

CHAPTER TWO: OVERVIEW OF HURRICANE KATRINA AND ITS AFTERMATH

2.1 Hurricane Katrina

The path of Hurricane Katrina's eye is shown in Figures 2.1 and 2.2. Hurricane Katrina crossed the Florida peninsula on August 25, 2005 as a Category 1 hurricane. It then entered the Gulf of Mexico, where it gathered energy from the warm Gulf waters, producing a hurricane that eventually reached Category 5 status on Sunday, August 28, shortly before making its second mainland landfall just to the east of New Orleans early on Monday, August 29, as shown in Figures 2.1 and 2.2. The Hurricane had weakened to a Category 4 level prior to landfall on the morning of August 29, and it weakened further as it came ashore.

Because the eye of this hurricane passed just slightly to the east of New Orleans, the hurricane imposed unusually severe wind loads and storm surges (and waves) on the New Orleans region and its flood protection systems.

2.2 Overview of the New Orleans Flood Protection Systems

Figure 2.3 shows the main study region. The City of New Orleans is largely situated between the Mississippi River, which passes along the southern edge of the main portion of the city, and Lake Pontchartrain, which fronts the city to the north. Lake Borgne lies to the east, separated from developed areas by open swampland. "Lake" Borgne is not really a lake at all; instead it is a bay as it is directly connected to the waters of the Gulf of Mexico. To the southeast of the city, the Mississippi River bends to the south and flows out through its delta into the Gulf of Mexico.

The flood protection system that protects the New Orleans region is organized as a series of protected basins or "protected areas", each protected by its own perimeter levee system, and these are "unwatered" by pumps.

As shown in Figures 2.4 and 2.5, there are four main protected areas that comprise the New Orleans flood protection system of interest. A number of additional levee-protected units also exist in this area, but the focus of these current studies is the four main protected areas shown in Figures 2.4 and 2.5. These were largely constructed under the supervision of the U.S. Army Corps of Engineers, to provide improved flood protection in the wake of the devastating flooding caused by Hurricane Betsy in 1965.

Figures 2.4 and 2.5 show the locations of most of the levee breaches and severely distressed (but non-breached, or only partially breached) levee sections covered by these studies. Levee breaches are shown with solid blue stars, and distressed sections as well as minor or partial breaches are indicated by red stars. The original base maps, and many of the stars, were graciously provided by the USACE (2005), and a number of additional blue and red stars have been added to the map in Figure 2.4 as a result of the studies reported herein. The yellow stars shown in these figures correspond to deliberate breaches made after Hurricane Katrina, to facilitate draining the flooded areas after the storm.

The pink shading in Figures 2.4 and 2.5 shows developed areas that were flooded, and the areas shaded with blue cross-hatching indicate undeveloped swamp land that was flooded. The deeper blue shading (near the east end of New Orleans East) denotes areas that still remained to be unwatered as late as September 28, 2005. As shown in these figures, approximately 85% of the metropolitan area of New Orleans was flooded during this event.

As shown in Figure 2.4, the Orleans East Bank (Metro Orleans) section is one contiguously protected section. This protected unit contains the downtown district, the French Quarter, the Garden District, and the “Canal” District. The northern edge of this protected area is fronted by Lake Pontchartrain on the north, and the Mississippi River passes along its southern edge. The Inner Harbor Navigation Canal (also locally known as “the Industrial Canal”) passes along the east flank of this protected section, separating the Orleans East Bank protected section from New Orleans East (to the northeast) and from the Lower Ninth Ward and St. Bernard Parish (directly to the east.) Three large drainage canals extend into the Orleans East Bank protected section from Lake Pontchartrain to the north, for the purpose of conveying water pumped north into the lake by large pump stations within the city. These canals, from west to east, are the 17th Street Canal, the Orleans Canal, and the London Avenue Canal.

A second protected section surrounds and protects New Orleans East, as shown in Figure 2.4. This protected section fronts Lake Pontchartrain along its north edge, and the Inner Harbor Navigation Canal (IHNC) along its west flank. The southern edge is fronted by the Mississippi River Gulf Outlet channel (MRGO) which co-exists with the Gulf Intracoastal Waterway (GIWW) along this stretch. The eastern portion of this protected section is currently largely undeveloped swampland, contained within the protective levee ring. The east flank of this protected section is fronted by additional swampland, and Lake Borgne is located slightly to the southeast.

