Development of the New Orleans Flood Protection System prior to Hurricane Katrina

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Abstract: The system of flood protection surrounding New Orleans and its adjoining parishes prior to Hurricane Katrina evolved over a period of 280 years. The earliest drainage works sought to elevate the river's natural levees and excavate drainage canals leading towards Bayou St. John, the only natural break across the Metairie-Gentilly distributary ridge. An extensive zone of Cypress Swamps occupied the levee flank depression between the ridge and Lake Pontchartrain. 58 km of drainage canals were excavated across the natural levee backslope and through the swamp depressions bordering the lake between 1833 and 1878. These canals sought to drain the lower portions of the city, which suffered periodic outbreaks of yellow fever, which killed more than 100,000 people during the 19th century. The city has not suffered flooding from the Mississippi River since 1895, most damaging floods having emanated from hurricane surge off of Lake Pontchartrain. Since 1559, 177 hurricanes have struck the Louisiana coastline. A system of pump stations was constructed between 1895 and 1927, which pump water into the river, the lake, and adjacent bayous. The cypress swamps were replaced by the Lakeview and Gentilly residential districts, built after 1945. This old swamp zone has settled as much as 3+ m since 1895. After 1927 the Army Corps of Engineers assumed a leadership role in providing flood control infrastructure, supervising the Mississippi River & Tributaries Project in 1931–1972. In 1955 the Corps role was expanded to include the City of New Orleans, which included maintaining capacity and freeboard of the old drainage canals. After a series of lawsuits between 1961 and 1977, the Corps was forced to employ concrete flood walls along the subsiding drainage canals. These walls were constructed in the 1990s, though some transition elements remained incomplete when Hurricane Katrina struck in August 2005.

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Introduction

New Orleans was established by the French in 1718 to guard the natural portage between the Mississippi River and Bayou St. John, leading to Lake Pontchartrain (Fig. 1). The original settlement was laid out as 14 city blocks, with drainage ditches around each block. The first levee along the left bank of the Mississippi River was erected soon thereafter because the settlement was also prone to periodic flooding by the Mississippi River between April and August, compounded by the hurricane season between June and October. The city has unfavorable topography for drainage (Fig. 7) lying within a meter above sea level on the eastern margins of the Mississippi River deltaic plain, which is settling at a rate of between 0.6 and 3.0 m per century.

The swamps bounding the north side of New Orleans were referred to as "back swamps" on the oldest maps, and "cypress swamps" on maps prepared after 1816 (Fig. 8). During the steamboat era (post-1815), New Orleans emerged as the major transshipment 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 6,350 t annually. After completion of the Mississippi River jetties in 1879, New Orleans became a year-round deepwater port and experienced a 65-fold increase in seaborne commerce, increasing to 410,000 t annually, second only to New York. New Orleans retained its No. 2 position until well after World War II. 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 initiated (see profile in Fig. 7 to compare height of the back levee with that along the Mississippi River). Most of the lowland cypress swampland between Mid-City and Lake Pontchartrain was subdivided between 1900 and 1920, after the City began constructing a comprehensive drainage system. Draining the old swamps triggered a real estate boom that witnessed a 700% increase in the City's urban acreage, an 80% increase in assessed valuations during the same period (Campanella 2002). Most of these lowland lots were not developed until after World War I. Another 728 ha was reclaimed from the south shore of Lake Pontchartrain in 1928–1931 and the balance of the lowlands was built out following the World War II, between 1946 and 1975.

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Fig. 1. Map of modern Mississippi River Delta in vicinity of New Orleans, which lies between river and Lake Pontchartrain. New Orleans lies about 100 river mi. upstream of river's mouth in Gulf of Mexico (image reproduced with permission of the National Geographic Society, 1971).

Flood Hazards

Mississippi River

The Mississippi River has a watershed area of around 3,224,550 km^2 and drains 41% of the continental United States. When combined with the Missouri River, it is the longest river in North America with an aggregate length of 6,268 km. Prior to 1950, the sediment load averaged 500–680 million t per annum (Meade and Parker 1985). After 1950, this figure began plummeting, and hovers around ~200 million t/year at present (Meade and Parker 1985). This reduction is attributable to the construction of dams in the basin, levees, jetties, and dredging of the navigation channel.

The Mississippi's alluvial flood plain attains a maximum width of 130 km above Baton Rouge. 67,340 km^2 of flood plain was inundated during the 1927 flood; 52,608 km^2 in the 1973 flood, and 40,404 km^2 in the 1993 flood.

The vexing problem with the Mississippi River is that the main channel forms the high ground in the flood plain (Fig. 2). Suspended sediment tends to elevate the river's bed when flood surges subside, allowing the river to elevate its own bed. When the river spills out of its channel sediment is deposited on the adjoining lowlands. This "overbank" sediment is hydraulically sorted, becoming more fine grained with increasing distance from the channel, as shown in Fig. 3.

Tens of thousands of square kilometers of flood plain swamps and marshlands in the Mississippi Embayment downstream of Cape Girardeau, Mo. were reclaimed by a system of drainage ditches, beginning around 1910, when large dragline excavators became available. After 1928, boom and tower dragline excavators were employed for levee construction on the MR&T Project (described later).

A great number of floods have occurred in the lower Mississippi Valley during historic time. The most damaging to the New Orleans region 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. Surprisingly, the last river-derived flood of any consequence that inundated structures in New Orleans occurred in 1859.

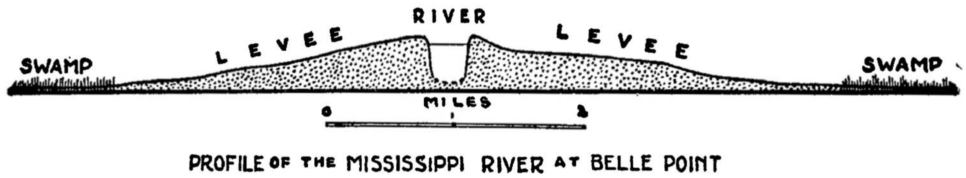


Fig. 2. Typical cross section through natural levees of Mississippi River at Belle Point, about 90 km upstream of New Orleans. It illustrates how river's main channel lies above surrounding flood plain, which was poorly drained swamp land prior to reclamation in 20th Century (from Williams 1928).

The city recorded its first brush with flooding in April 1719, when the city's founder, Jean Baptiste le Moyne, reported that the river filled the new settlement with "half a foot of water." He suggested constructing levees and drainage canals, and soon required similar measures to be undertaken by all the landowners. In 1734–1735 the Mississippi River remained high from December to June, breaking levees and inundating the new settlement.

Flood protection from the river was achieved by heightening of the river's natural levees (Hewson 1870), like those sketched in Fig. 4. On May 5, 1816 the river levee protecting New Orleans gave way at the McCarty Plantation, in present-day Carrollton, and within a few days 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 ditch was excavated through Metairie Ridge and channels connecting to Bayou St. John.

On May 4, 1849 the Mississippi River broke the levee at the Suavé Plantation at River Ridge, 24 km upstream of New Orleans. Within 4 days this water reached the New Basin Canal, and within 17 days, was flooding the French Quarter, north of Bienville and Dauphine Streets (Fig. 5). In 1849 flood waters rose at an average rate of 0.3 m every 36 h, which allowed residents ample time to evacuate. Uptown residents thought about severing the levee along the New Basin Canal to prevent water from building up on their side, but those living on the opposite side of the canal threatened armed forces to prevent such action. Shortly thereafter, the New Basin upper levee collapsed, diverting flood waters to Bayou St. John and Lake Pontchartrain. A 2.7 m deep lake developed in what is now the Broadmoor area, flooding 220 city blocks and necessitating the evacuation of 12,000 residents.

The 1849 crevasse at Suavé Plantation (Fig. 8) was eventually plugged by driving a line of timber piles and dumping thousands of sand bags against the land side of the piles. Drainage trenches were then excavated through Metairie Ridge to channel water out to Lake Pontchartrain. By mid-June 1849 residents began reentering 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 85.5 river km 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 2,134 m wide crevasse developed at Bonnet Carré which diverted flow from the Mississippi into Lake Pontchartrain for more than 6 months. This breach had to be filled so sufficient discharge could allow ships to reach New Orleans on the river.

The 1849 floods were the last time that the eastern bank of the Mississippi River was breached within New Orleans' city limits. 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. In January 1859 the rear portion of New Orleans again flooded, between Carrollton and Esplanade Avenues, moving eastward and flooding one-third of the city for 3 months.

