 1778, 1779, 1780 and 1794 hurricanes struck the New Orleans area destroying many buildings and sinking ships. The worst storm of the early ear was "The Great Louisiana Hurricane" of August 9, 1812. It rolled over the barrier islands and drowned Plaquemines and St. Bernard Parishes and the area around Barataria Bay under 15 feet of water. The parade ground at Fort St. Phillip was inundated by 8 feet of water and the shoreline along Lake Pontchartrain was similarly inundated, though this was far enough below the French Quarter to spare any flooding of the City.

The back side of New Orleans was afforded some natural protection by the Metairie, Gentilly, and Esplanade Ridges, which are recent distributary channels of the Mississippi River. These "ridges" were originally about 4 feet higher than the surrounding marshland, but much of the former cypress swamps and marshes (comprised of compressible peaty soils) have settled as much as 10 feet over the past 110 years , while the ridges, being underlain by sand, have only settled 1 to 2 feet. The ridges performed as quasi flood protection levees from storm surges emanating from Lake Pontchartrain during hurricanes. But, the ridge also prevented drainage from moving between the old French Quarter and Lake Pontchartrain.

The Carondelet, or Old Basin, canal was excavated between Basin Street and Bayou St. John, which formed the one low point between the elevated Metairie and Gentilly Ridge channels. The Old Basin Canal drained the French Quarter and allowed smaller craft to transit through the ridge to Lake Pontchartrain.

In June 1821 easterly winds surged off Lake Pontchartrain and pushed up Bayou St. John, flooding fishing villages and spilling into North Rampart Street until the winds abated and allowed the water to drain back into the lake. It was an ominous portent of things to come.

On August 16, 1831 "The Great Barbados Hurricane" careened across the Caribbean, striking the Louisiana coast west of New Orleans. The area south of town was again inundated by storm surge, while a three foot surge entered the city from Lake Pontchartrain. The Mississippi levee at St. Louis Street gave way, flooding the French Quarter. Heavy rains accompanying this storm added to the flooding and boats were the only means of moving about for several days.

Southeastern Louisiana suffered through three hurricanes during the summer and fall of 1860. On August 8th a fast moving hurricane swept 20 feet of water into Plaquemines Parish. The third hurricane struck on October 2nd making landfall west of New Orleans. It inundated Plaquemines, St. Bernard, and Barataria, causing a significant storm surge in Lake Pontchartrain which destroyed 20 lakeside settlements, washing out a portion of the New Orleans and Jackson Great Northern Railroad. Surge from this storm overtopped the banks of the along the Old and New Basin drainage canals and a levee along Bayou St. John gave way, allowing the onrushing water to flood a broad area extending across the back side of New Orleans.

Between 1860 and 1871 the city avoided serious flooding problems caused by hurricanes. In 1871 three hurricanes caused localized flooding, which proved difficult to drain. Flooding emanating from storm surges on Lake Pontchartrain during these storms overtopped the Hagen Avenue drainage canal between Bayou St. John and New [Basin] Canal, spilling flood waters into the Mid-City area. City Engineer W. H. Bell warned the city officials about the potential dangers posed by the drainage canals leading to Lake Pontchartrain, because the Mid-City area lay slightly below sea level (as seen on the 1895 Brown map in Figure 3.17).

The record hurricane of October 2, 1893 passed south of New Orleans generated winds of 100 mph and a storm surge of 13 feet, which drowned more than 2,000 people in Jefferson Parish, completely destroying the settlements on the barrier island of Cheniere Caminada. This represented the greatest loss of life ascribable to any natural disaster in the United States up until that time. Seven years later, in August 1900, a hurricane passed directly over Galveston, TX, demolishing that city and killing between 6,000 and 8,000 people, which remains the deadliest natural disaster in American history. Prior to impacting Galveston, that hurricane tracked westerly parallel to the Gulf Coast about 150 miles south of New Orleans. Its flood surges were noted along the Gulf Coast, including Lake Pontchartrain's south shore (Cline, 1926).

Prior to Katrina's landfall in 2005, the most damaging hurricane to impact New Orleans was the Grand Isle Hurricane of September 29, 1915, a Category 4 event which produced winds as great as 140 miles per hour (mph) at Grand Isle. It slowed as it made landfall and eventually passed over Audubon Park, seriously damaging structures across New Orleans. Electrical power was knocked out, preventing the City's new pumps from functioning. The storm surge on Lake Pontchartrain rose to 13 ft, easily overtopping 6-foot high shoreline levee and destroyed the lakefront villages of Bucktown (at end of 17th Street Canal), West End, Spanish Fort, and Lakeview (these lakeside settlements were swallowed up by the infilling of the Lake Ponchartain shoreline in 1928-31). The drainage canals were also overtopped, flooding the city behind Claiborne, leaving Mid-City and Canal Street under several feet of water. This storm overwhelmed the City's defenses so quickly that 275 people were killed, mostly in the Lake Pontchartrain shoreline zone.

On September 19, 1947 an unnamed hurricane made landfall near the Chandeleur Islands, producing wind gusts between 90 and 125 mph, with 1 minute maximum of 110 mph. A storm surge of 9.8 ft reached Shell Beach on Lake Borgne. The runways at Moisant Airport were covered by 2 ft of water while Jefferson Parish was flooded to depths of 3+ ft. Sewage from an overwhelmed City treatment plant stagnated in some of the drainage canals, producing sulfuric acid fumes that nearby homes in the Lakeview area painted with lead-based paint turned black. 51 people drowned and New Orleans suffered $100 million in damages. City officials were unable to clear floodwaters through the drainage canals in the Lakeview, Gentilly, and Metairie neighborhoods for nearly two weeks. This was the first significant hurricane to strike New Orleans which generated a large body of reliable storm surge data, which was subsequently used in design of flood protection works by the Corps of Engineers (Figure 4.11). The New Orleans Times-Picyaune prepared a map that showed reported depths and locations of flooding in the 1947 hurricane.

After the 1947 storm, hurricane protection levees were heightened along the south shore of Lake Pontchartrain and extended westward, across Jefferson Parish (constructed in 1949). In addition, the embankments along the old drainage canals were raised by earthfill to protect the Orleans and Jefferson Parishes from future storm surges off Lake Pontchartrain. The precise height of these additions depended on position and historic settlement up till that time. The entire Lakeview area north of what is now Interstate 610 (excluding the area filled by the Lakefront Improvement Project) was already <-2 ft below sea level by the late 1930s (WPA-LA, 1937).

Hurricane Betsy was a fast moving storm that made landfall at Grand Isle, LA on September 9-10, 1965. Wind meters at Grand Isle recorded gust of up to 160 mph and a 15.7 ft storm surge that overwhelmed the entire island. Winds gusts up to 125 mph were recorded in New Orleans along with a storm surge of 9.8 ft, which overwhelmed both sides of the Inner Harbor Navigation Canal (IHNC), flooding the Ninth Ward, Gentilly, Lake Forest, and St. Bernard Parish areas (Figure 4.12), as well as all of Plaquemines Parish, causing the worst flooding since 1947, and revealing inadequacies in the levee protection system surrounding the city. 81 people were killed by the storm (58 in Louisiana), which was the first natural catastrophe in America to exceed $1 billion in damages (USACE, 1965). Damage in southeast Louisiana totaled $1.4 billion, with $90 million of that being to New Orleans.

In October 1965 Congress approved a $2.2 billion public works bill that included $250 million for Louisiana projects and $85 million down payment for a system of levees and barriers around New Orleans (Figure 4.13). This work included raising the Lake Pontchartrain levee to a height of 12 ft above Mean Gulf Level (MGL) in response to the flooding caused by Betsy. The Orleans Levee Board also let contracts to pound steel sheetpile walls along the crests of their drainage canal levees to increase their effective height, so storm surges on Lake Pontchartrain would not overtop the drainage canals (which had occurred in 1915, 1947, and 1965, but without catastrophic loss of the canal levees). The uncased sheetpiles were intended to be a temporary measure, awaiting a permanent solution that envisioned placement of concrete flood walls using the sheetpiles as their foundations, funded by the Federal government. These short-term improvements spared the city from similar flooding in 1969 when Hurricane Camille struck the area.

Prior to Katrina, the only other Category 5 hurricane to make landfall on the United States was Hurricane Camille in August 1969 (the atmospheric pressure on landfall was second only to the Labor Day Hurricane of 1935). Camille made landfall on August 17th, its eye crossing the Mississippi Coast at Pass Christian, about 52 miles east northeast of New Orleans. Wind velocities in the eye of the storm reached 190 mph, while gusts on land exceeded 200 mph, casing most wind meters to fail (the highest recorded gust was 175 mph). Camille annihilated the coastal communities between Henderson Point and Biloxi, and caused extensive flooding 3,900 mi^2 of coastal lowland between lower Plaquemines Parish and Perdido Pass, AL. The peak storm surge measured 25 feet above MGL near Pass Christian, MS (a record), 15 ft in Boothville, LA, 9 ft in The Rigolets, and 6 ft in Mandeville, LA. The death toll form Camille was 258 people, with 135 of these being from the Mississippi coast (9 were killed in Louisiana). 73,000 families either lost homes or experienced severe damage and the official damage toll was $1.4 billion, with damages in Louisiana totaling $350 million. A particularly vexing aspect of Camille was that it occurred just four years after Hurricane Betsy, which had been touted as something between a 1-in-200 to 1-in-300 year recurrence frequency event (USACE, 1965).

On September 28, 1998 Hurricane Georges wrecked havoc across the Caribbean, pummeling Haiti, the Dominican Republic, Puerto Rico and other islands. Georges appeared to be headed straight for New Orleans, but suddenly turned east, making landfall near Biloxi, MS on September 28th (about 68 miles east northeast of New Orleans). Georges produced sustained winds of over 100 mph at landfall, generating a storm surge of 8.9 ft at Point à la Hache, LA. Maximum storm surge along the Gulf Coast was 11 ft, in Pascagoula, MS. Hurricane Georges severely eroded the Chandeleur Islands in outer St. Bernards Parish.

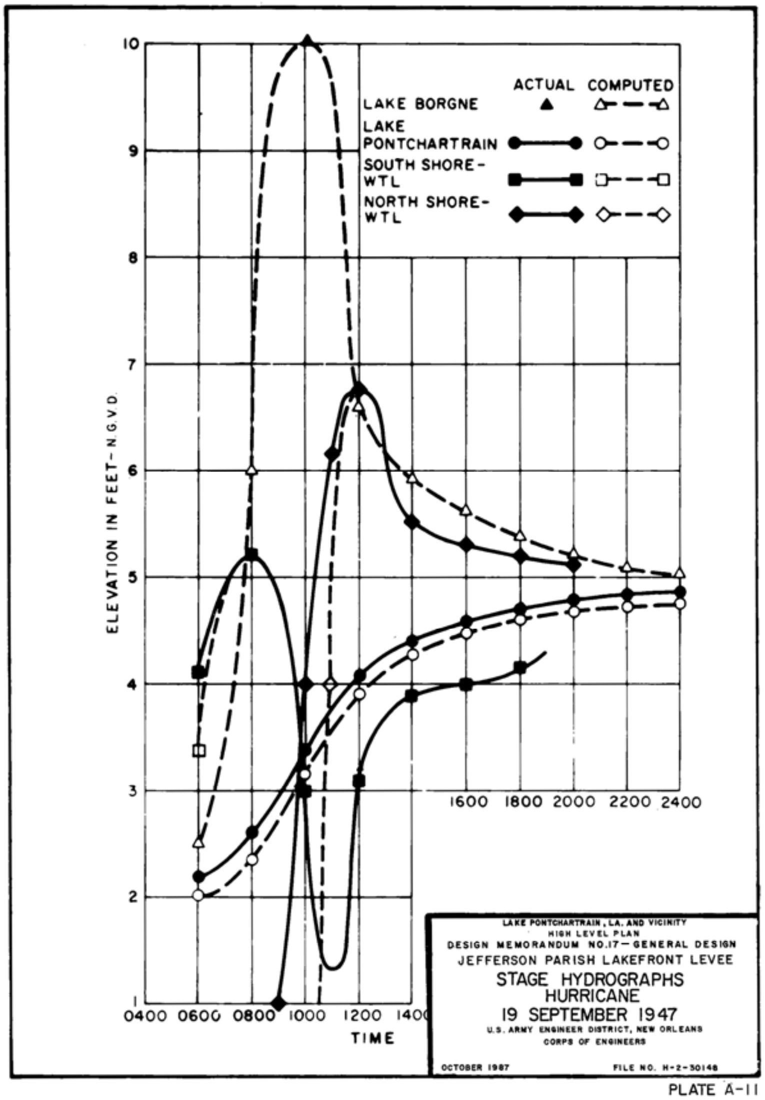

Figure 4.11: Stage hydrographs on Lakes Borgne and Pontchartrain from the September 1947 hurricane (from USACE DM-17, 1987). The 10 foot surge on Lake Borgne was the highest recorded value up to that time, though short-lived. A 13 foot surge was reported along lake Pontchartrain duiring the 1915 Grand Isle Hurricane, but this was before storm surge recorders were emplaced along the shorelines.

Despite forewarnings and evacuation orders 460 people were killed, all outside of Louisiana. Dozens of camps not protected by levees were destroyed along the south shore of Lake Pontchartrain. Hurricane Georges provided the last pre-Katrina test of the vulnerability of New Orleans levee protection system to hurricanes, and efforts resumed to improve the levee system along the canals that connect the city with Lake Pontchartrain.

Figure 4.12: Portion of the flood inundation map from Hurricane Betsy in 1965, showing the areas on either side of the Inner Harbor Navigation Channel which were affected by overtopping, from storm surges on Lakes Borgne and Pontchartrain (from USACE, 1965).