The third main protected section contains both the Lower Ninth Ward and St. Bernard Parish, as shown in Figure 2.4. This protected section is also fronted by the Inner Harbor Navigation Canal on its west flank, and has the MRGO/GIWW channel along its northern edge. At the northeastern corner, the MRGO bends to the south (away from the GIWW channel) and fronts the boundary of this protected area along the northeastern edge. Open swampland occurs to the south and southeast. Lake Borgne occurs to the east, separated from this protected section by the MRGO channel and by a narrow strip of undeveloped marshland. The main urban areas occur within the southern and western portions of this protected area. The fairly densely populated Lower Ninth Ward is located at the west end, and St. Bernard Parish along approximately the southern half of the rest of this protected area. The northeastern portion of this protected section is undeveloped marshy wetland, as indicated in Figure 2.4. A secondary levee, operated and maintained by local levee boards, separates the undeveloped marshlands of the northeastern portions of this protected area from the Ninth Ward and St. Bernard Parish urban areas.

The fourth main protected area is a narrow, protected strip along the lower reaches of the Mississippi River heading south from St. Bernard Parish to the mouth of the river at the Gulf of Mexico, as shown in Figure 2.5. This protected strip, with “river” levees fronting the Mississippi River and a second, parallel set of “storm” levees facing away from the river forming a protected corridor less than a mile wide, serves to protect a number of small communities as well as utilities and pipelines. This protected corridor also provides protected access for workers, supplies and

gas and oil pipelines servicing the large offshore oil fields out in the Gulf of Mexico. This will be referred to in this report as “the Plaquemines Parish” levee protected zone.

The current perimeter levee and floodwall defense systems for these four protected areas were largely designed and constructed under the supervision of the U.S. Army Corps of Engineers in the wake of the catastrophic flooding caused by Hurricane Betsy of 1965. These flood protection improvements typically involved either new levee construction, or raising existing levee defenses and/or adding new floodwalls, to provide storm flood protection for higher elevations of storm surge waters (and waves) at locations throughout the region.

2.3 Overview of Flood Protection System Performance During Hurricane Katrina

2.3.1 Storm Surge During Hurricane Katrina

The regional flood protection system had been designed to safely withstand the storm surges and waves associated with the Standard Project Hurricane, which was intended to represent a scenario roughly “typical” of a rapidly moving Category 3 hurricane passing close to the New Orleans metropolitan region. Chapter 12 (Section 12.5.1) presents a more detailed discussion of the “Standard Project Hurricane”, and the criteria for which the regional flood protection system was designed. In simple terms, the system was intended to have been designed to safely withstand storm surge levels (plus waves) to specified elevations at various locations, as shown in Figures 2.6 and 2.7.

In general, the “Standard Project Hurricane” provided for design to safely withstand storm surge rises (plus waves) to prescribed elevations at various locations throughout the system. The levels selected correspond generally to the storm surge level (mean peak storm surge water elevation, without waves) associated with the “Standard Project Hurricane” conditions plus an additional allowance for most (but not always all) of expected additional wave run-up.

As shown in Figures 2.6 and 2.7, this resulted in a targeted protection level of about elevation +17 feet to +19 feet (MSL), or 17 to 19 feet above Mean Sea Level, at the eastern flank of the system, and + 13.5 feet to +18 feet (MSL) along much of the southern edge of Lake Pontchartrain. The storm surge levels within the various drainage canals and navigational channels varied, and the storm surge levels for design were typically on the order of Elev. + 14 feet to + 16 feet (MSL) along the GIWW and IHNC channels, and Elev. + 12.5 feet to + 14.5 feet (MSL) along the 17th Street, Orleans, and London Avenue Canals in the “Canal District”. There is some minor confusion as to the most recent “Standard Project Hurricane”, and the most recent storm surge design levels at some locations; the values indicated in Figure 2.6 are an interpretation by the Government Accountability Office (GAO, 2006) based in part on initial research by the staff of the New Orleans Times Picayune, and the values shown in Figure 2.7 have been added to this figure by our team, and are our own current best interpretation.

The situation is further clouded a bit, as the actual targeted levee and floodwall heights along a given section also varied slightly as a function of waterside topography, obstacles and vegetation, levee geometry, orientation and potential wind fetch (distance of potential wind travel across the top of open water), etc. as these would affect the potential run-up heights of storm waves. Variations for these types of issues were typically minor, on the order of two feet or less.

There is, however, no “typical” hurricane, nor associated storm surge, and the actual wind, wave and storm surge loadings imposed at any location within the overall flood protection system during an actual hurricane are a function of location relative to the storm, wind speed and direction, orientation of levees, local bodies of water, channel configurations, offshore contours, vegetative cover, etc. These loadings vary over time, as the storm moves progressively through the region.