In 1850 Army Engineer A.A. Humphreys and civilian engineer Charles Ellet were charged by Congress to make independent scientific examinations of the Mississippi River and report their findings. Ellet completed his work in 1851, but Humphreys suffered a nervous breakdown and did not complete his report until 1861. Humphreys went on to assume control of the Mississippi River as Chief of the Corps of Engineers between 1866 and 1879. His "levees only policy" of flood control was fundamentally flawed, but remained accepted doctrine until the great flood of 1927 (Morgan 1971; Barry 1997). Humphries maintained that the Mississippi River could be constrained within its natural low flow channel by extending its natural levees upward. This theory assumed the channel would downcut its bed vertically during high flows, and thereby remain within its confined channel. The prob-

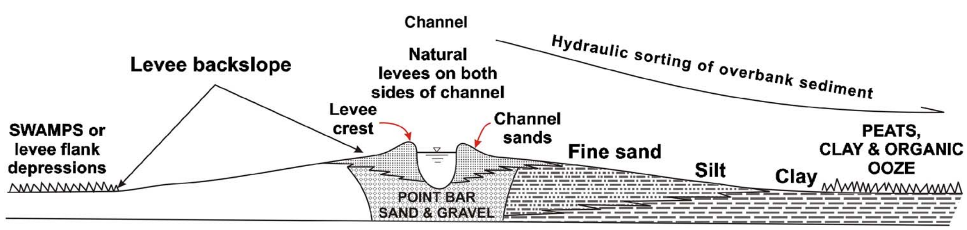


Fig. 3. Cross section illustrating hydraulic sorting of sediments with increasing distance from Mississippi River, in vicinity of Carrollton. Levee backslope zone lies between elevated levees and poorly drained swamps. In New Orleans, Carrollton, Uptown, French Quarter, and Central Business Districts are all situated on natural levee and its backslope, while midcity area was built on levee flank depression, between natural levees of Mississippi River and Metairie distributary channel (Fig. 5). Lakeview, Gentilly, and Ninth Ward areas occupy old cypress swamps (Saucier 1963, 1994).

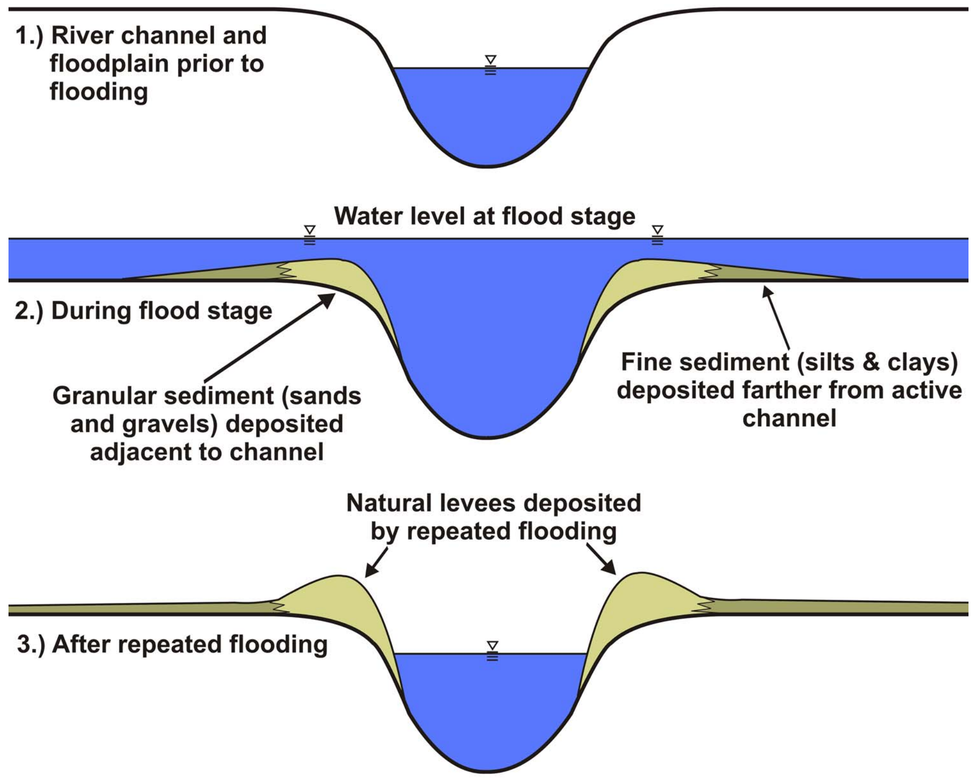


Fig. 4. Natural levees exist along most perennial channels subject to periodic overbank flooding emanating from prominent low flow channel, as sketched above. Man-made levees originated by piling up additional earthen fill on top of these natural levees.

lem with this precept was that it was fundamentally two dimensional, assuming the channel to be straight and possessing a symmetrical cross section, like those depicted in Fig. 4. In realty the Mississippi exhibits a serpentine curvature, which causes the channel to exhibit marked asymmetry, with deep and shallow sides, as shown in Fig. 6. Channel asymmetry was accompanied by marked changes in the hydraulic grade, which is generally inversely proportional to river curvature, using a principle known as "curve compensation" (Leopold et al. 1964). River channels increase their thalweg gradient to overcome increased friction, in proportion to the radius of curvature around bends in the channel, because of increased friction. By this manner a river's hydraulic grade and channel characteristics tend to adjust themselves so as to yield the velocity needed to transport the sediment load supplied by its own drainage basin (Leopold and Maddock 1954). The result is that meandering channels tend to migrate toward the outer side of sharp bends, undercutting their own natural levees, upon which engineers often construct man-made levees.

In 1871 the Mississippi River once again spilled its eastern bank at Bonnet Carré, 53 km upstream of New Orleans. The break diverted much of the river's flow into Lake Pontchartrain, raising its level. A strong north wind pushed the elevated lake water up into the Metairie and Gentilly Ridges (Fig. 5), filling the city's drainage canals. A levee on the Hagan Avenue (now the Jefferson Davis Parkway) drainage canal gave way, flooding the back side of New Orleans.

During the late 19th Century most engineers began to appreciate that levee breaks upstream or downstream of the city provided "safety valves," which served to retard flood stages along the city's waterfront. Breaks in adjoining areas give rise to rumors about levees being purposefully undermined to save the more valuable property in the city, which reached epic proportions during the record flood of 1927, when the levees adjoining Plaquemines Parish were dynamited seven times by New Orleans businessmen and politicians (Barry 1997).

The 1927 flood was the largest ever recorded on the lower Mississippi Valley. The deluge was preceded by a record 46 cm of rain falling on New Orleans in a 48 h period in late March 1927, which was followed by 6 months of flooding. The levees that were supposed to protect the valley broke in 246 places, inundating 70,000 km^2 of bottom land; displacing 700,000 people, killing 1,000 more (246 in the New Orleans area), and damaging or destroying 137,000 structures.

Flooding from Hurricanes

Hurricanes strike the Louisiana Coast with a mean frequency of two every 3 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 2.44 m. Had the river not been running low prior to the storm, it might have overtopped its banks by as much as 4.6 m. In 1778, 1779, 1780, and 1794 hurricanes struck the New Orleans area destroying buildings and sinking ships. The worst storm of the early years 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 4.6 m of water. The parade ground at Fort St. Phillip was inundated by 2.4 m of water and the shoreline

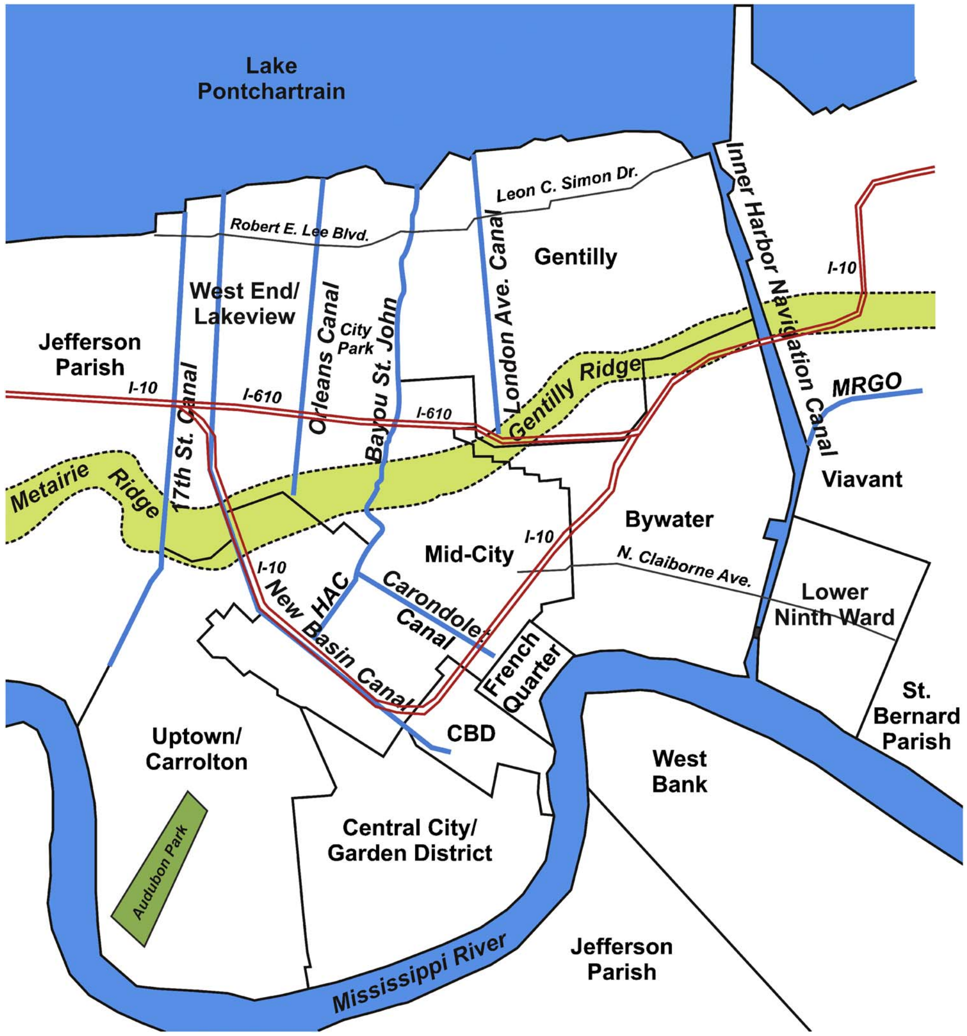


Fig. 5. Generalized map of prominent drainage features and neighborhoods of New Orleans. System of drainage canals have been expanded and adjusted for more than 200 years. Parallel lines denote locations of Interstates 10 and 610 through city. Note how portion of I-10 follows infilled New Basin Canal.