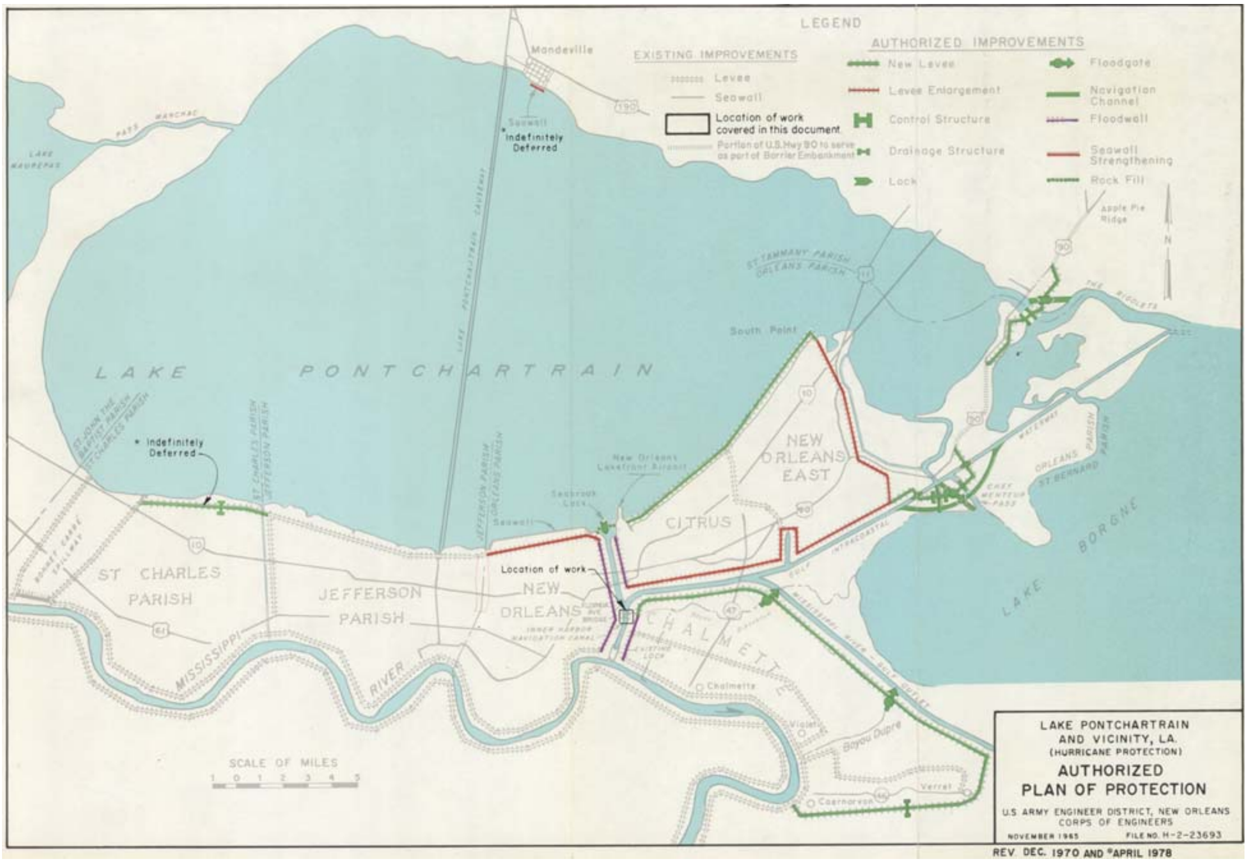

Figure 4.13: South Lake Pontchartrain flood protection measures authorized by Congress in the wake of Hurricane Betsy in 1965. These included heightening of the protective levees along the IHNC and the Lake Pontchartrain shoreline to the Orleans-Jefferson Parish boundary, and around Chalmette in St. Bernard's Parish. This system was subsequently enlarged to include the Pontchartrain levee all the way to the Bonne Carré Spillway and along the principal drainage canals in New Orleans and Jefferson Parishes.

4.5 Flooding of New Orleans caused by intense rain storms

As mentioned previously, the New Orleans area receives an average of about 52 cumulative inches each year. In the winter of 1881 severe rainstorms caused flooding of the downtown area, up to 3 feet deep. Rain storms of severe intensity also caused significant flooding of New Orleans in 1927, 1978 and 1995.

The 1927 storm dumped 14 inches on Good Friday, overwhelming Sewerage & water Board's vaunted system of Wood pumps, at least temporarily. Uptown streets were flooded, with the Broadmoor and Mid-City areas inundated by 6 feet of water and 2 feet in the old French Quarter. This storm occurred simultaneously with the onset of the record high flows along the lower Mississippi River, which lasted almost six months.

On May 3, 1978 a line of rain squalls approaching New Orleans from the west became stalled over the city when it intersected a stationary front sitting over Lake Pontchartrain. The resulting storm dropped 10 inches of rain during the morning, with a peak sustained intensity of two inches per hour rain. The runoff exceeded the aggregate capacity of the city's pumps operated by the S&WB, causing extensive flooding of low lying areas that lasted about 24 hours.

A series of intense rain storms struck Louisiana, Mississippi, and Alabama in two consecutive sequences in March and April of 1980. The first storm occurred from March 26 to April 2nd, striking southeastern Louisiana and portions of Mississippi. The second storm sequence rolled through the same area from April 11 to April 13, affecting much of Mississippi, but especially intense in the area bounded by Baton Rouge and New Orleans to Mobile, Alabama. The 2-hour rainfall in Mobile on April 13 had a recurrence interval of 100 years. As a result of this rainfall, Mobile experienced the worst flash floods in the city's history. In New Orleans flood waters being pumped into the London Avenue Canal overtopped the eastern side of the Canal just south of Robert E. Lee Boulevard, where steel sheetpiles providing additional flood freeboard had recently been removed. This was the same portion of the northern London Avenue Canal which subsequently experienced incipient failure during Hurricane Katrina in 2005, moved two feet laterally (the area shown in Figure 4.20 - upper).

On the evening of May 8-9, 1995 a cold front approaching New Orleans from the west staled after moving east of Baton Rouge. A nearly continuous chain of thunder storms befell the New Orleans area, dropping 4 to 12 inches of rain across New Orleans. The storm's intensity overwhelmed the S&WB's pump capacity (47,000 cfs) and almost the entire city experienced severe flooding, including the Interstate highways. More severe storms struck the coast the following evening, but was not as severe over New Orleans proper, though the two day totals reached a record 24.5 inches in Abita Springs, LA. The 1995 storm sequence had a duration of 40 hours and damaged 44,500 homes and businesses, causing $3.1 billion in damages. This was the costliest single non-tropical weather related event to ever affect the United States.

4.6 New Orleans Drainage Canals

The drainage canals of New Orleans are a unique feature of the bowl-shaped city that are much older than most people realize. The city's first drainage canal was the Old Carondelet Canal originally excavated in 1794, by order of Spanish Governor Baron de Carondelet. It was dug by convicts and slaves and it was later enlarged to accommodate shallow draft navigation (row boats and keel boats) between the City and Lake Pontchartrain. Its name was later changed to the Basin Canal because it terminated at Basin Street, in the French Quarter. Its name was later changed to the Old Basin Canal. It was infilled in the 1920s, when it became Lafitte Avenue and railroad tracks were placed down the street's centerline. Figure 4.14 shows the systems of drainage ditches and canals established by 1829, leading to Bayou St. John.

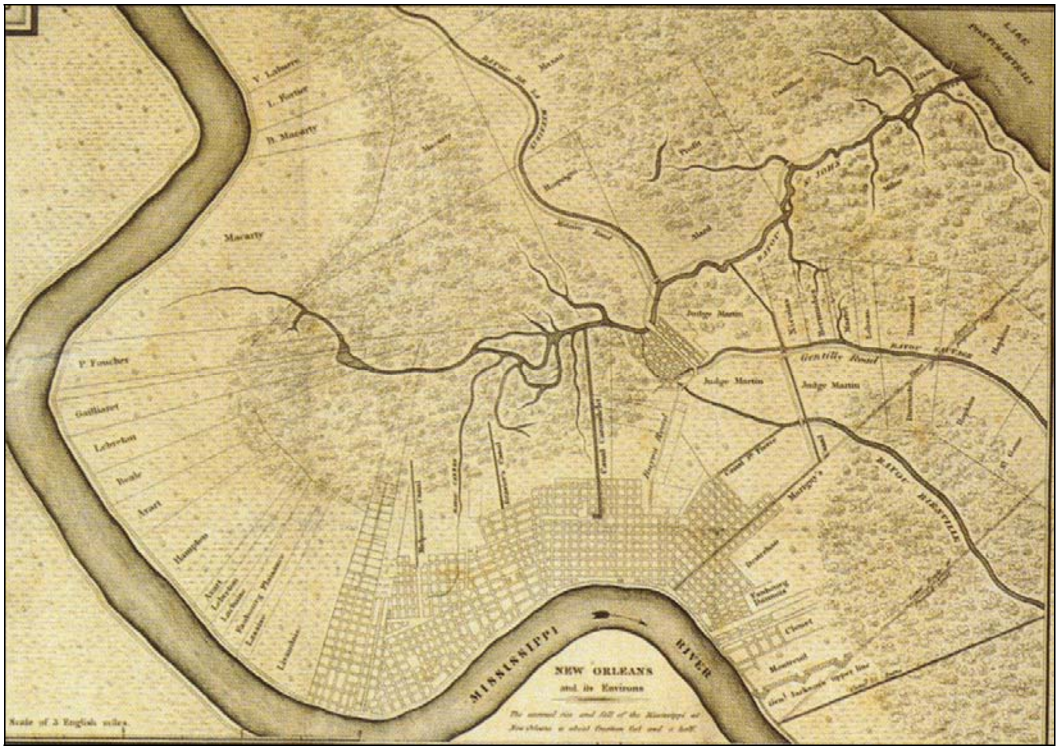

Figure 4.14: Plan of the City of New Orleans prepared by Francis Ogden in 1829. Note the linear drainage canals feeding into Bayou St. John, thence into Lake Pontchartrain (from the Historic New Orleans Collection).

The New Basin Canal was excavated by Irish immigrants in the early 1830s in the American Sector, but an outbreak of yellow fever killed 10,000 workers. The New Orleans City Railroad paralleled this canal in post Civil War era. The New Basin Canal was the first to cut through Metairie Ridge. The severing of Metairie Ridge was a double edged sword, as flood waters came up the Old Basin Canal and inundated the downtown area in 1871. The portion south of Metairie Ridge was filled in the 1930s; and the remainder in the 1950s, with the Pontchartrain Expressway replacing the old canal.

The six piece Topographic Map of New Orleans and Vicinity prepared by Charles F. Zimpel in 1833-34 suggest that portions of the Orleans Canal had been excavated and were proposed to be extended by that date to convey water from Bayou Metairie to Lake Pontchartrain (Lemmon, Magill, and Wiese, 2003). The Turnpike Road ran along the west side of this canal. In 1835 the New Orleans Drainage Company was given a 20-year charter by the city to drain the cypress swamps between the riverbank and Lake Pontchartrain. The company consulted State Engineer George T. Dunbar and evolved a scheme to drain the area using underground canals beneath prominent uptown streets which would collect water and convey it down the natural slope to the Clairborne Canal and then to the newly completed Orleans Canal (then called the Girod Canal) into Lake Pontchartrain. This ambitious scheme was derailed by the financial panic of 1837, though a system of ditches were completed which conveyed runoff from the French Quarter to the upper Orleans Canal, from which it had to be transferred to Bayou St. John using steam-powered pumps.

A review of historic maps (Figures 4.15 thru 4.17) suggests that the Upper Line Protection Levee or 17th St. Canal along the Orleans-Jefferson Parish boundary was excavated between 1854 and 1858 (shown as completed). The 17^{th} Street Canal is not indicated on the 1853 Pontchartrain Harbor and Breakwater Map, although the Jefferson and Lake Pontchartrain Railroad is shown along the Orleans-Jefferson Parish boundary. The 1858 map shows 17^{th} Street canal just east of the railroad tracks and the new village of Bucktown, along the shore of Lake Pontchartrain adjacent to the mouth of the 17^{th} St. Canal. The 1878 Hardee map (Figure 4.17) calls the 17^{th} St. Canal the “Upper Line Protection Levee and Canal.” 17th Street was renamed Palmetto Avenue in 1894. The early rail lines serving the docks on Lake Pontchartrain remained in operation for many years after the Civil War (Figure 4.16).

Disastrous outbreaks of yellow fever in the 1850s spurned new ideas to drain the cypress swamps. Between 1857-59 City Surveyor Louis H. Pilié developed a drainage plan using open drainage canals with four steam-powered paddle wheel stations to lift collected runoff into brick-lined channels throughout lower New Orleans, which was poorly drained because the Metairie-Gentilly Ridge presented a natural barrier between the downtown slope and Lake Pontchartrain (Figure 4.18). In 1858 the Louisiana Legislature divided the city into four “draining districts,” providing a commission for each district and a method of assessment for the operation and maintenance of drainage facilities. These names of these were the New Orleans First and Second, Jefferson City, and Lafayette Draining Districts (Beauregard, 1859). In 1859 the legislature mandated issuance of 30-year bonds totaling $350,000 for each of the four districts. This allowed a program of local taxation to fund the pumps and maintain the four lift stations were called “draining machines.”

These steam-powered pumping machines were located at: the Dublin machine at the head of the New Canal (old 17^{th} St.) at Dublin and 14^{th} Streets; the Melpomene machine at the head of the Old Melpomene Canal (at Melpomene and Claiborne); the Bienville machine at the head of Bayou St. John (at Hagan and Bienville); and the London machine (just north of Gentilly and London Avenues). These facilities became a city trademark for many years thereafter. Shortly before the outbreak of the American Civil War in 1861, the legislature passed another bill that allowed any of the draining districts to make special assessments to make necessary repairs, based on the recommendations of their respective boards.

Figure 4.16 is a portion of the Map of New Orleans area completed under direction of Brigadier General Nathaniel P. Banks of the Union Army in February 1863, during the American Civil War. This map shows the position of the Jefferson and Lake Pontchartrain Railroad along the 17^{th} St. Canal alignment, but not the canal itself. It also shows the New Basin Canal (a short distance east), the upper Orleans Canal, feeder canals emptying into Bayou St. John, and the Pontchartrain Railroad (near today’s IHNC), which operated between 1831-1932, its northern terminus being named Port Pontchartrain.