Figures 2.8 and 2.9 show plots of storm surge levels resulting from numerical modeling simulations performed by the LSU Hurricane Research Center, for two different points in time during Hurricane Katrina, based on analyses of the storm track, wind speeds, regional topography and local conditions (marsh growth, soil stiffness, offshore contours, etc.) (Louisiana State University Hurricane Center, 2005.) The water levels shown in Figures 2.8 and 2.9 were predicted using a regionally calibrated numerical model, and the results shown in Figure 2.8 represent a point in time when the eye of the hurricane was first approaching the coast from the Gulf of Mexico, and those shown in Figure 2.9 correspond to a time when the eye of the storm was passing slightly to the east of New Orleans. These calculations are part of an overall single analysis of storm surge levels throughout the region, and throughout the continuous period of time as the storm approached and then passed through the region. Based on actual field observations and measurements of maximum storm surge levels at more than 100 locations throughout the region, this global analysis of storm surge levels is expected to be accurate (relative to surge levels that actually occurred) within approximately $\pm 15\%$ at all locations of interest for these current studies (IPET, 2006.)

Predicted and actual storm surge heights varied over time, at different locations, and the water levels shown in Figures 2.8 and 2.9 do not represent predictions of the peak storm surges noted at all locations. Instead, these images show calculated conditions at two interesting points in time when: (a) [Fig. 2.8] the initial large surge was being driven up against the coast of the Gulf of Mexico in the New Orleans region by the approaching storm, and (b) [Fig. 2.9] at a particularly critical moment when a large storm surge had first “inflated” (raised the level of) Lake Borgne, then the locally prevailing westward swirl of the counterclockwise hurricane winds threw the risen waters of Lake Borgne westward over the adjacent levees protecting eastern flanks of the New Orleans East and St. Bernard/Lower Ninth Ward protected areas, as shown schematically in Figure 2.11.

These types of storm surge modeling calculations are being performed by a number of research and investigation teams, and are constantly being calibrated and updated based on actual field measurements of high water marks, etc. The USACE’s IPET investigation team are devoting significant effort to these types of hydrodynamic analytical “hind-casts”, and the IPET back analyses provided to date to our UC Berkeley-led ILIT study team are in good agreement with the storm surge predictions shown in Figures 2.8 and 2.9 at most locations of interest for these studies (IPET; Draft Final Report, June 1, 2006).

Figure 2.10 shows an aggregate summary of the calculated peak storm surges, at any point in time during Hurricane Katrina, based on similar calculations performed by the IPET study (IPET; March, 2006). These calculations are very similar to those developed by the Louisiana investigation team, and both the IPET and Team Louisiana analyses will be used as a partial basis for estimation of storm surge levels and wave conditions in these current studies. The maximum flood stages calculated (predicted) by the two sets of analyses are generally in good agreement at

most points of interest. Agreement regarding storm waves is also generally good, but the differences between the two sets of predicted storm waves are a bit more significant at a few locations of interest. Discussions of the IPET and Team Louisiana hydrodynamic storm surge and storm wave calculations will be presented, in more detail, at locations of interest in the chapters that follow.

It should be noted that a number of different datums have been used as elevation references throughout the historic development of the New Orleans regional levee systems, and this situation is further complicated by ongoing subsidence in the region. This investigation has elected to resolve these differences between different datums, and to refer to all elevations in this report (as consistently as possible) in terms of elevation with respect to the NAVD88 (2004.65) datum; approximately “mean sea level” in the region. This particular version of the NAVD88 datum is currently thought to be within about 3-inches of Mean Sea Level (MSL) in the New Orleans region. For a more in-depth discussion of differences between the various datums used in the greater New Orleans region, please see IPET Interim Report No. 2 (IPET; March, 2006).

2.3.2 Overview of the Performance of the Regional Flood Protection System

Hurricane Katrina, as expected, produced a large onshore storm surge from the Gulf of Mexico. As shown in Figures 2.8 through 2.10 this produced significant overtopping of storm levees along the lower Mississippi River reaches in the Plaquemines Parish area, and numerous levee breaches occurred in this area, as shown previously in Figure 2.5. In simple terms, the “storm” levees of Plaquemines Parish were largely overwhelmed by the large storm surge; they were overtopped by the storm surge and by the large storm waves that accompanied the average rise (storm surge) in water levels. Fortunately, the Plaquemines Parish protected corridor is only sparsely populated, and the local inhabitants were acutely aware of the risk that they faced so that evacuation in advance of the storm was unusually complete.