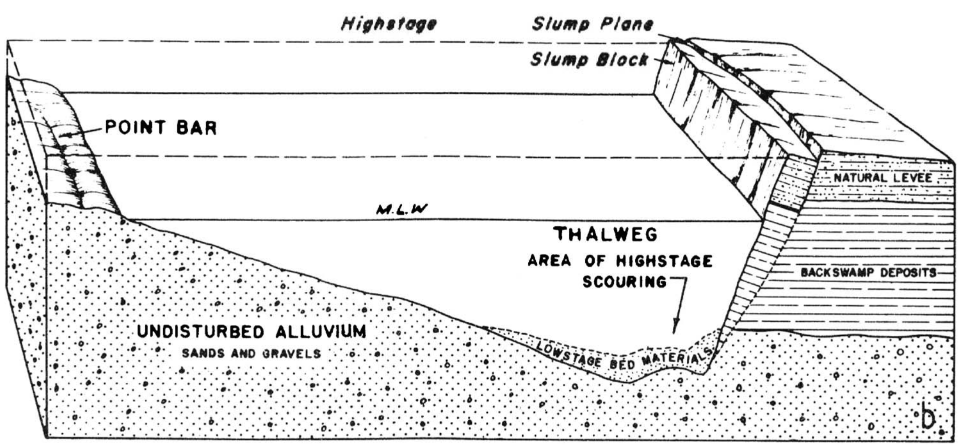


Fig. 6. Asymmetric channel cross section typical of Mississippi River, showing slumping of oversteepened banks on outside of its turns and relative position of river's thalweg, line connecting lowest points along bed of river. Channel asymmetry promotes lateral migration along sharp turns in river, which undermine levees and flood walls situated close to slumping banks. "Levees only policy" failed to recognize this three-dimensional aspect of low gradient rivers flowing on relatively broad, flat flood plains (image from Fisk 1952).

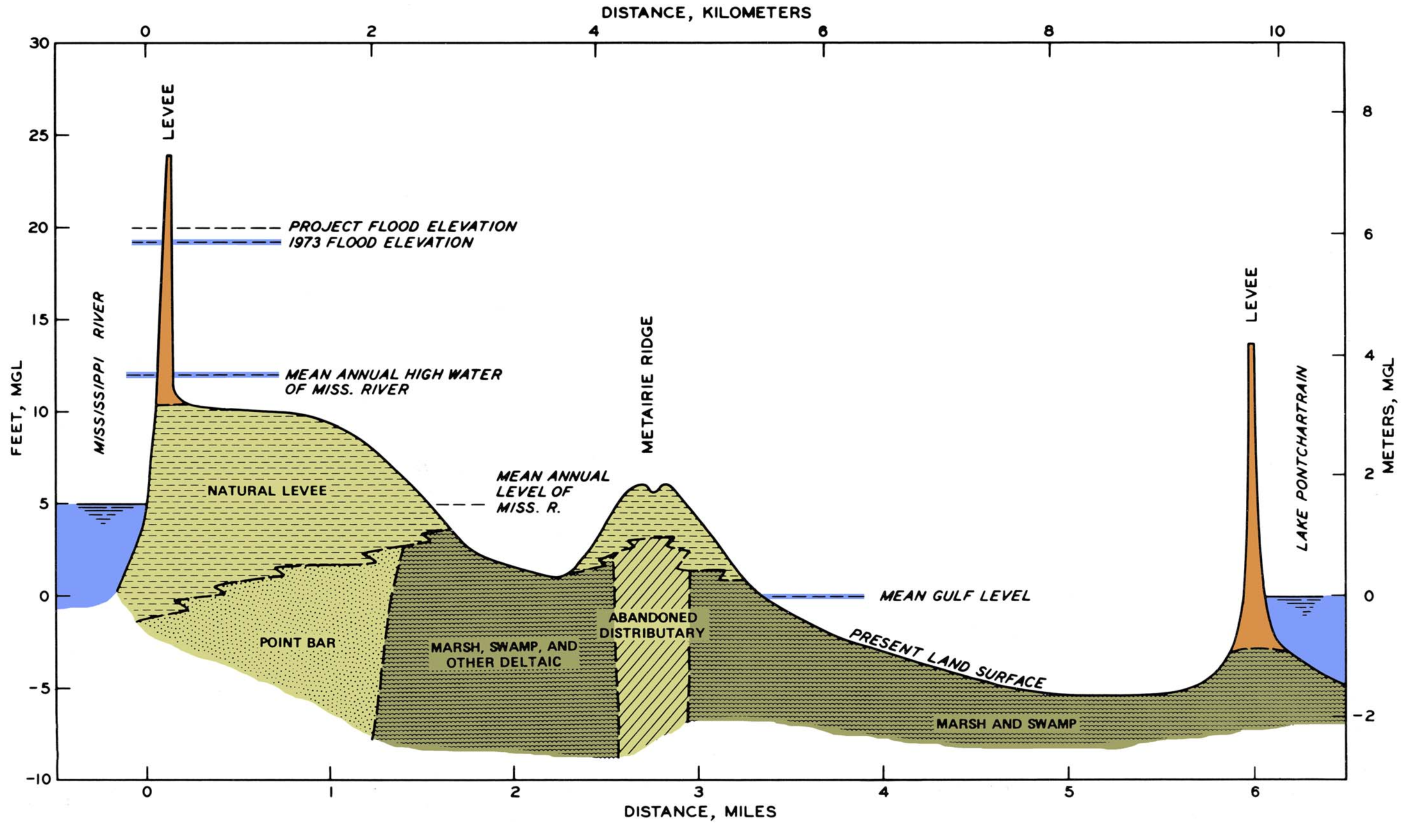


Fig. 7. This geologic section illustrates how much of New Orleans lies below mean gulf level, requiring every drop of rain water to be pumped out. Height of Mississippi River levee is 7.5 m while Lake Pontchartrain levee crests at 4.1 m (adapted from Kolb and Saucier 1982).

along Lake Pontchartrain was similarly inundated, though this was sufficiently far from the city to spare it from damage.

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 (Fig. 5). These "ridges" are about 1.2 m higher than the surrounding lowland (Fig. 7), but much of the former cypress swamps and marshes have settled as much as 3 m over the past 110 years, while the ridges, being underlain by sand, have only settled 0.3–0.6 m. The ridges provided quasi-flood protection levees from storm surges coming off Lake Pontchartrain during hurricanes (Fig. 7). But, the ridge also prevented runoff from draining away from the old French Quarter, towards Lake Pontchartrain. In 1794 the Carondelet (Old Basin) Canal was excavated between Basin Street and Bayou St. John (Fig. 5), 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 inundated by a storm surge, while a 1 m 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 three hurricanes during the summer and fall of 1860. On August 8 a fast moving hurricane swept 6.1 m of water into Plaquemines Parish. The third hurricane struck on October 2 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, and washed out a portion of the New Orleans and Jackson Great Northern Railroad. Surge from this storm overtopped the banks of the Old and New Basin drainage canals and a levee along Bayou St. John, allowing onrushing water to flood 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 floodwaters into the Mid-City area (Fig. 5). 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.

The record hurricane of October 2, 1893 passed south of New Orleans, generating winds of 160 km/h and a storm surge of 4 m, which drowned more than 2,000 people in Jefferson Parish (it also destroyed 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, Tex., demolishing that city and killing between 6,000 and 8,000 people (Cline 1926), which remains the deadliest natural disaster in American history

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 gusts of up to 225 km/h at Grand Isle. It slowed as it made landfall and passed over Audubon Park (Fig. 5), seriously damaging structures across the city. Electrical power was knocked out, preventing the city's new pumps from functioning. The storm surge on Lake Pontchartrain rose to 4 m, easily overtopping the 1.8 m tall shoreline levee and destroying the lakefront villages of Bucktown (at the end of 17th Street Canal), West End, Spanish Fort, and Lakeview. The drainage canals were also overtopped, flooding the city from its relatively unprotected north side, leaving Mid-City and Canal Street under almost 1 m of water. The storm surge off Lake Pontchartrain killed 275 people in the shoreline zone.