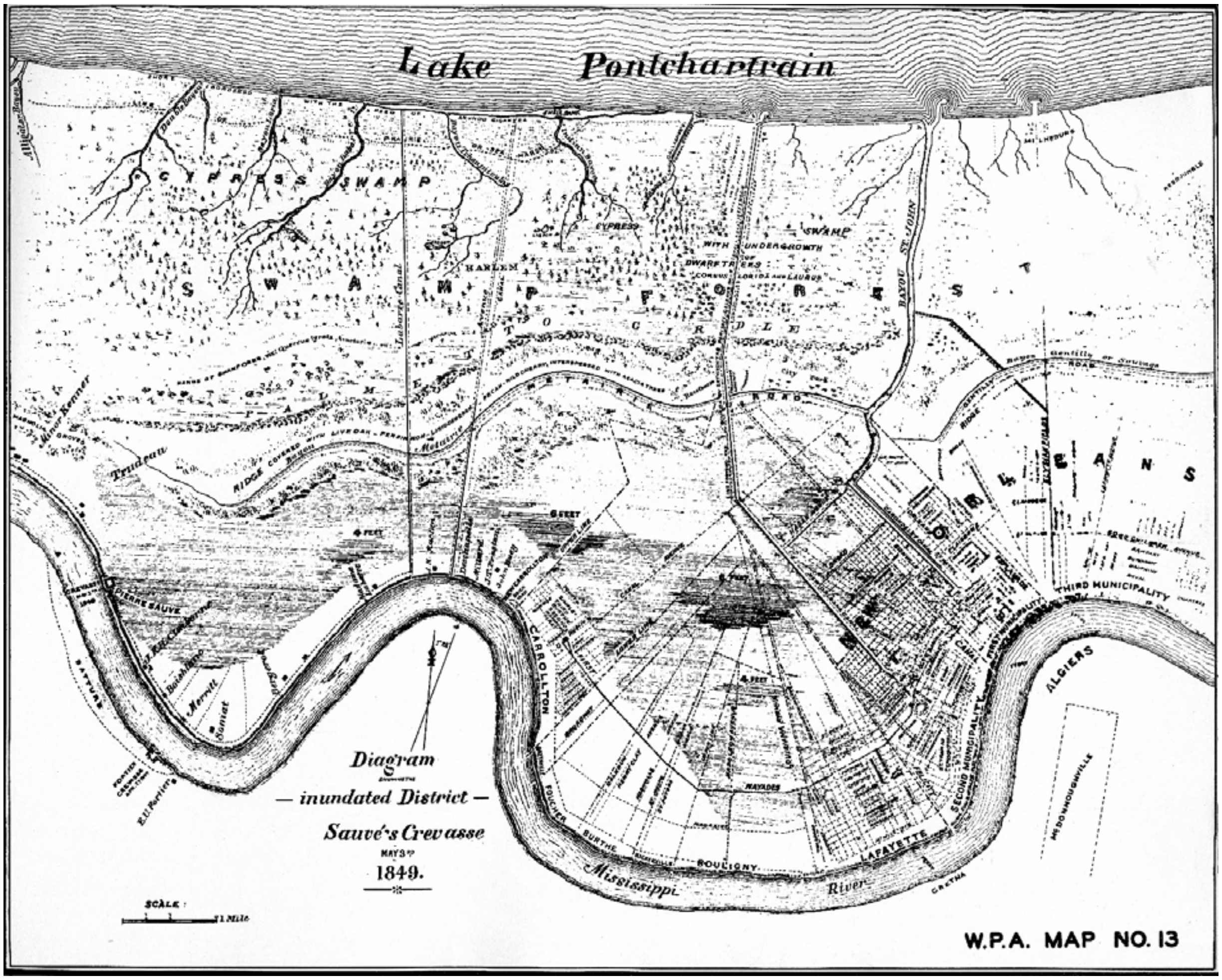

Figure 4.15 - Map of Sauvés Crevasse and the portions of New Orleans inundated by the flooding of 1849, the last significant flood to affect the city emanating from the Mississippi River. This 1849 map shows the extensive cypress swamps lying between the uptown and French Quarter areas and Lake Pontchartrain. The Carondelet and New Orleans Canals are clearly shown, but curiously omits the New Basin Canal (built in the 1830s). The map clearly shows the projected path of the 17th Street Canal between Orleans and Jefferson Parishes, suggesting it was being proposed (it appears to have been completed in 1857-58). The Labarre Canal in Jefferson Parish (near today's Bonnabel Canal) was likely never built (taken from WPA, 1937).

The upper end of the London Avenue Canal appears to have been constructed in the 1860s, north of Bayou Gentilly. One of the afore-mentioned steam-powered draining machines was located near the intersection of London and Pleasure Street, which lifted water from the upper London Canal into the cypress swamp near what is now Dillard University, north of Gentilly Ridge. Based on a comparison of the 1873 Valery Sulakowski map and the 1878 Thomas Hardee maps, the lower London Avenue Canal appears to have been extended out to Lake Pontchartrain sometime between 1873-78.

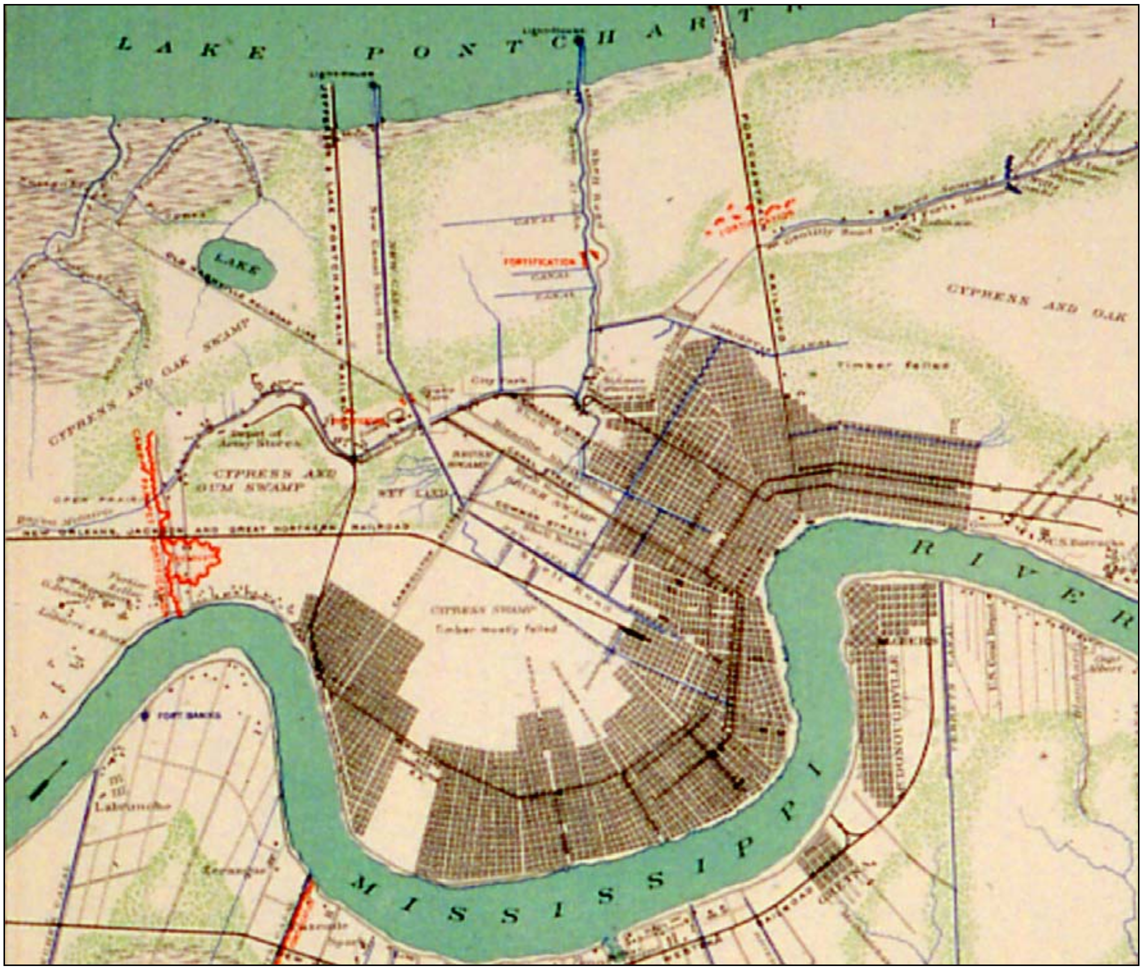

Figure 4.16: By 1863 there were a series of east-west feeder canals serving Bayou St. John from the west side and a series of north northeasterly trending drainage canals in St. Bernard Parish (from The Historic New Orleans Collection).

In 1878 City Engineer and Surveyor Thomas S. Hardee compiled the most accurate map of the City to that date, after a yellow fever epidemic that year which killed 4% of New Orleans' population (which brought to City's accumulated death toll to Yellow Fever in excess of 100,000 people). The map sought to delineate improvements for the city's drainage system to enhance sanitation. It would take another two decades before a substantive drainage plan eventually evolved.

New Orleans drainage dilemma can be appreciated from a review of the earliest cross section drawn through the city, reproduced in Figure 4.19. The Mississippi River's natural levees form the highest ground in New Orleans. The natural levee slopes northerly towards Lake Pontchartrain. This slope is interrupted by the Metairie-Gentilly Ridge, a geologically-recent distributary channel, lying between 3 and 6 feet above the adjacent swamp land.

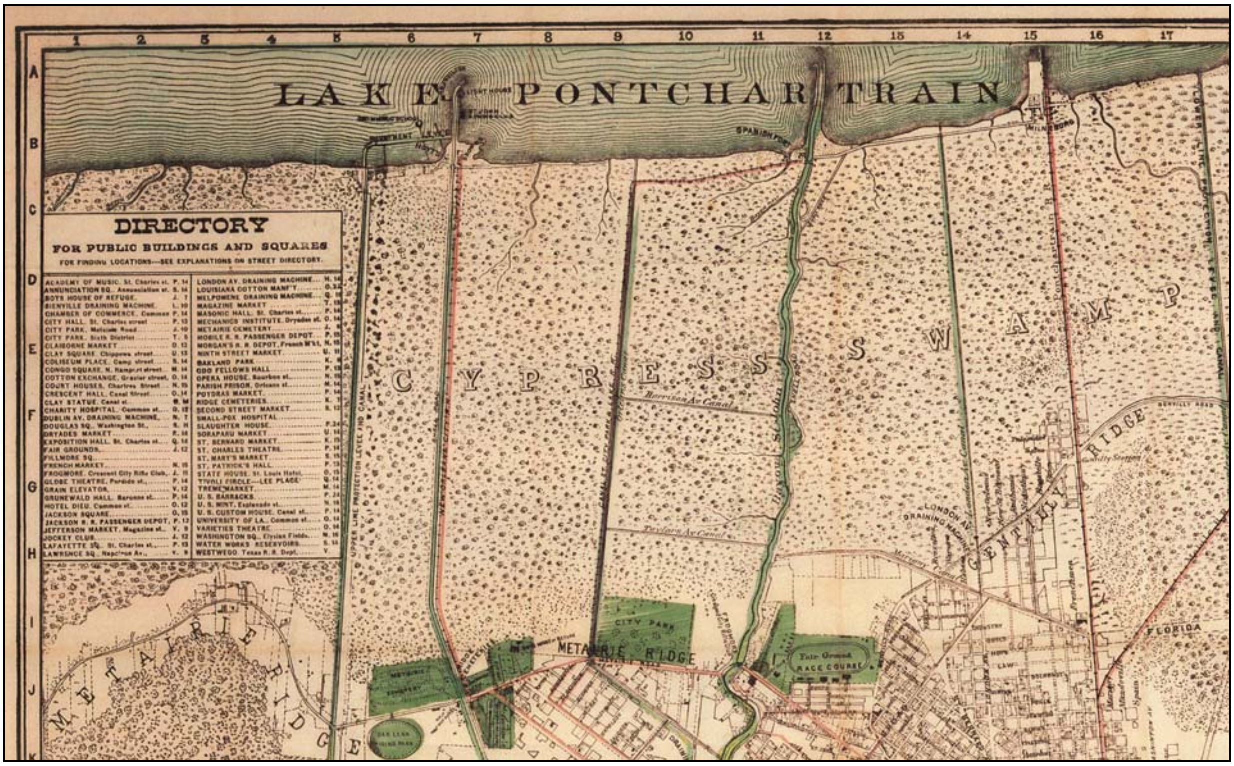

Figure 4.17: All 36 miles of drainage canals in the Lakeview and Gentilly areas are shown in this portion the 1878 Hardee Map (courtesy of The Historic New Orleans Collection). The canals are, from left: 17th Street, New Basin (infilled), Orleans, Bayou St. John, and London Avenue, and the Lower Line Protection Levee.

The protection levee along Lake Pontchartrain (Figure 4.19) was erected after the 1893 hurricane, which generated a storm surge of up to 13 feet (described in Section 4.4). This protective structure was known as the “shoreline levee” and was 6 feet above the normal surface of Lake Pontchartrain. The creation of this structure was a double-edges sword: it served to keep rising water from Lake Pontchartrain out of the city, but also prevented gravity drainage from the city into the Lake, except through drainage canals, into which runoff must be pumped to gain sufficient elevation to flow by gravity into the Lake. Discharge could not be conveyed to Lake Pontchartrain during hurricane-induced storm surges. The gravity of this problem was not fully appreciated until the 1915 Grand Isle Hurricane.

Figure 4.18 – Photo taken in 1890 looking north along the "shell road" than ran along the west side of the New Basin Canal, seen at extreme right. Note the modest height of the original embankment, no more than 5 feet above the adjacent cypress swamp at left. The original embankments were heightened after hurricane-induced overtopping in 1915 and 1947 (image from the University of New Orleans Special Collections, New Orleans Views).

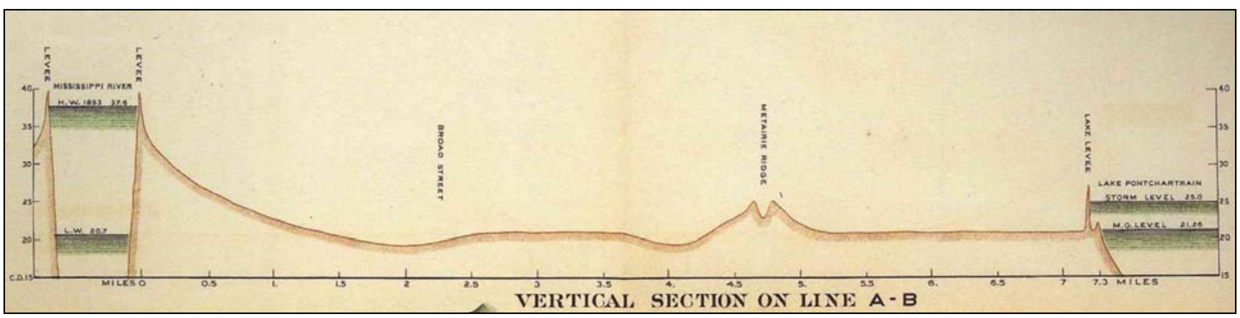

Figure 4.19: Cross section through New Orleans prepared by City Engineer L. W. Brown in 1895 (from the Historic New Orleans Collection). This shows the elevated position of the Mississippi River and the Metairie-Gentilly Ridge distributary channel, which lies 3 to 6 feet above the surrounding area. The green lines denote high and low levels in the river and Lake Pontchartrain. Elevations are in the old Cairo Datum (21.26 ft above MGL).