Plaquemines Parish was largely inundated by the massive storm surge and the numerous resulting levee breaches. Most breaches appear to have been primarily the result of overtopping and erosion, and it is interesting to note that these breaches occurred mainly in the “storm” levees, while the “river” levees often better withstood the storm surge (and waves) without catastrophic erosion. The devastation within Plaquemines parish produced by this flooding was very severe, as described in Chapter 5. By approximately 7:00 a.m. on the morning of Monday, September 29, most of Plaquemines Parish was under water.

A more detailed discussion of the performance of the flood protection systems in the Plaquemines Parish area is presented in Chapter 5.

As the storm surge began to raise the water levels throughout the New Orleans region, it began to raise the water levels within the GIWW, MRGO and IHNC channels. As the water level within the IHNC began to rise, the first “breach” within the metropolitan New Orleans region (north of Plaquemines Parish) occurred at about 5:00 a.m. somewhere along the IHNC. This was evidenced by a pronounced, and short-lived, decrease in the rate of water level rise at two gage stations along the IHNC at this point in time. There are several breaches along this section of the IHNC that might have accounted for this observed water level gage behavior, and this is discussed in Chapter 8. This was a “non-catastrophic” failure; although the breach eroded and became enlarged by the flow, the “lip” of the breach remained above sea level. As a result,

although water flowed for a while into the protected area, this flow later stopped as the storm surge subsequently subsided. Simple calculations, based on flood stages and breach sequences and dimensions, suggest that less than 5% of the water that eventually flowed into the main Orleans East Bank (downtown) protected zone entered through this breach.

The large onshore storm surge also raised water levels within Lake Borgne (which is directly connected to the Gulf.) Lake Borgne rose up, and outgrew its normal banks. As the storm then passed to the east of New Orleans, the prevailing counterclockwise swirl of the storm winds drove the waters of Lake Borgne as a large storm surge to the west, against the eastern flank of the regional flood protection systems as shown schematically in Figure 2.11. This produced a storm surge estimated at approximately +16 to +18 feet (MSL), as shown in Figures 2.9 and 2.10.

This storm surge level exceeded the crest heights of the levees along a nearly 11-mile long stretch of the northeastern edge of the St. Bernard/Lower Ninth Ward protected area. The levees along this frontage were intended to be built to provide protection to a level of approximately +17.5 feet (MSL), but at the time of Hurricane Katrina many of the levees along this frontage had crest elevations approximately 2 to 4 feet lower than that. This was because the levees along this frontage had not yet been completed. These were “virgin” levees, being constructed on swampy foundation soils that had not previously had significant levees before. Accordingly, the swampy shallow foundation soils were both weak and compressible, and the levees were being constructed in stages to allow time for consolidation and settlement of the foundations soils. This process also allowed time for the drying of the very wet locally excavated soils used for some portions of the levee embankment fills, and also for increases in strength of the underlying foundation soils as they compressed under the weights of the growing levees.

Construction of the first phase of the levees along this frontage began in the late 1960’s. The last major work in this area prior to Katrina had been the construction of the third phase, in 1994-95. Since that time, the USACE had been waiting for Congressional appropriation of the funds necessary to construct the final stage (to the full design height, with allowance for anticipated future settlements.) Now it is too late.

In addition to the levees along this frontage being well below design grade, the manner of construction and the materials used were non-typical of most other USACE levees in the region. Ordinarily, the USACE requires the use of “cohesive” (clayey) soils to create an embankment fill that is both strong and relatively resistant to erosion. The levees along the “MRGO” frontage at the northeast edge of the St. Bernard Parish/Ninth Ward protected area were instead “sand core” levees (USACE, 1966). These levees were constructed using locally available soils, including dredge spoils from the excavation of the adjacent MRGO channel.

This is a region with predominantly marshy deposits, consisting largely of organic soils and soft paludal swamp clays with very high water contents. Beneath these generally poor surficial soils, the most common materials occurring at shallow, relatively accessible depths tend to be predominantly sandy soils that are highly erodeable and generally unsuitable for levee embankment fill. A decision was made, however, to attempt to use the locally available soils rather than importing higher quality soil fill materials. The USACE Design Memorandum describing this design refers to these as “sand core” levees (USACE, 1966).