On September 19, 1947 an unnamed hurricane made landfall near the Chandeleur Islands, producing wind gusts between 145 and 200 km/h. A storm surge of 3.0 m reached Shell Beach on Lake Borgne. The runways at Moisant Airport were covered by 0.6 m of water while Jefferson Parish was flooded to depths of +1 m. Sewage from the city's overwhelmed treatment plant stagnated in some of the canals, producing sulfuric acid fumes that turned lead-based paint black on many homes. Fifty one people drowned and New Orleans suffered $100 million in damages. City officials were unable to clear these floodwaters for nearly 2 weeks. This was the first New Orleans hurricane that generated reliable storm surge data, which were subsequently used in design of flood protection works.

In 1948–1949 the levees along the south shore of Lake Pontchartrain were heightened and extended westward, across Jefferson Parish. In addition, the embankments along the old drainage canals were raised with earth fill to provide increased freeboard. The precise height of these additions depended on position and historic settlement at the time. The entire Lakeview area north of what is now Interstate 610 (excluding the area filled by the Lakefront Improvement Project) was already more than 0.6 m below sea level by 1937 (WPA 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 258 km/h and a 4.8 m storm surge overwhelmed the entire island. Winds gusts up to 200 km/h were recorded in New Orleans along with a storm surge of 3.0 m, which overtopped both sides of the Inner Harbor Navigation Canal (IHNC), flooding the Ninth Ward, Gentilly, Lake Forest, and St. Bernard Parish, revealing inadequacies in the levee protection system surrounding the city. Eighty one 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 in 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. This work included raising the Lake Pontchartrain levee to a height of 3.66 m above mean gulf level (MGL). The Orleans Levee Board began providing additional freeboard by installing steel sheetpiles along the crests of their drainage canal levees. These exposed sheetpiles were intended to be a temporary measure, awaiting placement of concrete flood walls that would utilize the sheetpiles as their foundations. 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. Camille made landfall on August 17, its eye crossing the Mississippi Coast at Pass Christian, about 84 km east northeast of New Orleans. Wind velocities reached 306 km/h, while gusts on land exceeded 322 km/h, causing most wind meters to fail. Camille annihilated the coastal communities between Henderson Point and Biloxi, and flooding 10,101 km^2 of coastal lowland between lower Plaquemines Parish and Perdido Pass, Ala. The peak storm surge measured 7.62 m above MGL near Pass Christian, Miss., 4.57 m in Boothville, La., 2.74 m in The Rigolets, and 1.83 m in Mandeville, La. The death toll form Camille was 258 people, with 135 of these being from the Mississippi coast. Seventy three thousand families either lost homes or experienced severe damage and the aggregate damage amounted to $1.4 billion, with damages in Louisiana totaling $350 million. A particularly vexing aspect of Camille was that it occurred just 4 years after Hurricane Betsy, which had been touted as something between a 1-in-200 and 1-in-300 year recurrence frequency event (USACE 1965).

On September 28, 1998 Hurricane Georges wreaked havoc across the Caribbean, pummeling Haiti, the Dominican Republic, Puerto Rico, and other islands. Georges appeared to be headed straight for New Orleans, but turned east just before making landfall near Biloxi, Miss. (about 110 km east northeast of New Orleans). Georges produced sustained winds of over 160 km/h at landfall, generating a storm surge of 2.71 m at Point à la Hache, La. Maximum surge along the Gulf Coast was 3.35 m, in Pascagoula, Miss. Hurricane Georges severely eroded the Chandeleur Islands in outer St. Bernards Parish.

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 flood protection system.

Flooding from Rainfall

The New Orleans area receives an average rainfall of about 132 cm/year. In the winter of 1881 severe rainstorms caused flooding of the downtown area, up to 0.9 m deep. Rain storms of severe intensity also caused significant flooding of New Orleans in 1927, 1978, 1980, and 1995.

The 1927 storm dumped 35.6 cm on Good Friday, temporarily overwhelming the Sewerage & Water Board's (S&WB) vaunted system of pump stations. Uptown streets were flooded, with the Broadmoor and Mid-City areas inundated by 1.8 m of water and 0.6 m 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 6 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 25.4 cm of rain during the morning, with a peak sustained intensity of 5 cm/h. The runoff exceeded the aggregate capacity of the S&WB pump stations (located along the drainage canals and buried conduits), causing extensive flooding of low lying areas that lasted about 24 h.

A series of intense rain storms struck Louisiana, Mississippi,

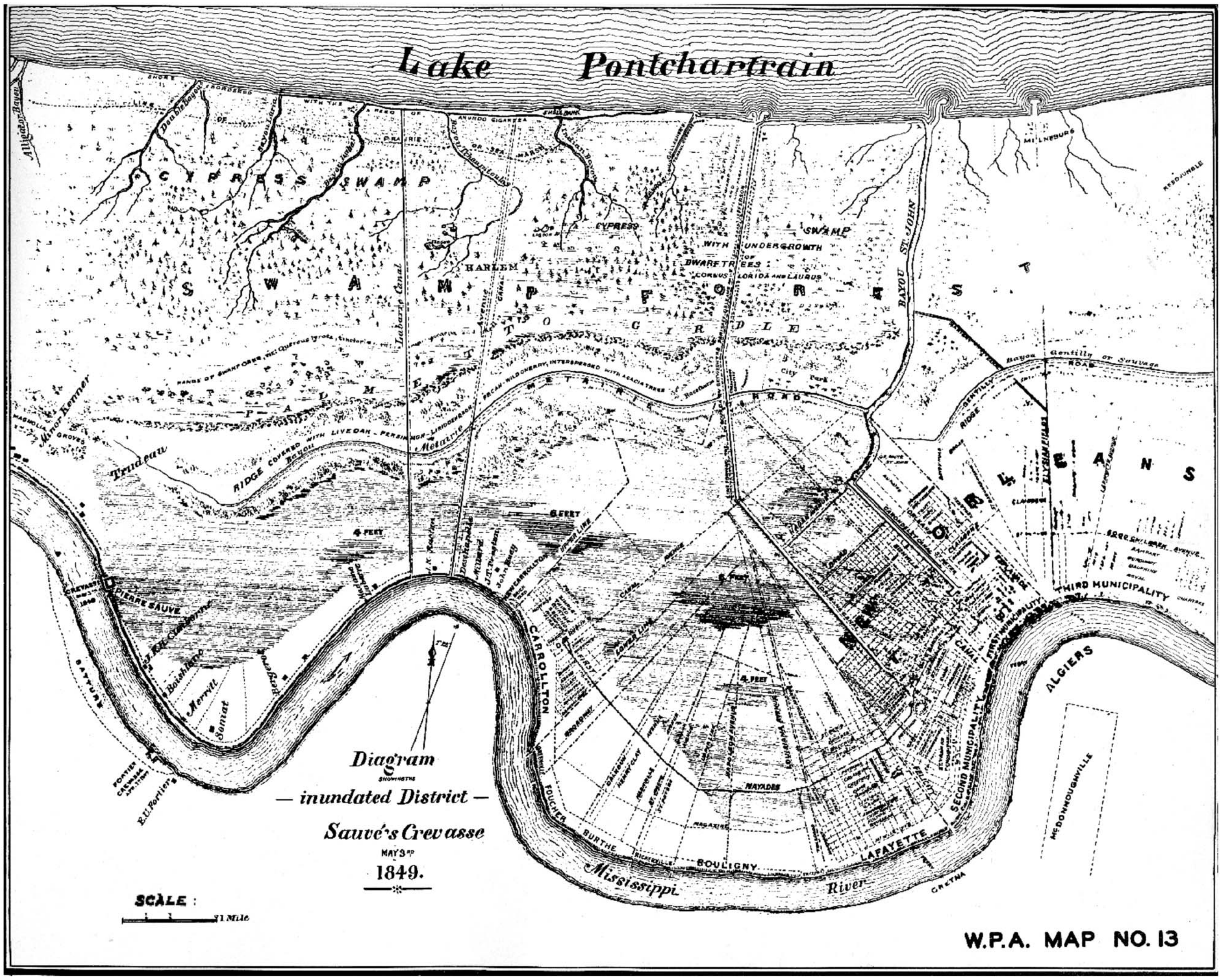


Fig. 8. Map of Sauvés Crevasse and portions of New Orleans inundated by flooding of 1849. This map shows extensive cypress swamps lying between Uptown and French Quarter areas and Lake Pontchartrain. Carondelet and New Orleans Canals are clearly shown, but curiously omits New Basin Canal (built in 1830s). Map shows projected path of 17th Street Canal on border between Orleans and Jefferson Parishes, but it appears to have been completed few years later, in 1857–1858 (taken from WPA 1937).

and Alabama in two consecutive sequences in March and April of 1980. The first storm occurred from March 26 to April 2, 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 the area bounded by Baton Rouge, New Orleans, and Mobile, Ala. 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 (Fig. 5), where steel sheetpiles providing additional freeboard had recently been removed for replacement.