4.7 City Adopts Aggressive Drainage System

The failure of the Hagan Avenue Canal levee in 1871 signaled the beginning of a political crisis, hastened by hurricane-induced surges on Lake Pontchartrain. The City sought to consider a better solution than it had heretofore employed in providing for reliable drainage to Lake Pontchartrain, and vice versa. New Orleans City Surveyor W.H. Bell warned of the potential dangers posed by the big outfall drainage canals. He told city officials to place pumping stations on the lakeshore, otherwise "*heavy storms would result in water backup within the canals, culminating in overflow into the city*."

A new attempt to construct an integrated drainage system was undertaken by the Mississippi and Mexican Gulf Ship Canal Company, which excavated many miles of canals in New Orleans between 1871-78, before going out of business. By 1878 the City assumed responsibility for maintenance of a 36-mile long system of drainage canals feeding into Lake Pontchartrain. The city's old network of steam-powered paddle-wheel lift stations could only handle 1.5 inches of rainfall in 24 hours, which represented slightly more than a nominal 1-year recurrence frequency storm. This meant that the city began suffering flooding problems with increasing frequency because of insufficient runoff collection, conveyance, and pumping/discharge capacity.

The drainage problem was greatly exacerbated by a growing sewage treatment crisis. The City's population grew from about 8,000 in 1800 to nearly 300,000 residents by 1900. The need for space enticed development into the low lying cypress swamps, which were being reclaimed by construction of shallow drainage ditches feeding into the newly completed system of drainage canals. In the 1880s houses began to appear on the old marsh and swamp areas below Broad Street. No one regulated the inflow to the drainage canals and the abject lack of a modern sewerage collection, conveyance, treatment, and outfall system. Residents on the high ground near the Mississippi River could install pipes that conveyed their effluent to the Mississippi River, but this was not a practical option for people living below Broad Street, which lay below the river level.

The drainage crisis grew throughout the 1880s. In 1890 the Orleans Levee Board offered $2500 for the best drainage plan for the troubled city, but no suitable plans were submitted because of the paucity of reliable topographic data. In the wake of this disappointing result, newspaper editorials and civic leaders recognized the city could not continue growing without a substantive effort to handle drainage and sewage. After several more unsuccessful attempts to encourage someone credible to come forward with a plan, in February 1893 the City Council created a Drainage Advisory Board (DAB) and provided $700,000 to gather the necessary topographic and hydrologic data, study the situation, and make recommendations on how the problems might be solved. The DAB sought to gather together the City's best and brightest engineers from public, private, and academic ranks. Chief among this work was the preparation of an accurate topographic map of the city, prepared under the direction of City Engineer L. W. Brown (shown in Figure 3.22).

The first DAB's findings were presented to the city in January 1895 (Advisory Board, 1895; Kelman, 1998). The Drainage Board recommended that the city create a modern system of drainage collection, conveyance, and discharge, which included street gutters, drop inlets, buried storm drains beneath city streets, with gravity flow to the principal drainage canals leading to Lake Pontchartrain. At that juncture, the conveyance problems became unprecedented, insofar that the city would need to install a series of pump stations to convey collected runoff into Lakes Borgne and Pontchartrain. The projected cost of such a system would be enormous.

The following year (1896) the Louisiana legislature authorized the creation of the Drainage Commission of New Orleans, which began preparing a comprehensive drainage plan for the city, and, how to fund such work. In 1897 the Drainage Commission began issuing contracts for new pumping stations, an electric power generations station, and the construction of additional feeder canals into the existing network of drainage canals.

In June 1899 voters passed a municipal bond referendum in a special election, which allowed a property tax of two mils per dollar to fund municipal waterworks, sewerage and drainage. With this revenue mechanism in place, the Sewerage & Water Board (S&WB) of New Orleans was shortly thereafter established (in 1899) by the State Legislature to furnish, construct, operate, and maintain a water treatment and distribution system and sanitary sewerage system. In 1900 the Drainage Commission began re-aligning and shifting the existing system of drainage canals, filling in a number of the cross-cutting canals and feeder canals which contained much stagnant water, which was encouraging the proliferation of mosquitoes and summertime yellow fever epidemics. In 1903 the S&WB was merged with the Drainage Commission to consolidate operations under one agency for more efficient operations. The drainage infrastructure at this time is shown in Figure 4.20.

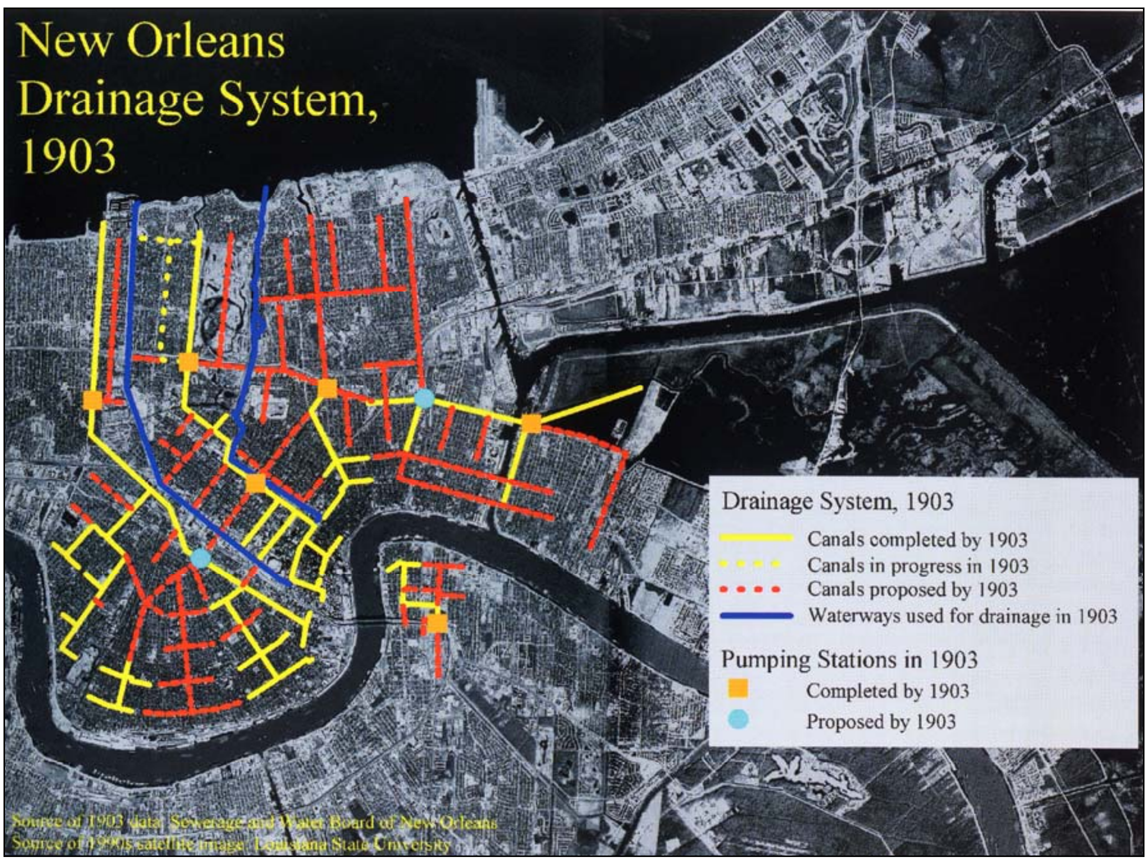

Figure 4.20: Principal elements of drainage system infrastructure as it existed in 1903 (taken from Campanella, 2002). The 17th Street and London Avenue Canals had already been in operation for several decades.

The combined organization retained the name Sewerage & Water Board, which it retains today. S&WB then set about the Herculean tasks at hand, which more or less continued at a feverish pace until the early 1930s, when the economic downturn caused by the Great Depression curtailed revenue. By 1905 the S&WB had completed 40 miles of drainage canals (in addition to the 36 they inherited), constructed six new electrically powered pumping stations and had a pumping capacity of 5,000 cfs, which represented about 44% of the original plan. At this time the S&WB provided drainage for 34.4 mi^2 of city area, all on the eastern side of the Mississippi River.

As the S&WB tackled the tough drainage problems plaguing lower New Orleans, rapid development of these low lying areas ensued, with the real estate values increasing dramatically, with many of the city's residents engaged in speculation, purchasing lots and then selling them as prices inflated. Because of this, many of the lots in lower New Orleans were developed in different eras instead of all at once, leading to the heterogeneity of architectural styles and ages that have made New Orleans neighborhoods famous. An unforeseen downside of the rapid pace of development was the increase in runoff which accompanied the emplacement of impervious surfaces, such as streets, roofs, sidewalks, and the like, which increased drainage problems, necessitating enlargement of pump capacity each decade.

By 1910 the S&WB system was rapidly being overwhelmed and something needed to be done to increase capacity. A. Baldwin Wood was a young Sewer & Water Board mechanical engineer who joined the Sewer & Water Board as assistant manager of drainage upon his graduation from Tulane University in 1899. Wood was a retiring and shy personality who took on the various challenges facing the S&WB with unparalleled enthusiasm and imagination. Within a few years (at age 27 in 1906) Wood filed his first patent, for a 6-ft diameter centrifugal water pump that was the largest of its kind in the world. After this he invented an ingenious flap-gate that prevented backflow when the pumps were not in use.

In 1913 Wood made his greatest contribution to New Orleans continued growth when he introduced his novel design for the low-lift "Wood Screw Drainage Pump," an enormous 12-foot diameter screw pump that employed an enormous impellor powered by a 25 cycle per second (or Hertz, abbreviated as Hz) Alternating Current (AC) electrical motor. The motive power was highly efficient, using 20 feet diameter Allis Chalmers dynamos that spin up to 87 rpm. The low-lift screw pumps employ a siphon action to maximize hydraulic efficiency. This was followed in 1915 by Wood's patented Trash Pump, capable of pumping record volumes of water as well as flotsam and trash without risk of shutting down the pumps (Junger, 1992). This latter feature was of particular value in maintaining pumping during storm events, which brought large volumes of organic debris into the drainage canals. In 1915 the City let a $159,000 contract for thirteen patented Wood screw pumps, installing 11 of them in three pump stations by the end of the year, when the Grand Isle Hurricane struck the city, causing widespread flooding of the old back swamps, which already lay at sea level. By that time (1915) there were 70 miles of drainage canals in place.

By 1926 the New Orleans S&WB was serving an area of 47 mi^2 with a 560 mile long network of drainage canals and storm drains with a total pumping capacity of 13,000 cfs. This impressive infrastructure had been constructed over a period of 47 years at a cost of

$27.5 million (1879-1926). Up to this time (1926) most of the S&WB's revenue had been generated by the special two-mill tax on all property and half of the surplus from the 1% debt tax. As the city grew and the S&WB's jurisdictional area increased to other areas adjacent to the city, the tax structure saw a number of amendments. Today the S&WB is funded by a number of sources, including three, six, and nine-mil property taxes.

The integrated drainage network allowed the water table of the old cypress swamps to be dropped so that subterranean cellars and burials became possible, and deaths from malaria and typhoid dropped 10-fold between 1899-1925. The City's last bout with summertime yellow fever was in 1905 (Campanella, 2002). During this same interim (195-26), the port authority saw enormous growth with the development of a massive Army Supply Depot along the riverfront during the First World War (1917-18) and the long-anticipated completion of the Inner Harbor Navigation Canal (IHNC) between the river and Lake Pontchartrain in mid-1923.

In the mid-1920s Wood increased the capacity of his patented screw pump to 14 feet diameter (Figure 4.21), using the same powerful siphon action to lift water. This increased the capacity of each pump unit by almost 40%. His improved capacity screw pumps were eventually marketed across the world; in China, Egypt, India, and Holland. Wood retired from the S&WB in 1945 and died in May 1956.

Figure 4.21: S&WB engineer A. Baldwin Wood standing next to one of his 14-foot diameter screw pumps in 1929 with several of the board's secretaries sitting inside the housing for scale (courtesy of the Sewerage & Water Board of New Orleans).

4.7.1 Pre-Katrina Conditions and Maintenance by the S&WB

Today the S&WB is responsible for draining 95.3 mi^2 of New Orleans and neighboring Jefferson Parish, which receive an average annual rainfall of 52 inches per year. The general layout of the drainage system is presented in Figure 4.22. The pre-Katrina system was intended to handle an average annual discharge of 12.9 billion cubic feet of water that had to be collected and pumped into Lake Pontchartrain, Lake Borgne, and the Mississippi River. The City's 22 main pump stations and 10 underpass pump stations still use about 50 of A.B. Wood's old pumps, and their system can lift an aggregate total of 47,000 cfs of water under peak operating conditions (the State Department of Transportation maintains the pumps for the General DeGaulle underpass at the Mississippi River Bridge ramps and on the East Bank at the Pontchartrain Expressway at the Southern Railway tracks and Metairie Cemeteries). A typical pump station (Pump Station No. 6) can lift 9,600 cfs using its old Wood pumps. New Orleans also employs vertical pumps with impellors to lift water from subterranean (below street) storm drains to the drainage canals, which outfall in Lake Pontchartrain. The S&WB maintains 90 miles of covered drainage canals, 82 miles of open channel canals, and several thousand of miles of storm sewer lines feeding into their system.