The levees along this MRGO frontage section (along the northeastern edge of the St. Bernard protected area) were, in the end, constructed using large volumes of the spoil material excavated during the dredging of the adjacent MRGO shipping channel, and they contained unusually large quantities of highly erodeable sandy soils. In addition, some of the more cohesive (clayey) soils were too wet to be compacted effectively, and some sections of the embankments remained wet and soft for many years after construction. Chapter 6 presents a more detailed discussion of the erodeability of the levee embankments along the MRGO frontage. In simple terms, these levees were unusually massively erodeable, and this (combined with their lack of crest height) caused them to be unusually rapidly eroded as the storm surge from Lake Borgne approached and passed over, and through, these levees.

Based on analytical storm surge analyses and analytical “hindcasts” performed by various investigation teams, as well as eyewitness reports and timings of flooding and damages in St. Bernard Parish and the Ninth Ward, it is estimated that the storm surge passed over and through the MRGO levee frontage between approximately 6:00 to 7:00 a.m. The storm surge along the northeastern frontage of the St. Bernard Parish protected area peaked at approximately 7:30 to 8:00 a.m. (see Figure 2.9.) By the time the storm surge peaked along this important frontage, however, the unfinished “sand core” levees fronting Lake Borgne had been massively eroded and the brunt of the storm surge passed over and through the levees and raced across the undeveloped swamplands shown in Figure 2.11 towards the developed areas of St. Bernard Parish.

This is illustrated schematically in Figure 2.11. The levees along this frontage were so badly eroded, and so rapidly, that they did little to impede the passage of the storm surge which then crossed the roughly 7 to 10 miles of open swamp and reached the secondary levee that separates the northern (undeveloped) swampy section of this protected area from the populated southern section.

The secondary levee had not been intended to face the full fury of a storm surge of this magnitude; it had been assumed that the MRGO frontage levees would absorb much of the energy and provide more resistance. Accordingly, the storm surge passed over the secondary levee (which had lesser typical crest heights of only + 7.5 feet to + 10 feet, MSL) and washed into the populated regions of St. Bernard Parish. A number of minor breaches were produced by the overtopping (and erosion) of this secondary levee, but it is interesting to note that although this secondary levee must have been massively overtopped along much of its length, relatively little erosion damage resulted. The secondary levee was properly constructed, using compacted clayey soils, and the resulting levee embankment generally performed well with regard to resisting erosion. It was not, however, tall enough to restrain the massive overtopping from the storm surge which had passed so easily through the MRGO frontage levees.

The resulting carnage in St. Bernard Parish was devastating. A wall of water raced over the secondary levee; pushing homes laterally (Figure 2.16), flipping cars like toys and leaving them leaning against buildings, and driving large shrimp boats deep into the heart of residential neighborhoods (see Chapter 6.) The flooding of St. Bernard Parish was unexpectedly rapid. The peak depth of flooding in St. Bernard Parish was also unexpectedly deep because the floodwaters were pushed by the still rising storm surge (rather than having to flow more slowly, over time, through more finite breaches as the storm surge subsided; as occurred in most other parts of the greater New Orleans area) so that the top of the floodwaters at their peak within the developed areas were at an elevation well above mean sea level (approximately Elev. +12 feet, MSL.)

Indeed, after the storm surge subsided, “notches” were excavated through a number of local levees to let floodwaters drain under gravity loading from the significantly “plus mean sea level” flooding entrapped in some areas.

Figure 2.12 shows a plot of the locations where dead bodies were retrieved after the disaster as of December 2005. This map shows locations for only approximately 960 of the approximately 1,296 official deaths (to date) in the greater New Orleans area, but this map serves well to show the general distribution of deaths attributed to the flooding produced by this event. As shown in Figure 2.12, approximately 30% of these deaths occurred in St. Bernard Parish. In addition to those who perished, considerable damage was done to many thousands of homes and businesses in this area (see Chapter 6.)

The same storm surge from Lake Borgne that topped and eroded the levees along the “MRGO” frontage also pushed westward over the southeastern corner of the New Orleans East protected section, as shown in Figures 2.9 through 2.11, and this produced overtopping and a number of breaches, as shown previously in Figure 2.4. This was a principal source of the catastrophic flooding that subsequently made its way across the local undeveloped swamplands and into the populated areas of New Orleans East. Like the MRGO levee frontage discussed above, large portions of this levee frontage section had been constructed using materials excavated from the adjacent shipping channel (in this case the GIWW channel), and large portions of the levee were comprised of highly erodeable sandy and lightweight shell sand fill.