On the evening of May 8–9, 1995 a cold front approaching New Orleans from the west stalled after moving east of Baton Rouge. A nearly continuous chain of thunder storms befell the New Orleans area, dropping 10–30.5 cm of rain on New Orleans. The storm's intensity overwhelmed the S&WB's aggregate pump capacity of 1,331 m^3/s and most of the city was temporarily flooded, including portions of the Interstate highways. More severe storms struck the coast the following evening, but not as severe over New Orleans proper, although the 2 day totals established a record 62.23 cm in Abita Springs, La. The 1995 storm lasted 40 h and damaged 44,500 homes and businesses, causing $3.1 billion in damages. This was the costliest single nontropical weather related event to ever affect the United States.

Flood Control Infrastructure

Drainage Canals (1794–Present)

The drainage canals of New Orleans are a unique feature of the city. The first drainage canal was the old Carondelet Canal excavated in 1794, by order of Spanish Governor Baron de Carondelet. It was dug by convicts and slaves and was later subsequently enlarged to accommodate shallow draft vessels 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. That name later changed to the Old Basin Canal. It was infilled in the 1920s, when it became Lafitte Avenue and railroad tracks were laid down the street's centerline.

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 the post-Civil War era. The New Basin Canal

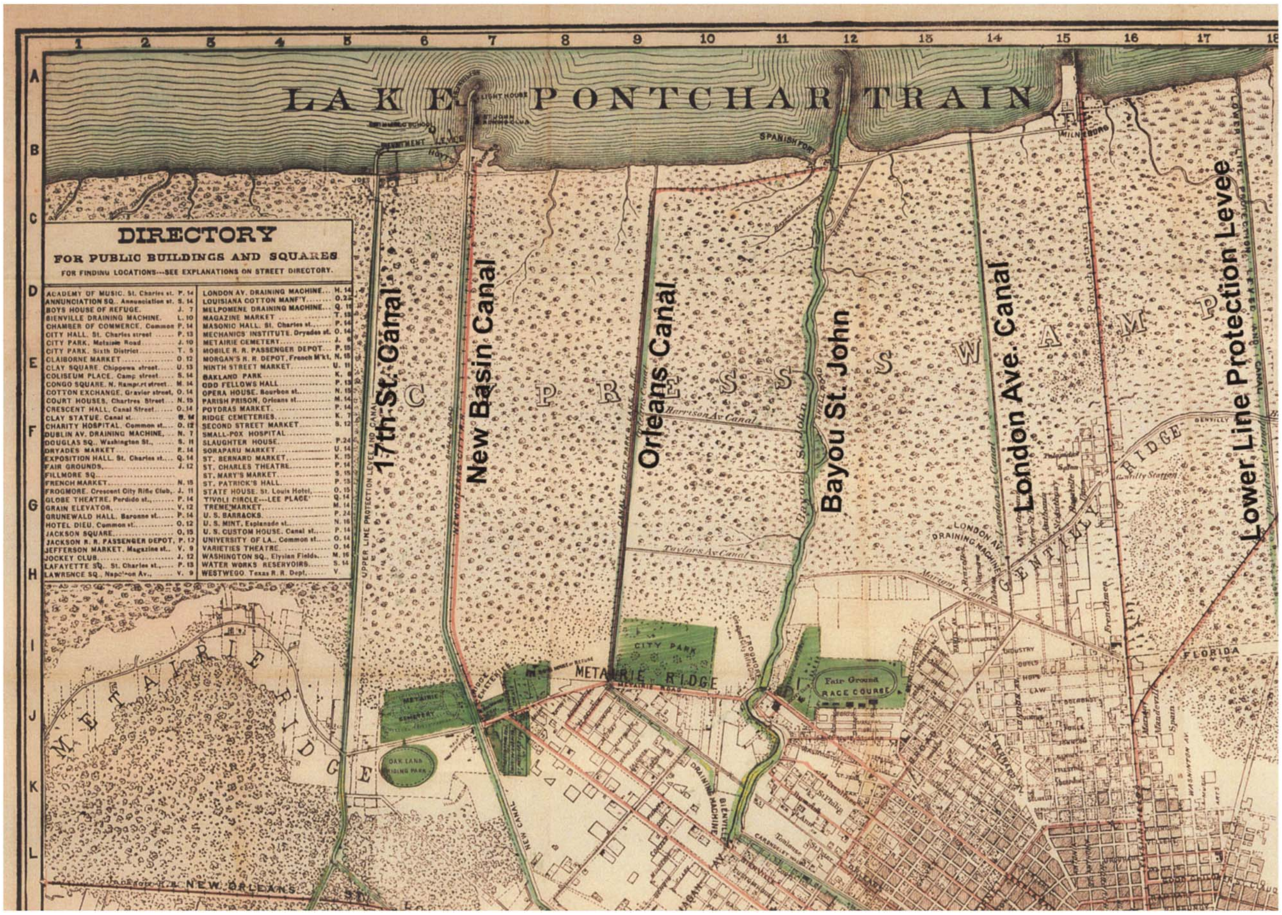


Fig. 9. All 58 km of drainage canals in Lakeview and Gentilly areas are shown in this portion of 1878 Hardee map (Courtesy of The Historic New Orleans collection). Canals are, from left: 17th Street, New Basin (infilled), Orleans, Bayou St. John, and London Avenue, and Lower Line Protection Levee.

was the first to cut through Metairie Ridge (Fig. 5). The severing of Metairie Ridge was a double edged sword, as flood waters from Lake Pontchartrain were afterward capable of rising into the downtown area along this path, which initially occurred in 1871. The portion south of Metairie Ridge was filled in the 1930s; and the remainder in the 1950s, when the Pontchartrain Expressway replaced the old canal.

The Topographic Map of New Orleans and Vicinity prepared by Charles F. Zimpel in 1833–1834 suggests that portions of the Orleans Canal had already been excavated and were proposed for extension at that time to convey water from Bayou Metairie to Lake Pontchartrain (Lemmon et al. 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 Claiborne Canal, and thence 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, although 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 maps at the Historic New Orleans Collection suggests that the Upper Line Protection Levee or 17th St. Canal along the Orleans-Jefferson Parish boundary was excavated between 1854 and 1858. The 17th 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 17th Street canal just east of the railroad tracks and the new village of Bucktown, along the shore of Lake Pontchartrain. The 1878 Hardee map (Fig. 9) calls this 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.

Disastrous outbreaks of yellow fever in the 1850s spurned new ideas to drain the cypress swamps. Between 1857 and 1859 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 (Fig. 5). 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. The 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, called "draining machines."

These steam-powered pumps were located: at the head of the New Canal at Dublin and 14th Streets; at the head of the Old Melpomene Canal (at what is now Martin Luther King and Claiborne); at the head of Bayou St. John (at Hagan and Bienville); and just north of Gentilly and London Avenues. These draining machines were a city trademark for many years thereafter. Shortly before the outbreak of the Civil War in 1861, the legislature passed another bill that allowed the draining districts to levy special assessments to make repairs based on the recommendations of their respective governing boards (see Fig. 8).

The Banks Map of February 1863 shows the position of the Jefferson and Lake Pontchartrain Railroad along the 17th 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, which operated between 1831 and 1932, its northern terminus being named "Port Pontchartrain."

The upper end of the London Avenue Canal was constructed in the 1860s, north of Bayou Gentilly. One of the steam-powered draining machines was located near London and Pleasure Street, which lifted water from the upper London Canal into the cypress swamp north of Gentilly Ridge. The lower London Avenue Canal appears to have been extended out to Lake Pontchartrain, sometime between 1873 and 1878.

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 the 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 2 decades before a substantive drainage plan eventually evolved).

New Orleans drainage dilemma can be appreciated from a review of the cross section presented in Fig. 7. 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 0.5 and 1 m above the adjacent swamp land (see Fig. 9).

Raising Drainage Canal Levees in 1915 and 1947

The protection levee along Lake Pontchartrain was erected after the 1893 hurricane, which generated a storm surge of up to 4 m (described previously). This protective structure was known as the "shoreline levee" and was 1.8 m above the normal surface of Lake Pontchartrain. The creation of this structure was a double-edged 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. After this flooding, S&WB general superintendent George Earl ordered the levees along the drainage canals to be raised approximately 0.91 m (3 ft), and the Pontchartrain shoreline levee was also raised.

The hurricane of September 1947 caused storm surges of up to 3 m above MGL along the shores of Lakes Borgne and 1.68 m along the south shore of Lake Pontchartrain which overwhelmed levees in the IHNC and the old drainage canals, within 1.6 km 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 17th 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 1947–1948 (see Fig. 10).

Fig. 10. Photo taken in 1890 looking north along "shell road" that ran along west side of New Basin Canal, seen at extreme right. Note modest height of original embankment, no more than 1.5 m above adjacent cypress swamp at left. Canal levees were heightened after hurricanes in 1915 and 1947. (Image from University of New Orleans special collections)

System of Pumped Conveyance (1895–Present)

The failure of the Hagan Avenue Canal (HAC) levee in 1871 signaled the beginning of a political crisis, hastened by hurricane-induced surges off Lake Pontchartrain. The City sought a better solution than it had heretofore employed in providing reliable drainage to Lake Pontchartrain. City surveyor W.H. Bell warned of the potential dangers posed by the 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 58 km of canals in New Orleans between 1871 and 1878, before going out of business. In 1878 the city assumed responsibility for maintenance of this system of canals feeding into Lake Pontchartrain. The city's old network of steam-powered paddle-wheel lift stations could only handle 3.8 cm of rainfall in 24 h, which accommodated the nominal 1-year recurrence frequency storm. As a consequence, the city began suffering flooding problems with increasing frequency.