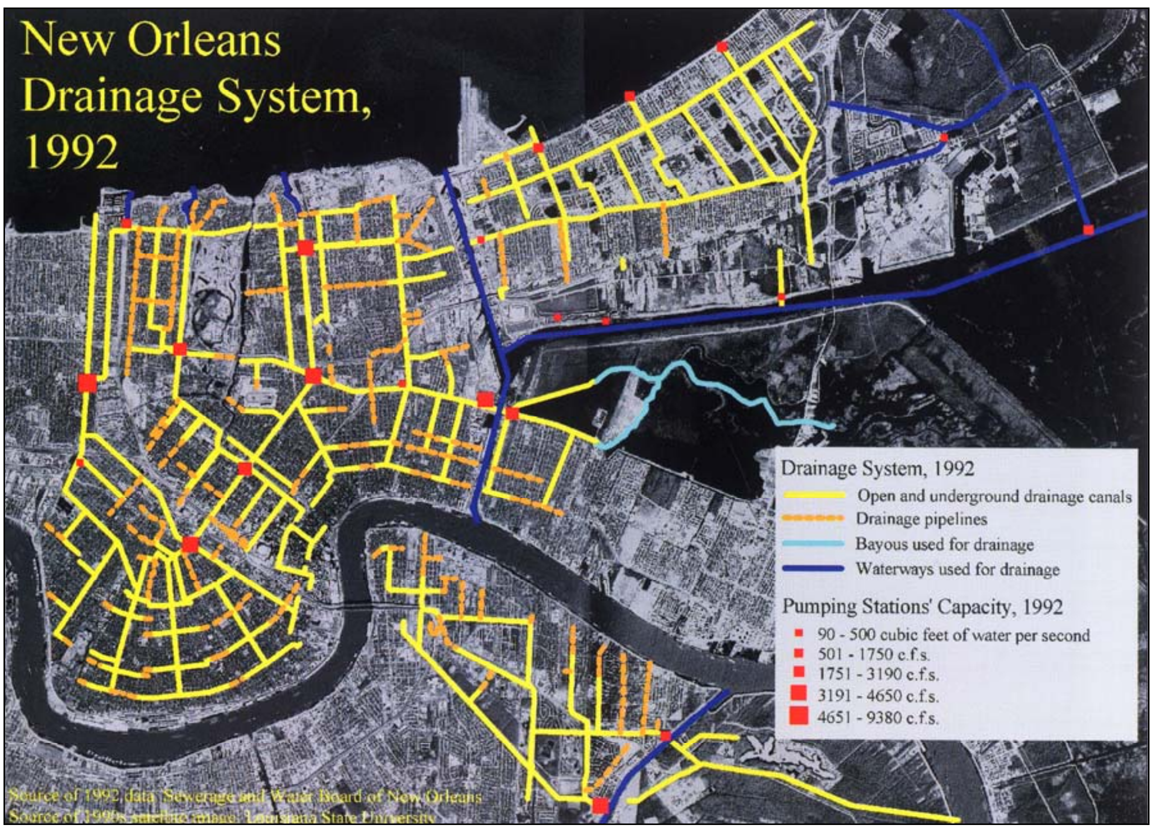

Figure 4.22: Principal elements of the pre-Katrina drainage system infrastructure as it existed in 1992 (taken from Campanella, 2002). The aggregate pump capacity could have cleared the city of flood waters in less than three days if the levees had simply been overtopped without failing.

The S&WB maintains that their agency installed two sets of piezometers along the canal in the early 1980s, but that these revealed little correlation between transient flow levels in the canals and the adjacent piezometers. They took this result to mean that the canal floored in materials of relatively low permeability. In 1988 the S&WB received a permit from the Corps of Engineers to deepen and widen the 17th Street Canal, based on the "positive" indicators garnered from the piezometers that had been installed a few years previous. The Corps warned that dredging might weaken the stability of the canal, but a system of monitoring pore water (groundwater) pressures adjacent to the canal was not undertaken and the canal was substantially enlarged using a track-mounted excavator.

Although the S&WB system is highly efficient from an energy expenditure perspective, the 25 Hz AC electrical power requires the board to produce its own electricity, in lieu of purchasing 60 Hz AC off the national electrical power grid. As a consequence, approximately 60% of the S&WB's electrical power has to be generated locally, at their own 20 MW generator stations (Snow, 1992). Unfortunately, all of these generating stations are located below mean gulf level and subject to shut-down by flooding.

4.7.2 Damage to S&WB facilities and capabilities caused by Hurricanes Katrina and Rita

During Hurricane Katrina the following pump stations were incapacitated and closed due to flooding: Pump Station #1 (2501 S. Broad Street), #3 (2252 N. Broad St.), #4 (5700 Warrington Dr.), #6 (345 Orpheum), #7 (5741 Orleans Ave.), #10 (9600 Haynes Blvd.), #14 (12200 Haynes Blvd.), #15 (Intercoastal Waterway), #16 (7200 Wales St.), and #19 (4500 Florida Ave.). These pump stations were gradually brought back online and were all at least partially operational within six months. 100% pumping capacity had not been restored to the S&WB system by the time of this writing (May 1, 2006). Drainage for Jefferson Parish, west of the city, remained online in wake of Hurricanes Katrina and Rita. This failure of the S&WB drainage system was without historic precedent, and pointed to fundamental flaws in the drainage system, with respect to operational redundancy.

During Hurricanes Katrina and Rita the Eastbank Sewer Treatment Plant was also closed (and has not reopened as of May 1, 2006). City residents were immediately advised to boil water before using by the city's Department of Health and Hospitals immediately following flooding of the city. This restriction was lifted for the neighborhoods west of the IHNC on October 6, 1005 and for the New Orleans East, Southshore and Ventian Isles areas on December 8, 2005. Water quality had not been restored to The Lower Ninth Ward in Zip Code 70117 by the time of this writing (May 1, 2006).

4.7.2 Reclamation of the Mid-City Lowlands (early 1900s)

The Mid-City area occupies a natural basin that formed between the levees of the Mississippi River and Metairie Ridge. The City's original network of pie-shaped property boundaries and streets converged on this area from their points of origin perpendicular to the broad crescent-shaped bend of the Mississippi River upstream of the French Quarter, from which the city derives its motto "the Crescent City." The area was a close depression (Figure 4.18), which had to fill up with water to drain into Bayou St. John, thence three miles into

Lake Pontchartrain. A series of feeder canals were excavated to convey drainage into Bayou St. John and the New Basin Canal after the Civil War. But, stagnant water occupied these feeder ditches, promoting the existence of mosquitoes and yellow fever outbreaks, which were recognized to favor poorly drained areas decades before the scientific connection between the two was established (beginning around 1905). In the early 1900s it was decided to begin filling the lowest areas of the Mid-City area to provide better drainage and accommodate growth into this area, which had been subject to frequent flooding. Sand from Metairie Ridge and from dredging of nearby canals was used to provide the fill material and the feeder canals in this area were filled in and replaced with buried storm drain pipes beneath the streets (discussed in Section 4.7).

4.7.3 1915 Flood triggers heightening of drainage canal levees

On September 29, 1915 The Grand Isle Hurricane lifted the water level in Lake Pontchartrain to 13 feet above mean gulf level. The Lake Pontchartrain shoreline levee and many of the drainage canals were overtopped and much of the lower city flooded, killing 275 people. The City's new pump system was overwhelmed when the power generating stations for the new Wood screw pumps were flooded. After the 1915 flood, Sewerage and Water Board General Superintendent George Earl ordered the levees along the drainage canals to be raised approximately three feet, while the Pontchartrain shoreline levee was also raised. It is not known if this work was carried out by the S&WB or the Orleans Levee District.

4.7.4 The Lakefront Improvement Project (1926-34)

The southern shore of Lake Pontchartrain supported a number of small commercial wharves and fishing camps during the late 19th Century, including Milneburg, Spanish Fort, and West End. Shanties and structures along the shore were founded on wood pilings. The old Lake Pontchartrain shoreline levee had been constructed along the south shore to protect New Orleans from flood surges off the lake around 1893. This levee was overtopped by the storm surge on Lake Pontchartrain during the Grand Isle Hurricane in 1915 (described in Section 4.4). This levee was difficult to maintain because the shoreline was actively receding southward, towards New Orleans (Figure 3.16). In 1921 the Orleans Levee Board were granted increased powers by the state legislature to reinforce the Pontchartrain shoreline. In 1924 the board's chief engineer, Colonel Marcel Garsaud, embarked on developing an ambitious plan to construct a permanent seawall along Pontchartrain's south shore and reclaim several square miles of land by filling the gap between the new seawall and the eroding shoreline.

In 1926 the levee board began construction of a temporary wooden bulkhead wall constructed one-half mile north of the existing shoreline, within Lake Pontchartrain. This temporary structure extended two feet above mean gulf level (MGL). The nearshore area between this bulkhead wall was initially backfilled to an elevation of +2 feet above MGL, creating 1,800 acres of "made ground." The fill material was sand taken from the floor of Lake Ponchartrain, placed using hydraulic dredges. The wooden bulkhead was then raised another two feet and hydraulic fill placed behind it to a level of +4 ft. This process was repeated yet again, creating a fill platform 4 to 6 feet above MGL and up to 10 ft higher than the old cypress swamps that subsequently became the Lakeview and Gentilly neighborhoods (even higher than the Metairie-Gentilly Ridge). The reclamation plan envisioned the construction of a permanent stepped concrete seawall along the new shoreline, replacing the wooden bulkhead wall and construction of this permanent barrier began in 1930.

To offset the hefty price tag of $27 million for this work, the levee board secured special legislation (in 1928) creating the Lakefront Improvement Project, which allowed them sweeping powers to reclaim land along the Pontchartrain shoreline. In 1931-32 another sizable fill was placed along Lake Pontchartrain behind another concrete seawall to create an additional 300-acre fill for a municipal airport. This was christened Shusan (now Lakefront) Airport, which has a 6,900 ft runway, used as a flight training facility during World War II.

When the lakefront improvement project was completed in 1934, a public debate erupted as to how best utilize the reclaimed land. A battle soon developed between private development, public access to the shoreline, and those forces promoting its adoption as open space parkland. A compromise plan was eventually adopted which allowed public access for recreation along with residential and public facility development (University of New Orleans). The new acreage was sold to developers to help the levee board pay off the construction bonds, and the Lakeshore, Lake Vista, Lake Terrace, and Lake Oaks neighborhoods were developed between 1939-1960.

After the Second World War the Lakeview, City Park, Fillmore, Gentilly, and Pontchartrain Park areas behind the lakefront emerged as desirable bedroom communities with yacht harbors, parks, and pleasant summer breezes. This area experienced unprecedented growth, between 1945-75, adding about 100,000 residents to the City.

4.7.5 Second generation of heightening drainage canal levee embankments (1947)

The hurricane of September 1947 caused storm surges of up to 10 ft above MGL along the shores of Lakes Borgne and 5.5 ft along the south shore of Lake Pontchartrain which overwhelmed levees in the Inner Harbor Navigation Canal (IHNC) and the old drainage canals, within a mile of their respective mouths. After several of these drainage canal levees were overtopped in 1947, the state's congressional delegation asked the federal government to assist in protecting the city (culminating in the Lake Pontchartrain and Vicinity Hurricane Protection Plan passed by Congress in 1955). The Orleans Levee Board spent $800,000 to raise its levees, including both sides of their drainage canals (with the exception of 17^{th} Street, the west side of which is owned by the Jefferson Levee Board). Sheet piles were also reportedly used in by the port authority in the inner harbor area. We have not been able to determine how much additional freeboard was added by filling and/or sheet pile extensions in 1947-48.

4.7.6 Federal Involvement with the City Drainage Canals (1955 – present)

Federal involvement in the city's drainage canals began in 1955 with approval of the Lake Pontchartrain and Vicinity Hurricane Protection Project by Congress. The Corps studied the problems posed by the drainage canals, which had settled as much as 10 feet since their initial construction in the mid-19^{th} Century. This settlement had necessitated two generations of heightening following hurricane-induced overtopping in 1915 and 1947. Each of these upgrades likely added something close to three additional feet of embankment height to keep water trained within the drainage canals and provide sufficient freeboard to prevent storm surges emanating from Lake Pontchartrain from overtopping the canal levees. The maximum design capacity of the three principal drainage canals (17th Street, Orleans, and London Avenue) was about 10,000 cfs, but this figure was being reduced by settlement and sedimentation problems.

The Corps had several non-federal partners in the venture: the Orleans and Jefferson Parish Levee Boards, and the Sewerage & Water Board of New Orleans. The levee districts maintained the canals and the S&WB maintained the pump stations and controlled the discharge in the drainage canals. If the S&WB pumped at maximum capacity, the increased flow could accelerate erosion of the unlined canals, which floor in extremely soft soils. If they didn't pump much water, then the canals could fill up with sediment, and thereby experience diminished carrying capacity. By the time the Corps got involved, a dense network of single family residences abutted the drainage canals along their entire courses (the canals are 2-1/2 to 3-1/2 milers long). The encroachment of these homes adjacent to the canal embankments (Figure 4.24-upper) circumvented any possibility of using conventional methods to heighten the levees, which is usually accomplished by adding compacted earth on the land-side of the levees (Figure 4.23), which would require the condemnation and removal of hundreds of residences, which would be costly and time-consuming.

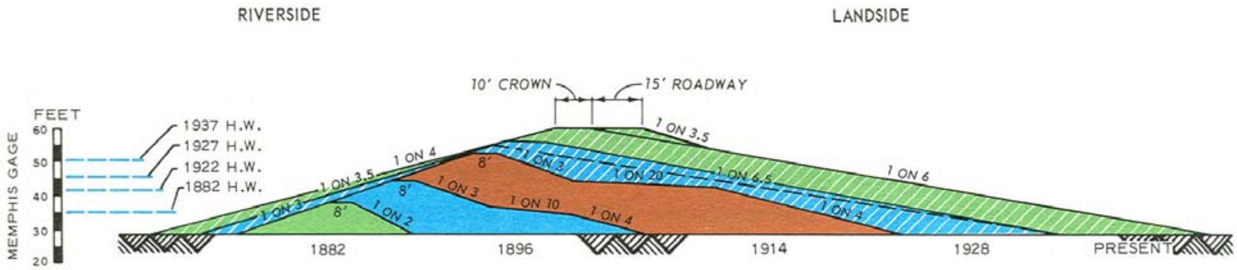

Figure 4.23: Evolution of the Corps of Engineers' standard levee section, 1882 to 1972 (from Moore, 1972). Earth embankments levees are generally heightened sequentially by compacting additional soil on the land side of the embankments (each sequence of heightening shown as different colors). Levees adjacent to drainage canals or perennial channels are not raised on the river side of the embankment because excess moisture would prevent meaningful compaction of the fill. Existing homes abutted the landslide of the drainage canal levees in New Orleans by the time the Corps of Engineers began analyzing them in the 1960s.