This storm surge from Lake Borgne also passed westward into a V-shaped “funnel” as it entered the shared GIWW/MRGO channel that separates the St. Bernard and New Orleans East protected areas, and this in turn resulted in an elevated surge of water that passed westward along the waterway to its juncture (at a “T”) with the IHNC channel, overtopping a number of levees and floodwalls on both the north and south sides of this east-west trending channel and producing levee distress and several breaches (as shown in Figures 2.4 and 2.11.) After reaching the “T” intersection with the IHNC channel, the surge then passed to the north and south (from the “T”) along the IHNC channel, periodically overtopping many (but not all) of the sections of levees and floodwalls lining the east and west sides of the IHNC, and causing a number breaches as shown in Figures 2.4 and 2.11. By about 6:45 to 7:00 a.m. overtopping (by up to as much as 1 to 2 feet at it’s peak at most locations) was occurring along a number of levee and floodwall sections lining the IHNC channel. This overtopping did not occur at all locations, and was only of limited duration (typically several hours or less) where it did occur.

A pair of major breaches occurred at the west end of the Lower Ninth Ward as this overtopping occurred along the IHNC, and the larger of these two breaches is shown (roughly seven weeks later, after construction of an interim repair embankment just outside the breach) in Figure 2.13. A large barge passed in through this breach, and can be seen in the rear of the photo. It is worth noting the tremendous scour-induced damage to the homes immediately inboard of this massive breach; most of the homes in Figure 2.13 were washed off of their foundations and transported laterally (often in pieces) by the inrushing floodwaters. A more detailed examination of the two large breaches at the west end of the Ninth Ward is presented in Chapter 6; Sections 6.4 and 6.5. The large breaches at the west end of the Lower Ninth Ward appear to have occurred by approximately 7:45 a.m. (Louisiana State University Hurricane Center, 2006.)

Like St. Bernard Parish, the breaches at the west end of the Lower Ninth Ward occurred before the storm surge peaked (at about 8:30 a.m. in the IHNC channel), so the Lower Ninth Ward was flooded to a level well above mean sea level before the storm surge subsequently subsided. This neighborhood, which had ground surface elevations of generally between about -3 to -6 feet (MSL) was flooded to elevations of up to as much as 10 to 12 feet above sea level. The resulting carnage, in terms of both loss of life (as shown in Figure 2.12) and destruction of homes and businesses was considerable, as the flooding rose above the tops of many of the one-story homes in this densely packed neighborhood.

The protected area of New Orleans East, directly to the north of the St. Bernard Parish/Ninth Ward protected area, had been breached at its southeastern corner by the initial storm surge and lateral rush from Lake Borgne (as shown schematically in Figure 2.11) by about 6:00 to 7:00 a.m., though the resulting breaches were confined to several locations so that the inflowing waters began to make their way across the undeveloped swamplands of the eastern portion of this protected area and timing is thus difficult to pin down with exactitude. The storm surge then passed laterally along the GIWW/MRGO east-west channel and produced another finite breach on the north side of this channel and several additional distressed sections. This breach added to the sources of water beginning to flow into this protected area.

The surge that passed west along the GIWW/MRGO east-west channel then pushed north along the IHNC, and produced several additional breaches and distressed sections, of varying severity, along the IHNC frontage as shown in Figure 2.4. These, too, added to the flow into the protected area of New Orleans East.

The lateral storm surge that passed westward along the east-west trending GIWW/MRGO channel between New Orleans East and St. Bernard Parish also attacked the west side of the IHNC channel, at the eastern edge of the main Orleans East Bank (downtown New Orleans) protected area. This produced three additional breaches along this frontage, as shown in Figures 2.4 and 2.11. Floodwaters began to flow into the main New Orleans metropolitan (downtown) protected area through these breaches between approximately 7:00 to 8:30 a.m. Although three of these breaches were relatively significant, all three breaches along this frontage failed to scour to significant depths. As a result, all three either had “lips” with lowest elevations above mean sea level, or there were points along the path from the IHNC to the breach that were above mean sea level. Accordingly, although all three breaches allowed some flow of water into the main Orleans East Bank (downtown) protected area, they allowed only limited flow and this flow stopped as the storm surge subsequently subsided. It would be the subsequent breaches in the drainage canals, to the northwest (along the edge of Lake Pontchartrain) that would prove to be devastating for this main (downtown) protected area.