The drainage problem was 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 of the low lying cypress swamps, which were being reclaimed by excavating shallow drainage ditches feeding into the system of drainage canals. In the 1880s houses began to appear on the old swamps below Broad Street. No one regulated the flow to the drainage canals and sewage simply made its way into the drainage canals, thence to Lake Pontchartrain. 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 roughly equaled the river's normal level.

The drainage crisis grew throughout the 1880s. In 1890 the Orleans Levee Board solicited bids for a workable drainage plan, but no plans were submitted because there were no reliable topographic data. Newspaper editorials and civic leaders recognized the city could not continue growing without a substantive effort to handle drainage and sewage. In February 1893 the city council established a Drainage Advisory Board (DAB) and provided \$700,000 to gather the necessary topographic and hydrologic data and make recommendations on how the problems might be solved. As part of this effort an accurate topographic map of the city was prepared under the direction of City Engineer L. W. Brown.

The first DAB findings were unveiled in January 1895 (Advisory Board 1895; Kelman 1998). The 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. The conveyance problems were unprecedented, insofar that the city would need to install a series of pump stations to convey runoff into Lakes Borgne and Pontchartrain, many miles distant. The projected costs were in excess of those believed feasible, given the limitations of revenue collection being used to fund drainage improvements at that time.

The following year (1896) the Louisiana legislature solved the impasse by creating a state-funded Drainage Commission of New Orleans, which began preparing a comprehensive drainage plan for the city and recommending a system of taxation to pay for it. In 1897 this commission began building new pump stations, a power generation station, and additional drainage canals and conduits feeding into the existing network.

In June 1899 voters passed a municipal bond referendum mandating a property tax of 2 mils/dollar to fund municipal waterworks, sewerage, and drainage. With this revenue mechanism in place, the Sewerage & Water Board of New Orleans was shortly thereafter established 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 realigning and shifting the existing system of canals, filling in those canals that contained stagnant water, which provided an unwanted habitat for mosquitoes. In 1903 the S&WB was merged with the Drainage Commission to consolidate operations under one agency.

By 1905 the S&WB had completed 64.4 km of drainage canals (in addition to the 58 km they inherited), constructed six new electrically powered pumping stations, and had a pumping capacity of 142 m^3/s (5,000 cfs), which represented about 44% of the nal plan. At this time the S&WB provided drainage for 89 km^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, some development of these low lying areas ensued, due to many of the city's residents purchasing lots on speculation, to sell later. This is why many of the lots in lower New Orleans were developed over a long period of time, leading to the heterogeneity of architectural styles that became a New Orleans trademark. A downside of this ongoing development was the ever-increasing runoff that accompanied emplacement of impervious surfaces, such as streets, roofs, sidewalks, and the like.

By 1910 the new S&WB system was being overwhelmed and something needed to be done to increase capacity. A young mechanical engineer named A. Baldwin Wood joined the S&WB upon graduation from Tulane in 1899. Wood took on the various challenges facing the S&WB with unparalleled enthusiasm and imagination. Within a few years he developed a 1.83 m (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 when he introduced his low-lift "Wood screw drainage pump," a 3.66 m diameter screw pump that employed an enormous impellor powered by a 25 Hz alternating current electrical motor. The motive power was highly efficient, using 6.1 m 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 New Orleans let a contract for 13 Wood screw pumps, installing 11 units in three pump stations. By that time there were 113 km of drainage canals in place. The city's new drainage system was overwhelmed when the power generating stations for the new pumps were flooded during the September 29, 1915 Grand Isle Hurricane (discussed previously).

By 1926 the New Orleans S&WB was serving an area of 122 km^2 with a 901 km long network of drainage canals and storm drains with an aggregate pumping capacity of 368 m^3/s. This impressive infrastructure had been constructed over a period of 47 years at a cost of \$27.5 million. Up to this time most of the S&WB's revenue had been generated by the special 2-mill property tax and half of the surplus from the 1% debt tax. As the city grew and the S&WB's jurisdiction increased beyond the original city limits, the tax structure was repeatedly amended. The S&WB is currently funded by a number of sources, including 3, 6, and 9-mil property taxes.

By 2005 the S&WB was responsible for draining 247 km^2 of New Orleans and neighboring Jefferson Parish, which receive an average annual rainfall of 132 cm/year. The pre-Katrina system shown in Fig. 11 was intended to handle an average annual discharge of 365 million m^3 of water that was pumped into Lake Pontchartrain, Lake Borgne, and the Mississippi River. The City's 22 main pump stations and ten underpass pump stations were still using about 50 Wood screw pumps, and their system was capable of lifting an aggregate total of 1,331 m^3/s of water under peak operating conditions. A typical pump station (No. 6) could lift 272 m^3/s using its' Wood pumps. New Orleans also employs vertical pumps with impellors to lift water from subterranean (below street) storm drains to the drainage canals, which discharge into Lake Pontchartrain. The S&WB maintains 145 km of covered drainage canals, 132 km of open channel canals, and several thousand kilometers of storm sewer lines feeding into their system (Fig. 11).

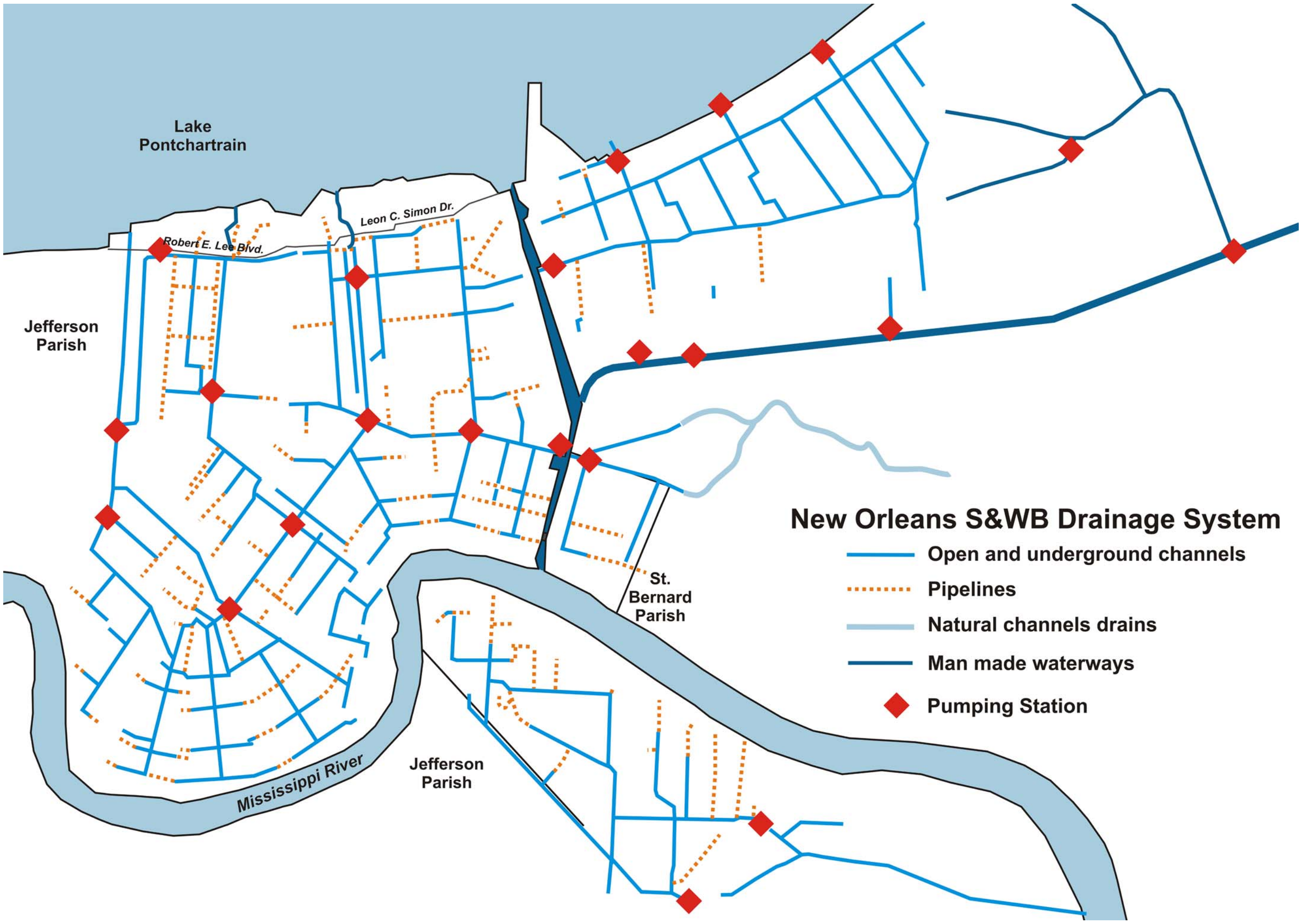


Fig. 11. Map showing municipal drainage system operated by New Orleans Sewerage & Water Board, as it existed prior to Hurricanes Katrina and Rita. Note that much of conveyance system has gradually been buried.