In 1960 the Corps of Engineers New Orleans District office issued its initial report detailing their plan for remedying the ongoing problems with the slowly sinking drainage canals. The Corps plan opted to solve the drainage canal freeboard problem by installing tidal gates and pumps at the drainage canal outfalls along Lake Ponchrtrain. This obviated the need for condemning all the homes built along the canal levees. The Corps soon found itself embroiled in a clash of cultures and goals with the levee districts, the S&WB, and the local citizenry, who flatly opposed the Corps' proposal. The S&WB and local residents feared that the tidal gates would malfunction, inhibiting outflow of pumped storm water, which would, in turn, allegedly, cause flooding.

The following year (1961) the Corps of Engineers unveiled a more grandiose plan to provide hurricane flood protection for New Orleans by constructing large flow barriers at the passes (The Rigolets) leading into Lake Pontchartrain, to prevent storm surges from reaching the lake. This scheme was expensive, and never garnered sufficient political support to gain appropriations (it was also proposed in the era before environmental assessments were required).

The issue of how to address improvement of the drainage canals dragged on for another 17 years. Between 1960-77 what few lots remained in lower New Orleans were rapidly built out by the end of the decade, and most of the post-1970 development in New Orleans focused on the areas east of the IHNC, in Jefferson Parish (west of New Orleans), and across the Mississippi River (Algiers, etc). In December1977 the Fifth U.S. District Court ruled against the Corps of Engineers plans for tidal gates at the mouths of the drainage canals because the Corps failed to examine the impacts of alternative schemes. From this juncture, the Corps focus shifted to heightening the drainage canal levees using concrete walls (Figure 4.24-lower), which was what the opposing groups desired. These walls were to be designed to withstand a Category 3 storm surge with 12 ft tides and 130 mph winds.

Figure 4.24 (upper): View looking up the east side of the London Avenue Canal near Robert E. Le Boulevard crossing showing the encroachment of homes against the slope of the levee. This situation was common across New Orleans (photo by C. M. Watkins).

Figure 4.24 (lower): Concrete flood wall along the west side of the 17th Street Canal in Jefferson Parish, where a street runs along the toe of the embankment. This scene is typical of the concrete I-walls constructed on steel sheetpiles driven into the crest of the drainage canal embankments in New Orleans in the 1990s to provide additional flood freeboard from hurricane-induced storm surges (photo by J. D. Rogers).

Construction began in 1993, but the wrong benchmark datums were selected for the contract drawings, so some of these walls were constructed almost two feet lower than assumed (IPET, 2006). Although the concrete flood walls were completed by 1999, concrete skirt walls on many of the bridges crossing the drainage canals had not been completed when Hurricane Katrina struck on August 29, 2005. So, the drainage canal system was not "tight," but it was generally believed that it could survive a Category 3 storm surge by surviving 6 to 8 hours of overtopping. The design storm surge values used by the Corps of Engineers are reproduced in Figure 4.25.

Flow records for the drainage canals in New Orleans indicate that between 1932-2005, a flow stage of +4 ft MGL was exceeded on at least 29 occasions; +5 feet was exceeded 13 times (including during Hurricanes Betsy in 1965 and Camille in 1969; +6 ft was exceeded only three times (including during Hurricanes Juan in 1985 and Isadore in 2002); and exceeded +7 feet for the first and only time on August 29, 2005 during Hurricane Katrina.

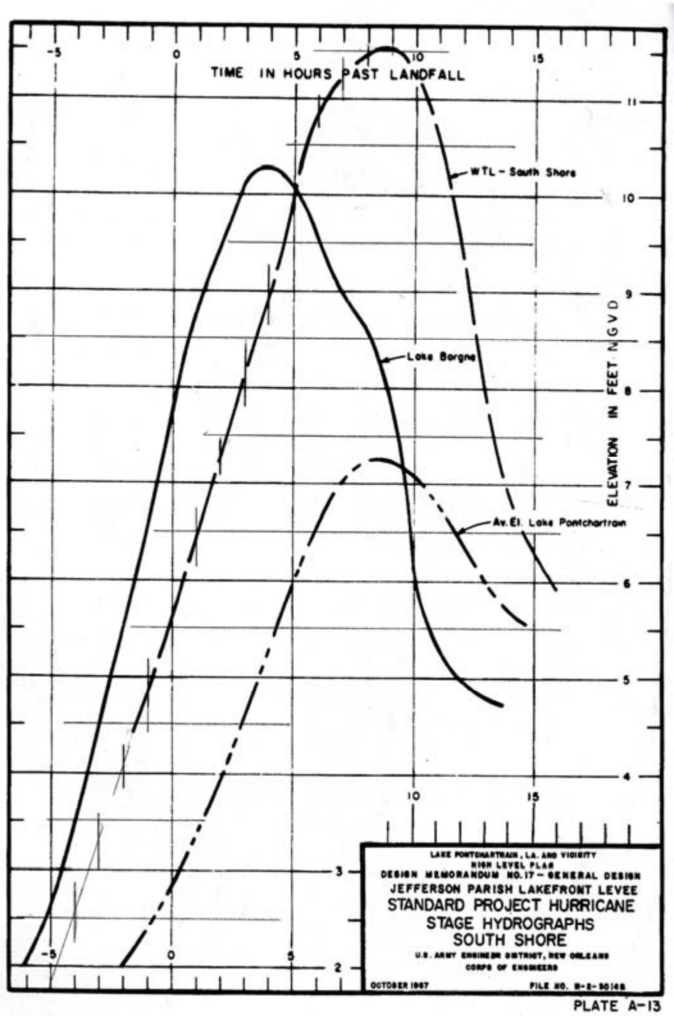

Figure 4.25: Assumed Category 3 storm surge curves for the Gulf of Mexico shoreline, Lake Borgne, and Lake Pontchartrain used by the Army Corps of Engineers for planning and design purposes prior to Hurricane Katrina in 2005. Note the short duration of extreme surges, about 12 hours duration above 5 ft MGL for Lake Pontchartrain (taken from USACE DM-17, 1987).

4.7.7 Hurricane Katrina strikes New Orleans – August 2005

A complex network of levees protected the City of New Orleans from flooding (Figure 4.26). New flood walls were constructed in the 1990s on the crowns of drainage canals and the Inner Harbor Navigation Canal to accommodate functionality during high storm surges. The walls in the lower Lakeview and Gentilly Districts topped out at +14 ft above MGL. Figure 4.28 shows deflection of the western 17th Street Canal flood wall, opposite the August 29, 2005 break of the eastern wall, near the Hammond Highway Bridge.

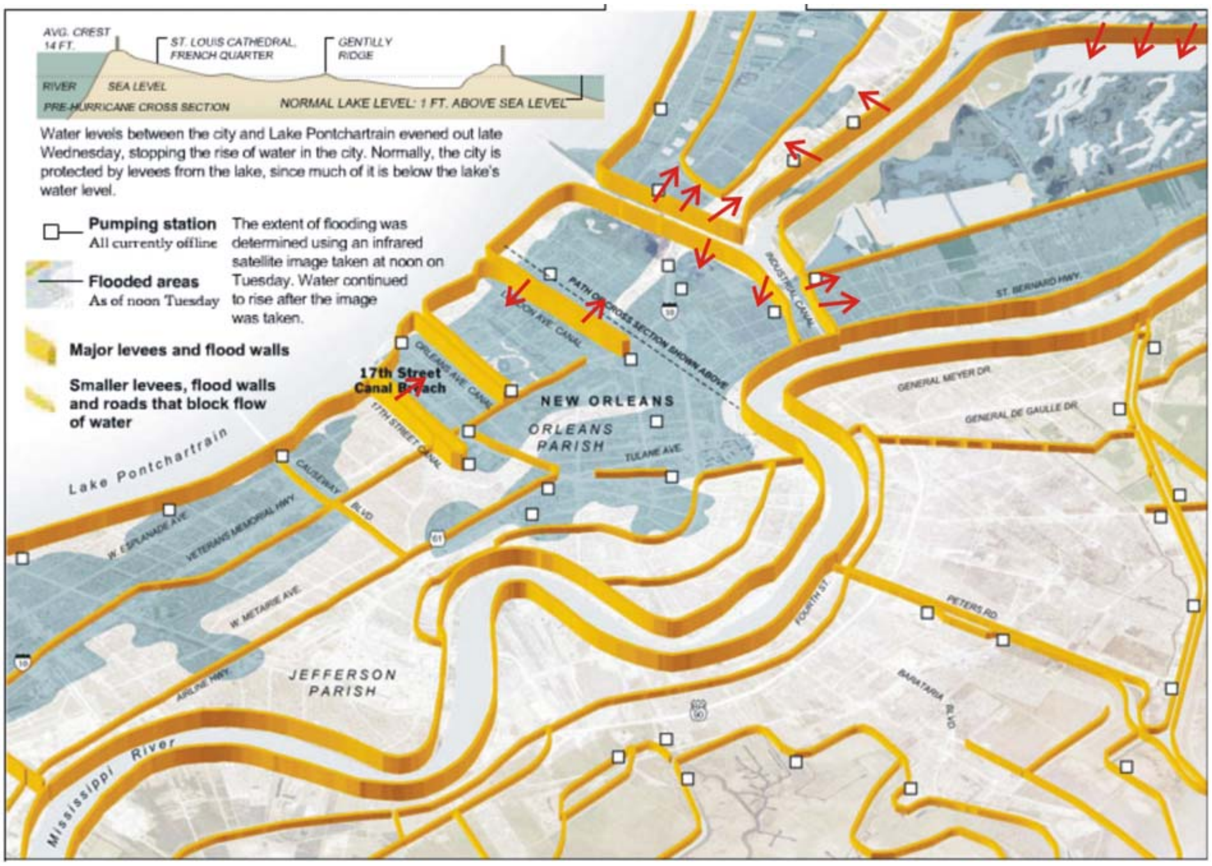

Figure 4.26: Schematic layout of levees and flood walls protecting the New Orleans area at the time Hurricane Katrina struck on August 29, 2005 (from image by the New York Times). Red arrows denote locations of levee failures.

This system of flood walls quickly failed on the morning of August 29, 2005, when water levels rose above 7 feet above MGL, higher than ever previously recorded in the drainage canals since 1932 (cited in previous section). Prior to Hurricane Katrina, the drainage canals feeding into Lake Pontchartrain never exceeded a flow height of between 6 and 7 feet above MGL. Many of the recording tidal gages failed during Hurricane Katrina. The incomplete record of the gage located closest to the 17th Street Canal failure is reproduced in Figure 4.27. This record shows several interesting trends. The first is the increase in diurnal high tide level each day after August 22nd. The second is a dramatic departure from the normal tidal cycle beginning the day before Hurricane Katrina made landfall, around 5 PM on August 28th. The third interesting aspect is the sharp increase in surge level on the morning of August 29th, which is much steeper than the assumed design storm surge for Lake Pontchartrain shown on the lowest curve in Figure 4.25.

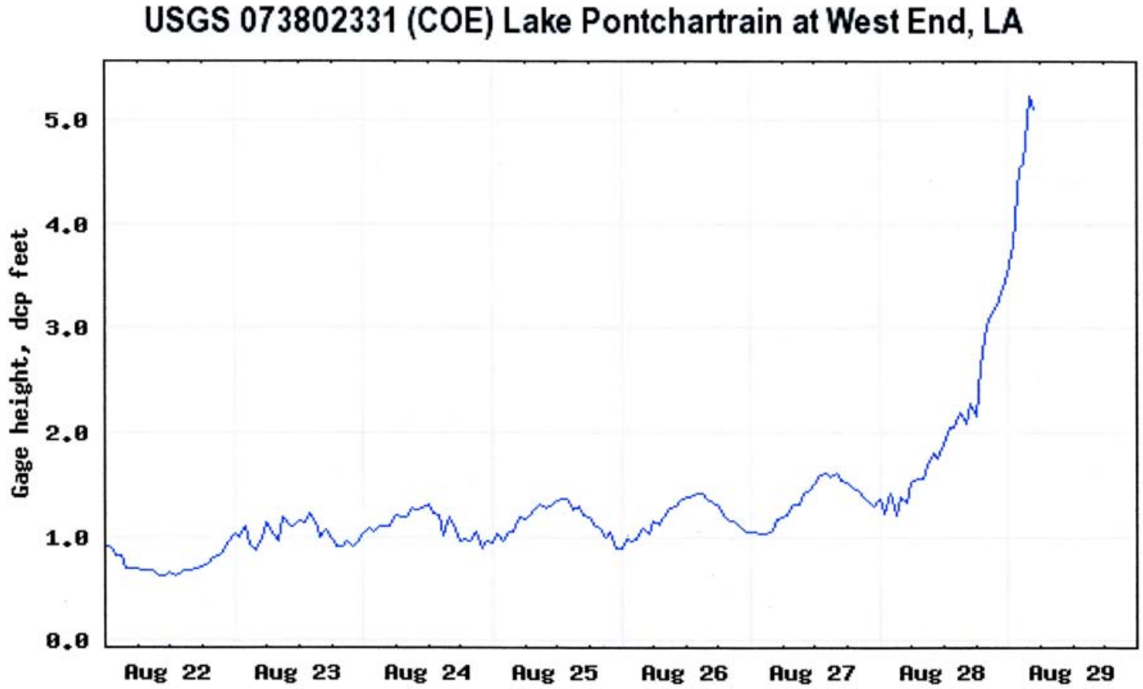

Figure 4.27: Incomplete record of the Lake Pontchartrain tidal stage gage at West End, near the mouth of the 17th Street Canal during the early stages of Hurricane Katrina (from U.S. Geological Survey). This record shows several steps in the storm surge, known as "ramping," beginning on August 28th, with the sharpest increase on the morning of August 29th, when the hurricane made landfall. The gage failed when the lake level reached 5.3 ft, before the peak surge was recorded.