As the hurricane then passed northwards to the east of New Orleans, the counterclockwise direction of the storm winds also produced a well-predicted storm surge southwards towards the south shore of Lake Pontchartrain. The lake level rose, but mainly stayed below the crests of most of the lakefront levees. The lake rose approximately to the tops of the lakefront levees at a number of locations, especially along the shoreline of New Orleans East, and there was moderate overtopping (or at least storm wave splash-over) and some resulting erosion on the crests and inboard faces of some lakefront levee sections along the Lake frontage. Significant overtopping occurred over a long section of concrete floodwall near the west end of the New Orleans East protected area lakefront (behind the Old Lakefront Airport), where the floodwall appears to have

been inexplicably lower than the adjacent earthen levee sections. This, too, added to the flow into the New Orleans East protected area, which was now continuing to fill with water even as the original storm surges subsided.

Farther to the west, the storm surge along the Pontchartrain lakefront (which peaked at about 9:00 to 9:30 a.m. at an elevation of about +10 feet, MSL) did not produce water levels sufficiently high as to overtop the crests of the concrete floodwalls atop the earthen levees lining the three drainage canals that extend from just north of downtown to Lake Pontchartrain; the 17th Street Canal, the Orleans Canal, and the London Avenue Canal. Three major breaches occurred along these canals, however, and these produced significant flooding of large areas within the Orleans East Bank protected area (as shown in Figure 2.4.) Figure 2.13 shows military helicopters lowering oversized bags of gravel into the levee breach on the east side of the 17th Street Canal, near the north end of the canal. Note that the flood waters have equilibrated, and that there is no net flow through the breach at the time of this photo.

The first breach along the drainage canals occurred near the south end of the London Avenue canal, between about 7:00 to 8:00 a.m. The second breach occurred near the north end of the London Avenue canal, and the best current estimates of the timing of this breach are between about 7:30 to 8:30 a.m. The third major breach occurred near the north end of the 17th Street canal. The main breach here occurred between about 9:00 to 9:15 a.m., but this may have been preceded by earlier visually observable distress at this same location. All three of these breaches rapidly scoured to depths well below mean sea level, so they continued to transmit water into the main Orleans East Bank (downtown) protected area after the storm surges subsided. A more detailed discussion and analyses of these catastrophic drainage canal breaches are presented in Chapter 8.

The resulting flooding of the main Orleans East Bank (Downtown) protected area was catastrophic, and resulted in at least 588 of the approximately 1,293 deaths attributed (to date) to the flooding of New Orleans by this event. Contributions to this flooding came from the overtopping and breaches along the IHNC channel at the east side of this protected area, but the majority of the flooding came from the three catastrophic failures along the drainage canals at the northern portion of this protected area.

In addition, one of the drainage canals (the Orleans Canal) had not yet been fully “sealed” at its southern end, so that floodwaters flowed freely into New Orleans during the storm surge through this unfinished drainage canal. A section of levee and floodwall approximately 200 feet in length had been omitted at the southern end of this drainage canal, so that despite the expense of constructing nearly 5 miles of levees and floodwalls lining the rest of this canal, as the floodwaters rose along the southern edge of lake Pontchartrain, the floodwaters did not rise fully within the Orleans canal; instead they simply flowed freely into downtown New Orleans.

Chapters 4 through 8 present a more detailed discussion of the performance of the flood protection systems nominally intended to protect the main Orleans East Bank area, and studies of the major failures and near failures within this critical area.

By approximately 9:30 a.m. the principal levee failures had occurred, and most of New Orleans was rapidly flooding.

2.3.3 Brief Comments on the Consequences of the Flooding of New Orleans

The consequences of the flooding of major portions of all four levee-protected areas of New Orleans were catastrophic. Approximately 85% of the metropolitan area of greater New Orleans was flooded, as shown in Figures 2.4 and 2.5. In Figure 2.4, the flooded areas are shown in pink, and those that remained still to be “unwatered” as late as September 28th are shown in darker blue. The blue cross-hatched areas were open, undeveloped swamplands, and these were also flooded but were not counted in determining the 85% flooding figure.

Large developed areas within all of the four main “protected areas” were flooded, and most remained inundated for two to three weeks before levee breaches could be repaired and the waters fully pumped out.

Figure 2.15 shows the approximate depth of flooding that remained on September 2nd, four days after Hurricane Katrina, in the St. Bernard Parish and Lower Ninth Ward protected area, based on an estimated surface water elevation of approximately +5 ft. (MSL) at that time. This is a significantly lower flood level than the estimated peak flooding to an elevation of up to +10 to 12 feet above mean sea level during the actual hurricane. The undeveloped swampland to the north of the populated areas can be seen in this Figure to also still be flooded on September 2nd, but the flood depths are not indicated.