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 it was referred to as The "Jadwin Plan," because Major General Edgar Jadwin was Chief of Engineers in 1927 (Jadwin 1928). This plan was incorporated into the Federal Flood Control Act of May 1928, which authorized $325 million to the Mississippi River Commission. This commission had been the dream of James B. Eads to circumvent the Army's abject control of flood control and navigation issues along the great river. Congress enacted legislation to create the commission in 1879, but the Corps managed to shift the original intent so they controlled a majority of the seats on the commission, and Eads resigned (Morgan 1971; Camillo and Pearcy 2006). The commission was charged with providing flood protection along the Mississippi River between Cape Girardeau, Mo. and Head-of-Passes, La. The Mississippi River Commission assumed responsibility for implementing the flood protection measures envisioned in the Jadwin plan. The commission's importance increased by an order of magnitude because of Congressional appropriations that accompanied the new plans (Watson 1982). After several years of design, construction began in 1931, when the authorized funds were appropriated by Congress.

The new system of flood protection along the lower Mississippi River was christened the Mississippi River and Tributaries Project (MR&T) (Camillo and Pearcy 2006). Army engineers selected a project flood of 66,828 m^3/s at the mouth of the Arkansas River and 85,800 m^3/s 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, 97 km downstream of Natchez, Miss.

The MR&T 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 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 2,586 km along the Mississippi River, with another 966 km along the banks of the lower Arkansas, Red, and Atchafalaya Rivers.

The MR&T plan 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 also constructed by the Corps of Engineers. These included: (1) the Birds Point-New Madrid Floodway between Cairo, Ill. and New Madrid, Mo.; (2) the Old River or Red River Landing Diversion structure, intended to divert half the project flood (42,481 m^3/s) from the main channel into the Atchafalaya River through the Morganza and West Atchafalaya floodways; and (3) the Bonnet Carré bypass and floodway, a concrete spillway capable of diverting 7,080 m^3/s into Lake Pontchartrain during periods of high flow, about 48 km upstream of New Orleans.

In addition to construction of these large structures, the corps implemented numerous channel improvement and stabilization measures along the entire course of the navigable channel, to enhance bank stability and navigation. The corps employed cutoffs to shorten the channel and increase hydraulic grades, to reduce flood heights. They also armored banks below water to retard channel migration and meandering. Countless dikes have been employed to direct the river's flow, most out of view, beneath the channel surface. Periodic 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 5.8–9.0 m in New Orleans and can draft off 7,080 m^3/s into Lake Pontchartrain. The Old River Control structure nearly failed catastrophically during the Flood of 1973, when the north side was completely undercut by back-eddy scour (Noble 1976; McPhee 1989). The structure was saved by the network of battered piles supporting it (MRC 1975). The Corps repaired this structure and added a second overflow weir, doubling the diversion capacity at this critical junction, at the mouth of the Red and head of the Atchafalaya Rivers (Camillo and Pearcy 2006).

The average height of the MR&T levees above the natural levees in the Gulf Region is about 4.9 m (Kolb and Saucier 1982). The crest of the flood protection levee along the eastern bank of the Mississippi River is 4.5 m MGL at Carrolton in New Orleans, shown in Fig. 7. The Lake Pontchartrain protection levee is 4.1 m MGL (also shown in Fig. 7). All of the New Orleans 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 could erode a massive breach that would overwhelm the city's lowest neighborhoods before residents could conceivably escape.

The 1928 Flood Control Act has been modified 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 and acquisition of lands for floodways, etc. These early changes resulted in the Overton Act of 1936, which established a national flood control policy to be administered by the Corps, 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 has continued to the present, usually following flood years. As a consequence the MR&T project has never officially been declared "complete" (Camillo and Pearcy 2006).

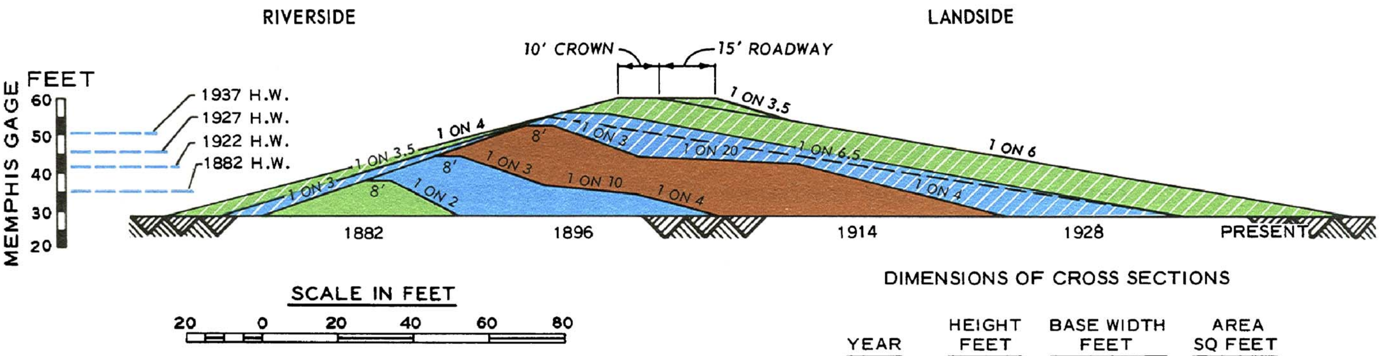
Today, 5,977 km of flood control levees have been authorized for construction under the MR&T project. 5,488 km of levees have been completed and 4,483.5 km are in place to grade and section. On the main stem of the Mississippi River 2,578 km of levees have been completed. Work on the main stem levees was about 89% complete and work on tributary levees about 75% complete when Hurricane Katrina struck.

Federal Involvement with New Orleans Drainage Canals (1955–2005)

Federal involvement with the city's drainage canals began in 1955 with approval of the Lake Pontchartrain and Vicinity Hurricane Protection Project by Congress (USACE 1984). The Corps studied the problems posed by the drainage canals, which had settled as much as 3 m since their initial construction between 1833 and 1878. 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 1 m of embankment height to keep water trained within the drainage canals and provide sufficient freeboard from storm surges emanating from Lake Pontchartrain. The maximum design capacity of the three principal drainage canals (17th Street, Orleans, and London Avenue) was about 283 m^3/s, but this figure was gradually reduced by ongoing settlement and sedimentation problems.

The Corps had several nonfederal partners in the venture: the Orleans and Jefferson Parish Levee Boards and the Sewerage & Water Board of New Orleans (USACE 1987). 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 flood in soft soils. If they didn't pump much water, then the canals could fill up with sediment, which reduces their capacity. By the time the Corps got involved, single family residences abutted the drainage canals along their entire courses (the canals are 4–5.6 km long). The encroachment of these homes circumvented any possibility of using conventional methods to heighten the levees, which is usually accomplished by compacting earth fill on the land side of the embankments (Fig. 12). Raising the embankments would have required condemnation and removal of hundreds of residences, which would have been costly and time consuming.

In 1960 the Corps of Engineers New Orleans District office issued its initial report outlining their plan for remedying the capacity problems with the slowly sinking drainage canals. The Corps wanted to solve the canal freeboard problem by installing tidal gates and pumps at the drainage canal outfalls along Lake



YEAR	HEIGHT FEET	BASE WIDTH FEET	AREA SQ FEET
1882	9.0	53.0	274
1896	15.5	120.5	951
1914	24.0	200.0	2455
1928	27.0	260.0	3645
PRESENT	30.5	315.0	4956

Fig. 12. Evolution of Corps of Engineers' standard levee section, 1882–1972 (from Moore 1972). Earth embankment levees are generally heightened sequentially by compacting additional soil on land side of embankments. Existing homes abutted land side of drainage canals in New Orleans by time Corps of Engineers began analyzing them in 1960s (Department of the Army, Corps of Engineers, Mississippi River Commission, Vicksburg, Miss.).

Pontchartrain. These gates were intended to remain open, unless the storm surge on Lake Pontchartrain elevated sufficiently to prevent outflow. If/when the lake waters rose, the plan envisioned that the gates would be closed by the Corps and pumps would have to be used to convey water from the drainage canals into Lake Pontchartrain. The Corps' plan obviated condemnation of existing homes that would be required if the canal levees required heightening using earth fill. 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 their proposal, because of worries about coordination with the Sewer & Water Board, who operated the pumping plants feeding into the drainage canals. The projects' detractors feared that the tidal gates would malfunction, inhibiting outflow of pumped storm water, and therein cause unnecessary 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 earthen dikes along the eastern shore of Lake Pontchartrain and massive gates at the passes (The Rigolets), to prevent storm surges from reaching the lake. This scheme was expensive, was opposed by environmental groups (the proposed embankment was almost 300 m wide), and never garnered sufficient political support to receive appropriations.

The issue of how to improve the drainage canals dragged on for another 17 years. Between 1960 and 1977 what few lots remained in lower New Orleans were built out and most of the post-1970 development focused on the areas east of the IHNC, in Jefferson Parish, and across the Mississippi River (Algiers, etc.). In December 1977 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. The Corps focus then shifted to heightening the drainage canal levees using concrete flood walls, which was the alternative favored by most neighborhood groups. These walls were to be designed to withstand a Category 3 storm surge with 3.66 m high tides and 210 km/h winds.