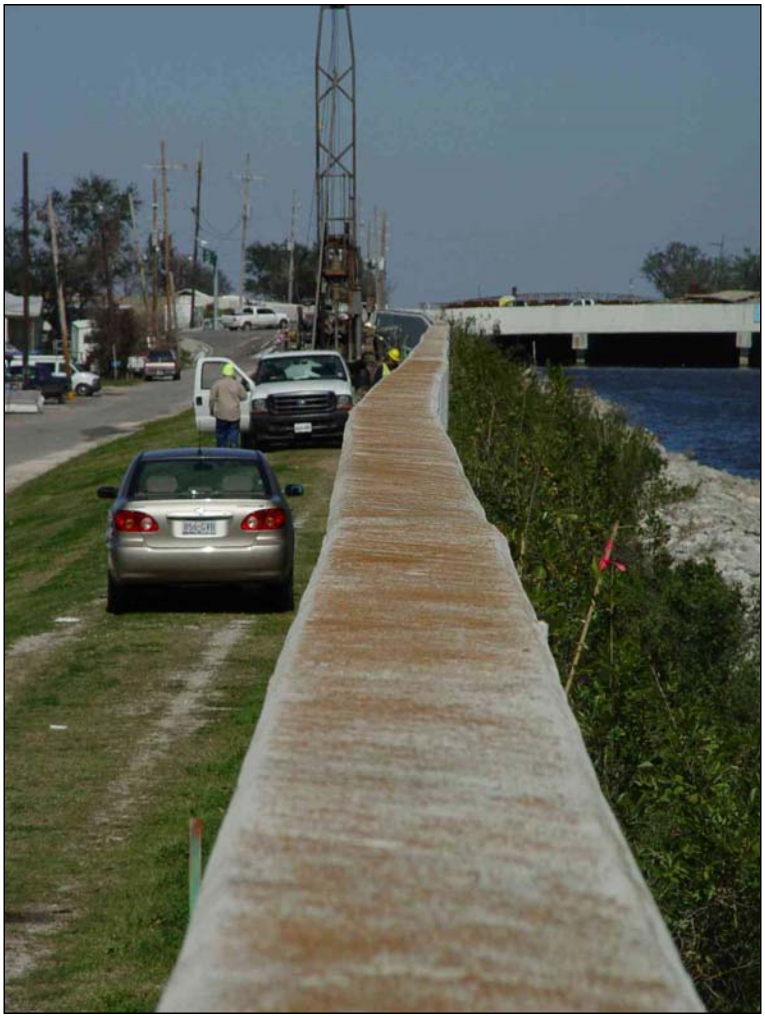

Figure 4.28: Localized deflection of the west flood wall on the Jefferson Parish side of the 17th Street Drainage Canal, opposite the breach that occurred on the eastern side on August 29, 2005. The gap formed at the construction joint was wider at the base than the crest, suggesting deep-seated strain beneath the embankment (photo looking north, by J. D. Rogers).

4.8 Commercial Navigation Corridors

4.8.1 Inner Harbor Navigation Canal/Industrial Canal

Ever since the founding of the city by the French in 1718, the concept of a navigation channel between the Mississippi River and Lake Pontchartrain had been proposed, which would allow intercoastal commerce to connect with river and seaborne commerce traveling up and down the Mississippi River. The Port Authority of New Orleans was established in 1896 as an agency of the State of Louisiana. The port engineers recognized that the problem with establishing a water borne link was the fluctuating flow of the river, which raised and lowered 20 feet, depending on flood stage. The river was also 10 to 26 feet higher than normal level of Lake Pontchartrain, so some impressive locks would be needed to control the flow between the river and the lake.

The idea never progressed too far until construction of the Panama Canal between 1906-14, which heralded advances in excavation and grading technology that allowed widespread programs of public works, drainage, and flood control in succeeding half century. In July 1914 New Orleans received authorization from the state legislature to locate and construct a deep water canal between the Mississippi River and Lake Pontchartrain, which was supposed to boost the capacity of the port by as much as 100%. The expansion of ship building facilities triggered by the First World War and construction of the Army's enormous supply depot along the river front hastened action. While the war was still raging, a committee was formed early in 1918 to examine the feasibility of a connecting canal, using the most modern technology. Their initial report was released in May 1918 and it surprised everyone by envisioning a much larger project than most supposed, with the creation of ship building facilities within a protected, fixed-level harbor, increasing the available wharf space by almost 60%. The canal would be 5.3 miles long and up to 1,600 ft wide, located just downstream of the Army's new riverfront Supply Center (about 2 miles downriver and parallel to Elysian Fields Avenue).

The Port Authority's Dock Board retained the services of the George W. Goethals Company as consulting engineers, borrowing upon General Goethals renown as chief engineer of the Panama Canal project a few years earlier. The local firm of J. F. Coleman Engineering Co. performed most of the actual detailed design work, as well as assisting the Port Authority in construction management. Construction commenced on June 6, 1918. The superior elevation of the Mississippi River dictated that excavation would necessarily proceed from the lake side towards the river, which the massive locks, the project's kingpin structure, would be placed at the river end of the canal.

Excavation work initiated with the construction of parallel dikes on either side of the proposed canal, from which hydraulic fill could be loosed through sluice pipes. Hydraulic excavation was used wherever possible to excavate the channel, when the materials were easily loosed (e.g low cohesion materials, such as gravel, sand, organic ooze and swamp muck). When more resistant clay was encountered large front tower cableway dragline excavators or conventional dragline excavators (Figure 4.29) were employed to scoop out the clay and drag it up onto the dikes, which were gradually built um to become permanent protective levees. The draglines employed 3.5 cubic yard buckets and could handle about 150 cubic yards per hour. From the onset, contractors battled problems with slope stability, as the soft oozy soils constantly slid back into the excavation (Campanella, 2002). Buried cypress stumps slowed progress by jamming suction dredges and stalling dragline buckets.

During construction the Port Authority decided to increase the size of the channel to a minimum depth of 30 feet at low water, with a minimum bottom width of 150 feet and a minimum channel width of 300 feet, roughly double the original design. Abreast of the new wharves the bottom width was increased to 300 feet, with a minimum canal width of 500 feet near piers and slips, and 600 feet adjacent to quays (Dabney, 1921). The canal excavation was completed in just 15 months, in September 1919. Everyone's attention then turned to the lock structure, located 2,000 ft from the Mississippi River, at the south end of the canal. The normal flow level of the river was 10 ft above that of Lake Pontchartrain, so cofferdams had to be constructed on either end of the locks to allow safe access and dewatering of the exposed foundations. The lock is 640 ft long and 74 ft wide. The footing excavations were

50 feet deep, where timber piles were pounded into the underlying sands. The lock structure was finally completed on January 29, 1923, and dedication ceremonies for the entire Inner Harbor Navigation Canal (IHNC) were convened on May 5th, 1923. The residents of New Orleans often refer to the IHNC as the "Industrial Canal."

Figure 4.29: Mobile dragline constructing the Morrison-Picayuneville Levee about 25 miles south of New Orleans in June 1931 (from Elliot, 1932). Tower draglines could excavate materials up to a quarter mile away, dragging it back up onto the new levee.

Almost immediately upon completion, the Port Authority set about developing piers, docks, and quays to increase cargo handling. Their first large structure was the Galvez Street Wharf, which was 250 ft wide and 2,400 ft long, costing $1.8 million (1923 dollars), completed in 1924. It was constructed of reinforced concrete and fitted with tracks for a local Beltline railroad. The Port Authority also made available adjacent lands for use by industries, but it took many years until the envisioned development occurred. The IHNC benefited from the completion of the Intracoatsal Waterway in the mid 1930s, as a cargo handing and provisioning stop. This was an unforeseen benefit, serving smaller vessels, which provided an economical means of transport prior to the establishment of the Interstate Highway network in the 1960s.

The massive Florida Avenue Wharf was added during World War II while the Gentilly Road section of the canal witnessed the sprawling expansion of shipbuilding facilities operated by Andrew Jackson Higgins, who pioneered the development of wooden PT boats and landing craft crucial to the war effort. Much of the area flanking the west side of the IHNC was built out during World War II (Figure 4.30). The eastern side was developed much later, after the Korean War (1950-53) and completion of the MRGO channel in 1964 (Figure 4.29). The immense France Road and Jordan Road Container Terminals (Berths 5 and 6) near the head of the MRGO channel were completed in the 1980s and 90s. The narrow width of the 1923 lock (74 feet) has restricted the passage of commerce, in particular, river barges, which often wait up to 36 hours to pass through.

Figure 4.30: Aerial oblique view of the Inner Harbor Navigation Canal between 1960-64, after the entry to the Mississippi River-Gulf Outlet Channel had been enlarged (upper right), connecting to the inner harbor area (photo from the Army Corps of Engineers).

4.8.2 Flooding problems around the IHNC

During the 1947 hurricane (Figure 4.11) a back protection levee adjacent to the IHNC was overtopped at Tennessee Street, spilling 10 feet of water into the East Side of New Orleans. Fortunately, the levee did not collapse, the area was undeveloped, and the flooding was quickly cleaned up. There was also quite a bit of flooding in the Metairie and Jefferson Parish areas, also attributable to temporary overtopping. There was a flood inundation map published in the *New Orleans Times-Picayune.*

Both sides of the IHNC experienced breaks and overtopping during Hurricane Betsy in September 1965. 6,560 homes and 40 businesses were flooded in water up to 7 ft deep on the west side of the IHNC. The east side of the IHNC also failed, flooding the west end of St. Bernard's Parish. A map of the flood inundation of New Orleans caused by Hurricane Betsy in September 1965 is shown in Figure 4.12. The Corps' report on Hurricane Betsy (USACE, 1965) states that both internal levee failures and overtopping occurred along the Inner Harbor Navigation Canal, on both the west and east sides. No details about the mechanisms of failure were described, however.

The IHNC was heightened using steel sheetpiles and concrete I-walls in the 1980s and 90s. On August 29, 2005 during Hurricane Katrina both sides of the IHNC were overtopped by the storm surge converging on the IHNC from Lakes Borgne and Pontchartrain. Sustained overtopping flow undermined the landside toe of the I-walls, in places gouging down as much as 5+ feet below the crest of the earthen levee. In addition, there was ample physical evidence of underseepage at both the eastern IHNC breaches, in the form of linear sand boils. These sheetpile-supported I-walls appear to have failed after about 3 to 4.5 hours of overtopping (between 4:30 and 9 AM on 8-29-05), allowing a large volume of water to sweep into the Lower Ninth Ward of New Orleans and the Chalmette area of St. Bernard Parish, to depths of up to 9 feet (Figure 4.31).

Figure 4.31: Seepage crevasse splay exposed on the water side of the east levee of the IHNC breach after Hurricanes Katrina and Rita. This same section of the IHNC levee failed in 1965 during Hurricane Betsy. Levees tend to fail during sustained high flow events because of underseepage problems, toe scour, and overtopping. Note the anomalous seepage in lower foreground, which suggests much higher permeability in this particular portion of the dike, close to the south end of the failed section (photo from Army Corps of Engineers).

4.8.3 Intercoastal Waterway

The Intracoastal Waterway (ICW) was originally conceived in 1808, but not authorized by Congress until 1919. The ICW was excavated by dredge in the late 1930s to a channel size measuring 9 ft deep by 100 feet wide, and completed between New Orleans and Corpus Christi, Texas by mid-1942. This was enlarged to 12 feet deep by 125 ft wide channel and officially completed in June 1949. The ICW forms a protected shipping lane between Port Isabel, Texas (the Mexican border) and Apalachee Bay, Florida. The first 15% of the Mississippi River-Gulf Outlet Channel follows the ICW, which then diverges northeastward, about five miles east of the Inner Harbor. The ICW then runs east, towards The Rigolets and on into Mississippi.

4.8.4 Mississippi River Gulf Outlet

When the IHNC was completed in 1923 the Port Authority announced that it intended to lobby the federal government to construct a Mississippi River Gulf Outlet (MRGO) channel connecting to the IHNC, to increase shipping capacity (Dabney, 1921). The idea didn't surface appreciably until 1943, during the Second World War, when thousands of amphibious assault craft and shallow draft vessels were being fabricated along the nation's inland waterways. The Corps of Engineers felt that a tidewater canal serving New Orleans and the nation's interior waterways would be able to compete with the Panama Canal for east-west shipping, crucial to the war effort (most industrial goods were manufactured in the eastern United States, which was being shipped to the Pacific via the Panama Canal). Competing priorities placed the project in limbo until the late 1940s, when it was resurrected. In the early 1950s the project was repeatedly voted down in Congress, because of competition with the St. Lawrence Seaway project between Canada and the U.S (approved in 1954).

After passage of the competing seaway, the Mississippi River Gulf Outlet (MRGO) project was authorized by Congress in March 1956. Kolb and Van Lopik (1958) of the Corps of Engineers prepared a geology report on the MRGO alignment in 1957-58. This study showed that the upper 2 to 5 feet was fibrous peat, although highly organic marsh deposits extend to depths of between 5 and 16 feet. These highly compressible materials are underlain by interdistributary and intratidal complex silts and clays over much of the proposed alignment (Figure 4.32). They graded these materials as soft marsh (500 to 900% water content), firm marsh (100 to 500% water content), and swamp substrate (highly organic peat with 600 to 800% water content). They noted that the soft marsh and swamp substrate materials would be unable to provide competent foundations for the protective levees bordering the channel, and these same materials would be unsuitable for use in such embankments.

During the first phase of dredging in 1958-59, 20 million cubic yards (mcy) of material was excavated between the IHNC and Paris Road (now I-510), essentially widening the ICW. In 1959-60 contractors excavated a "pilot channel" between the ICW and Breton Sound, excavating and placing 27 mcy of material. In the third and fourth phases completed between 1960-65, 225 mcy were excavated between Paris Road and Breton Sound. Dredge spoils were placed in a strip of land 4000 ft wide corridor paralleling the southwest side of the MRGO channel in St. Bernard Parish. The dredge soils from the initial excavations (1958-59) were placed on the land which now underlies the Jourdan Road Container Terminal, near the intersection of the MRGO and IHNC.

The MRGO channel was excavated as 500-feet minimum width channel with a minimum (low tide) depth of 36 feet (excavated to -38 feet; accepted at -36 ft). The route of the MRGO channel crosses 45 miles of delta marshland in Orleans and St. Bernard Parishes, with another 30 miles of open (dredged) channel across Breton Sound. This offshore section is slightly larger. Its 75 mile path is 37 miles shorter than that of the deep water navigation channel connecting New Orleans to the Gulf of Mexico via Southwest Pass. The project was finalized in 1968.

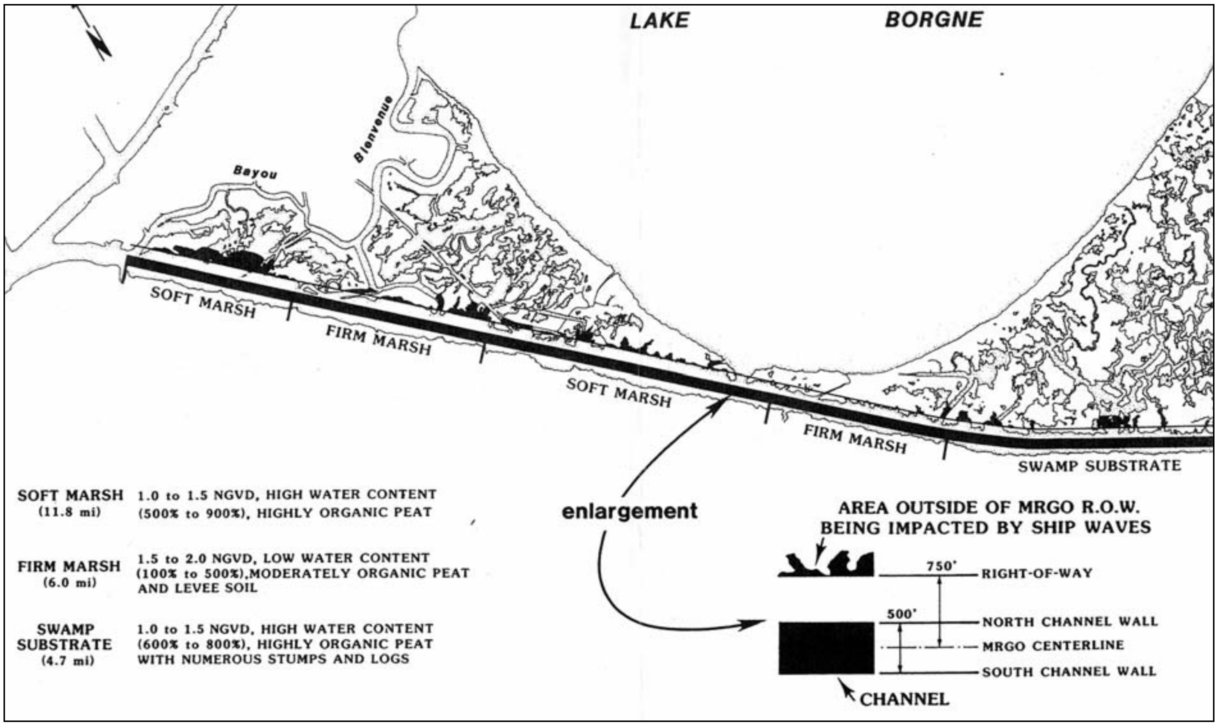

Figure 4.32: Portion of a map of the upper MRGO channel adjacent to Lake Borgne from the report by Coastal Environments, Inc. (1984). This shows the major soil subdivisions they identified: soft marsh, firm marsh, and swamp substrate. Much of this material was unsuitable for using in the adjoining levee embankments.

The flanking levees have experienced significant settlement since the project's completion, due to consolidation of prodelta clays underlying the flanking levee embankments, as well as plastic sagging due to low strength and creep properties of underlying organic material. The amount of settlement varies between 1.5 and 8 feet, depending on location. Many estimates have been offered regarding the tectonic rate of subsidence of the Mississippi Delta; from 0.4 ft/century (Saucier, 1963) to as much as 1.3 ft/century (Watson, 1982). The Corps of Engineers authorized two sequences of levee heightening, in

Since its completion, the seaway has eroded to a width of 2000 ft in places (Coastal Environments, 1984), due in large part to ship wakes in the relatively confined channel. In addition, siltation necessitates ongoing dredging, which cost the Corps of Engineers about $16 million per year. Salt water intrusion along the channel has impacted adjacent marshes, although significant quantities of salt water have not been conveyed inland during hurricanes, because the channel's width is relatively insignificant when compared to adjoining bodies of water, such as Breton Sound and Lake Borgne.

During Hurricane Katrina the MRGO channel was overtopped by the near-record storm surge that came from the east off of Lake Borgne, probably between 6 and 7 AM on August 29th (because the flood waters reached Paris Road in Chalmette between 8 and 8:30 AM). The overtopping caused by the severe storm surge quickly eroded the MRGO levees in those reaches where the levees were comprised of materials with little of no cohesion and high organic content. In long stretches the entire levee was washed away down to its original marsh foundations without a trace (Figure 4.33).

Figure 4.33: Area where the southwest bank of the MRGO channel levee within two miles southeast of Bayou Dupree was completely swept away by overtopping from Lake Borgne (photo by L. F. Harder).

4.9 Influence of Elevation Datums on New Orleans Flood Protection System

4.9.1 Introduction

Persistent subsidence of the Gulf Coast/Mississippi River Delta region has led to a complex relationship between the various geodetic datums used during historic surveys of the area. The underconsolidated and organic rich sediments of the Mississippi Delta are continually subsiding due to their compressible nature, the biochemical oxidation of the entrained organics, and all the other factors described in Section 3.7. Tectonic activity along active normal faults is also contributing to subsidence of nearly the entire Gulf Coast region. Rates of subsidence are highly variable throughout the region, resulting in a complex relationship between different geodetic datums at benchmarks in the New Orleans area. Subsidence combined with a slow rise in sea level (about 1 ft per century) has caused much of the Gulf Coast Region surrounding New Orleans to drop ten or more feet relative to sea level in historic times, both of which have made the city more vulnerable to tropical storms.

It is important to accurately determine elevations in relation to sea-level in order to design and construct flood protection systems in areas vulnerable to tropical storms. Unfortunately outdated terrestrial datums were referenced when constructing many of the floodwalls protecting New Orleans. Variations of the NGVD29 datum were used, which is based on terrestrial reference points, not sea level. The use of the outdated datums also neglected subsidence and sea level rise, resulting in a lesser protection height than intended in the floodwall designs. The subsidence of the region has made the correlation of datums a complex task. No single conversion factor may be used when converting between two datums.

4.9.2 17th St. Outfall Canal

Between 1952 and 2005, there has been a 2.345 foot decrease in the elevation of the benchmark ALCO at the mouth of the 17th St. Outfall Canal due to subsidence and adjustment of datums. In 1952, the benchmark elevation was 8.235' while it had decreased to 5.89' by 2005 (post Katrina) according to the NGVD29 (1952) and LMSL (1983-1992) datums, respectively.

When the concrete I-walls were placed atop the 17th St. Outfall Canal Levees during the 1990's, their tops were to extend to an elevation of 14.0 feet according to the NGVD datum. Contract reports do not specify which NGVD epoch was to be used in design and construction. It is possible that NGVD29 (09 Apr 1965) was used. In addition, NGVD is a terrestrial datum and is not directly referenced to sea level as is LMSL. The top of the 17th St. Outfall Canal Floodwall is presently between 1.3 and 1.9 below the design level of 14.0 feet according to LMSL (1983-1992). This is likely due to the use of an outdated datum (1.6 feet of difference) and settlement of the levee embankments and floodwalls (0.3 feet).

4.9.3 London Ave. Outfall Canal

The floodwalls bordering the London Ave. Outfall Canal were also designed and built during the 1990's. According to contract documents, the NGVD29 (09 Apr 1965) datum was used. The use of an outdated, terrestrial datum in conjunction with settlement has resulted in the floodwall heights being 1.6-1.8 feet below their intended heights of 14.4 feet (LMSL (1983-1992)).

4.9.4 Orleans Outfall Canal

The NGVD29 (01 Sep 1982) datum was referenced during the design and construction of the Orleans Outfall Canal floodwalls in the 1990's. Presently, the floodwalls surrounding this canal are up to 0.8 feet lower than called for than the 14.0-14.9 foot elevation called for in the designs (according to LMSL (1983-1992)).

4.9.5 Inner Harbor Navigation Canal – East Levee

Floodwalls were placed atop the Inner Harbor Navigation Canal's East Levee in 1970. The walls were to extend to 15.0 feet (MSL) according to the 1969 contract documents. MSL was tied to an earlier terrestrial datum and the exact correlation to modern adjustments has yet to be determined. Floodwalls presently reach heights between 12.3 and 13.2 feet according to the LMSL (1983-2001) datum. Overtopping did contribute to the three breaches that formed in this levee during Katrina.

4.9.6 Inability to Apply Universal Corrections for Elevation Datums

Although subsidence has played a role in the differences between designed and actual floodwall heights, most of the variance appears to have been caused by datum abnormalities. It is standard engineering practice to use an NGVD datum to determine sea level. The use of NGVD is not cause for concern in portions of the country away from coastlines but becomes troublesome in areas at or just above sea level.

Due to the highly variable rates of subsidence throughout the region, a common conversion factor cannot be used to adjust between datums, even over a short distance. The complex relationships between the various geodetic datums in the New Orleans Region are not discussed in great detail in this report. A more thorough discussion of this subject is presented in Chapter III of IPET's (2006) second report.

Datum	Conversion to Mean Sea Level 1929
Ellet Datum of 1850	unknown
Delta Survey Datum of 1858	0.86
Old Memphis Datum of 1858	-8.13
Old Cairo Datum of 1871	-21.26
New Memphis Datum of 1880	-6.63
Mean Gulf Level Datum (preliminary) 1882	0.318
Mean Gulf Level Datum of 1899	0
New Cairo Datum of 1910	-20.434
Mean Low Gulf Level Datum of 1911	-0.78

Figure 4.34: Table relating correction factors used when comparing various historic datums in the New Orleans area (Denny, 2002). Blanket corrections can no longer be made to adjust elevations to NAVD88-2004.65, which is the most oft cited datum currently used in New Orleans. The reason for these disparities is the gross differential settlement between reference benchmarks, which can be significant (order of magnitude difference).

4.10 Names of New Orleans Neighborhoods

Figure 4.35 presents the official neighborhood names recognized by the City of New Orleans. Local residents also use local ward and district numbers, and parish names to describe an area. A common example would be the Lakeview and Gentilly areas, which are used in a general sense to describe the former Cypress swamplands that now are among the City's lowest lying areas. The "Lakeview district" more or less encompasses Lakewood West End, Lakewood, Lakeview, Navarre, and City Park neighborhoods. The "Gentilly district" more or less includes the Fillmore, St. Anthony, Dillard, Milneburg, Gentilly Terrace, Pontchartrain Park and Gentilly Woods neighborhoods.

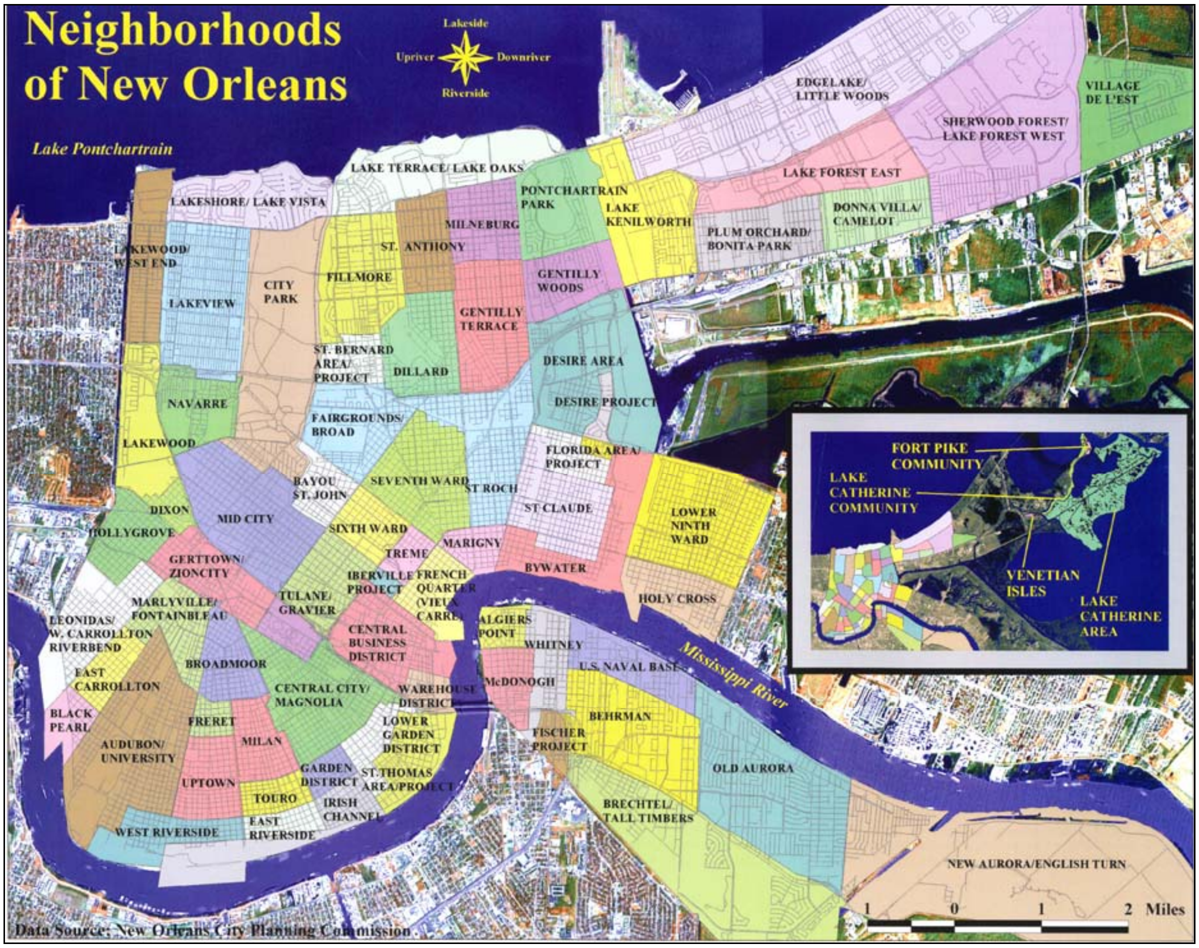

Figure 4.35: Official neighborhood names recognized by the City of New Orleans (taken from Campanella, 2002). The Ninth Ward used to extend across the IHNC, but that portion east of the IHNC has been re-named the "Lower Ninth Ward."

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