Construction began in 1993, but the wrong elevation datum were selected for the contract drawings, so some of these walls were constructed up to 0.6 m 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 6–8 h of overtopping.

Flow records for the drainage canals in New Orleans indicate that between 1932 and 2005, a flow stage of +1.22 m MGL was exceeded on at least 29 occasions; +1.5 m was exceeded 13 times (including Hurricanes Betsy in 1965 and Camille in 1969); +1.8 m was exceeded only three times (including Hurricanes Juan in 1985 and Isadore in 2002); and the stage exceeded +2.1 m for the first and only time on August 29, 2005, during Hurricane Katrina.

Conclusions

Historically, the main focus of energy with regard to flood control of New Orleans has revolved around protection from the Mississippi River, which has not flooded the city since 1859, although it came perilously close in 1927. Since 1928, the flood protection along the Mississippi River has been provided chiefly by the U.S. Army Corps of Engineers Mississippi River & Tributaries Project, a comprehensive system that extends hundreds of miles upstream of New Orleans, into the upper Mississippi, Red, White, Black, St. Francis, Missouri, Tennessee, Cumberland, and Ohio River systems tributary to the lower Mississippi River.

Within the City of New Orleans an elaborate system of drainage collection, pumping, conveyance, and discharge has been developed over the past 100 years, which continues to be expanded and upgraded, as the lower portions of their jurisdiction continue to subside and new areas of development are annexed into the drainage district administered by the Sewer & Water Board. Although the S&WB system was efficient from an energy expenditure perspective, the 25 Hz AC electrical power required 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 MGL and were subject to shutdown by flooding.

The Corps of Engineers gradually took on more and more of the responsibility for maintaining flood protection around the entire city, beginning in 1956. This activity was exacerbated by continuing enlargement of the city after 1956 and a series of lawsuits brought against the Corps during the 1960s and 1970s, which they ultimately lost. The drainage canals were excavated between the 1830s and 1870s, and the IHNC between 1918 and 1923; all without Corps involvement. These levees were heightened on a number of occasions (1915 and 1947) without significant broadening of their base footprints. All of these structures experienced settlement, often with noticeable differentials between adjacent reaches. After the Corps lost a series of lawsuits concluded in 1977, they were forced to employ concrete flood walls on the crests of drainage canal levees and the Inner Harbor Navigation Channel (some flood walls had already been constructed along the IHNC, beginning in the late 1960s). This system of flood walls were built in the 1980s and 1990s, with the intent of providing protection against a Category 3 hurricane, based on design assumptions formulated by the Corps in the wake of Hurricane Betsy in 1965. This system of flood walls was incomplete when Hurricanes Katrina and Rita struck New Orleans in 2005, although many of the flood walls failed well below their design heights, by mechanisms involving underseepage. 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, or felt themselves able to do so.

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References

Advisory Board (New Orleans). (1895). "Report of the drainage of the City of New Orleans by the Advisory Board, appointed by Ordinance No. 8327, adopted by the City Council (of New Orleans), November 24, 1893." *Rep.*, New Orleans.

Barry, J. M. (1997). *Rising tide: The great Mississippi flood of 1927 and how it changed America*, Simon & Schuster, New York.

Beauregard, P. G. T. (1859). "Report on proposed system of drainage for first draining district, New Orleans." *Rep. to Chief Engineer's Office*, U.S. Army Corps of Engineers, New Orleans.

Camillo, C. A., and Pearcy, M. T. (2006). *Upon their shoulders: A history of the Mississippi River Commission from its inception through the advent of the modern Mississippi River and Tributaries Project*, 2nd Ed., Mississippi River Commission, Vicksburg, Miss.

Campanella, R. (2002). *Time and place in New Orleans: Past geographies in the present day*, Pelican Publishing, Gretna, La.

Cline, I. M. (1926). *Tropical cyclones: Comprising an exhaustive study of features observed and recorded in sixteen tropical cyclones which have moved in on Gulf and south Atlantic coasts during the twenty-five years, 1900–1924 inclusive*, Macmillan, New York.

Fisk, H. N. (1952). *Geological investigation of the Atchafalaya Basin and the problem of Mississippi River diversion*, Vol. 1, U.S. Corps of Engineers Waterways Experiment Station, Vicksburg, Miss.

Hewson, W. (1870). *Principles and practice of embanking lands from river-floods, as applied to "levees" of the Mississippi*, 2nd Ed., Van Nostrand, New York.

Interagency Performance Evaluation Task Force (IPET). (2006). "Performance evaluation status and interim results." *Rep. No. 2 of a Series, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System*, Washington, D.C.

Jadwin, E. (1928). "The plan for flood control of the Mississippi River in its alluvial valley." *Great Inland Water-Way projects in the United States*, R. A. Yound, ed., Vol. CXXXV, American Academy of Political and Social Science, Philadelphia, 35–44.

Junger, S. (1992). "The pumps of New Orleans." *American Heritage Invention Technology*, 8(2), 42–48.

Kelman, A. (1998). "A river and its city: Critical episodes in the environmental history of New Orleans." Ph.D. dissertation, Brown Univ., Providence, R.I.

Kesel, R. H. (2003). "Human modification of the sediment regime of the lower Mississippi River flood plain." *Geomorphology*, 56, 325–334.

Kolb, C. R., and Saucier, R. T. (1982). "Engineering geology of New Orleans." *Rev. Eng. Geol.*, 5, 75–93.

Lemmon, A. E., Magill, J. T., Wiese, J. R., and Hebert, J. R., eds. (2003). *Charting Louisiana: Five hundred years of maps*, The Historic New Orleans Collection, New Orleans.

Leopold, L. B., and Maddock, T., Jr. (1954). *The flood control controversy: Big dams, little dams, and land management*, Ronald Press Co, New York.

Leopold, L. B., Wolman, M. G., and Miller, J. P. (1964). *Fluvial processes in geomorphology*, W. H. Freeman, New York.

McPhee, J. A. (1989). *The control of nature*, Farrar, Straus, Giroux, New York.

Meade, R. H., and Parker, R. S. (1985). "Sediment in rivers of the United States." *National water summary 1984—Water quality issues*, U.S. Geological Survey, Washington, D.C., 49–60.

Mississippi River Commission (MRC) and Lower Mississippi Valley Division. (1975). The *flood of '73*, Corps of Engineers, U.S. Army, Vicksburg, Miss.

Moore, N. R. (1972) *Improvement of the lower Mississippi River and tributaries 1931–1972*, Dept. of the Army, Corps of Engineers, Mississippi River Commission, Vicksburg, Miss.

Morgan, A. E. (1971). *Dams and other disasters: A century of the Army Corps of Engineers in civil works*, Porter Sargent, Boston.

Noble, C. C. (1976). "The Mississippi River flood of 1973." *Geomorphology and engineering*, D. R. Coates, ed., Dowden, Hutchinson & Ross, Halsted Press, Stroudsburg, Pa.

Reuss, M. (1998). *Designing the bayous: The control of water in the Atchafalaya Basin 1800–1995*, Office of History, Corps of Engineers, U.S. Army, Alexandria, Va.

Saucier, R. T. (1963). *Recent geomorphic history of the Pontchartrain basin*, Louisiana, Coastal Studies Series No 9, Louisiana State University Press, Baton Rouge, La.

Saucier, R. T. (1994). *Geomorphology and quaternary geologic history of the lower Mississippi Valley*, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss.

Shallat, T. (1994). *Structures in the stream: Water, science, and the rise of the U.S. Army Corps of Engineers*, University of Texas Press, Austin, Tex.

Shallat, T. (2000). "In the wake of Hurricane Betsy." *Transforming New Orleans and its environs: Centuries of change*, C. E. Colten, ed., University of Pittsburgh Press, Pittsburgh, 121–137.

Snow, R. F. (1992). "Low and dry." *American Heritage Invention Technology*, 8(2), 4–5.

U.S. Army Corps of Engineers (USACE). (1965). *Hurricane Betsy September 8–11, 1965*, U.S. Army Engineer Office, New Orleans.

U.S. Army Corps of Engineers (USACE). (1984). "Lake Pontchartrain, Louisiana, and vicinity hurricane protection project." *Reevaluation study*, New Orleans District, New Orleans.

U.S. Army Corps of Engineers (USACE). (1987). "General design, Jefferson Parish Lakefront Levee, Vol. 1." *Design Memorandum No. 17*, New Orleans District, New Orleans.

Watson, C. C. (1982). "An assessment of the lower Mississippi River below Natchez, Mississippi." Ph.D. dissertation, Colorado State Univ., Fort Collins, Colo.

Williams, F. E. (1928). "The Geography of the Mississippi Valley." Great Inland Water-Way Projects in the United States, *Annals of American Academy of Political and Social Science*, CXXXV, 7–14.

Works Projects Administration of Louisiana (WPA). (1937). *Some data in regard to foundations in New Orleans and vicinity*, New Orleans.