Figure 2.16 shows the approximate depth of flooding that remained on September 2nd, again four days after the hurricane, in the New Orleans East protected area. As this protected area filled slowly during and after the hurricane, and as it was “unwatered” relatively slowly over the days and weeks that followed, this represents nearly the full depth of flooding in this area.

Figure 2.17 shows the approximate depth of flooding of the main Orleans East Bank (downtown) protected area on September 2nd. Like the New Orleans East protected area, this large protected “basin” filled relatively slowly over time. By September 2nd, the breaches had not yet all been closed by emergency repairs, so the depths of flooding in Figure 2.17 represent the nearly the full depth of flooding at its worst in this area.

Neighborhoods that were inundated exhibit stark evidence of this catastrophic flooding. Water marks, resembling oversized bathtub rings, line the sides of buildings and cars in these stricken neighborhoods, as shown in Figure 2.18. Household and commercial chemicals and solvents, as well as gasoline, mixed with the salty floodwaters in many neighborhoods, and at the time of this investigation’s first field visits shortly after the event the paint on cars below the watermarks on adjacent buildings had been severely damaged, and bushes and shrubs were browned below the watermarks, but often starkly green above. Driving through neighborhoods that had been flooded, there was often the impression that one was viewing a television screen where the color of the picture was somehow distorted or altered below a horizontal line; the level at which the floodwaters had been ponded. The devastation in these neighborhoods, and its lateral extent across many miles of developed neighborhoods, was stunning even to the many experienced members of our forensic teams that had seen numerous devastating earthquakes, tidal waves, and other major disasters.

Close to major breaches, the hydraulic forces of the inflowing floodwaters often had devastating effect on the communities. Figure 2.13 shows the devastation immediately inboard

from the large breach at the west end of the Ninth Ward site after the area had been unwatered. Note the numerous empty slabs where homes had been stripped away and scattered, mostly in pieces, across a large area.

Figure 2.19 shows another aspect of the flooding. This photograph shows a region within St. Bernard Parish in which some of the homes were transported from their original locations by the floodwaters, and then deposited in new locations. Figure 2.20 shows a number of homes in the Plaquemines Parish polder that were carried across the narrow polder (from left to right in this photograph) as the west side (left side of photo) “hurricane levee” or back levee was breached, and were then deposited on the crest of the Mississippi River levee. The water side slope face of the Mississippi River levee is clearly shown in this photograph, as evinced by the concrete slope face protection on the outboard side of the riverfront levee in the right foreground of the figure.

Figures 2.18 through 2.25 show examples of the devastation that occurred within the stricken flooded areas. The spray painted markings on the sides of the buildings in these areas were left by search and rescue teams, and they denote a number of important findings within each dwelling, including toxic contamination, etc. The most important numbers are those centered at the base of the large “X”, as these denote the number of dead bodies found within the building. In most cases this number was “0”, as for example in Figures 2.18 and 2.22. But this was not always the case. Figure 2.24 shows the outside of a dwelling in the Ninth Ward with a “3” beneath the X, indicating three deaths within. This was a housing unit, and the wheelchair ramp from the front door is askew at the bottom of the photograph. Figure 2.25 shows the muddy devastation, and a wheelchair, within this flooded structure.

Figure 2.26 gives another sense of perspective regarding the terrible and pervasive devastation wreaked by the flooding of large urbanized areas. This photo shows the flooding of an area of New Orleans East, but it could just as well be any of a number of large areas of New Orleans. Figure 2.27 gives a similar sense of perspective. In this photo, the flooded Lower Ninth Ward is in the foreground, and virtually every neighborhood shown (including those in the far background behind the tall downtown buildings) is flooded, excepting only the small area occupied by the tall buildings of the downtown area.

At the time of the writing of this report, the death toll from the flooding of New Orleans has risen to 1,293. It is expected to continue to climb a bit higher as some of those currently listed as “missing” will likely have been drawn out into the swamps and the Gulf by the floodwaters. Loss projections continue to evolve, but estimates of overall losses have now climbed to the \$100 to \$ 200 billion range for the metropolitan New Orleans region.

The members of this investigation team extend their hearts and their deepest condolences to those who were devastated by Hurricane Katrina, and by the flooding of most of New Orleans. The suffering and losses of those most intimately involved are almost beyond comprehension. It must be the goal and objective of all of us that a catastrophe of this sort never be allowed to happen again.

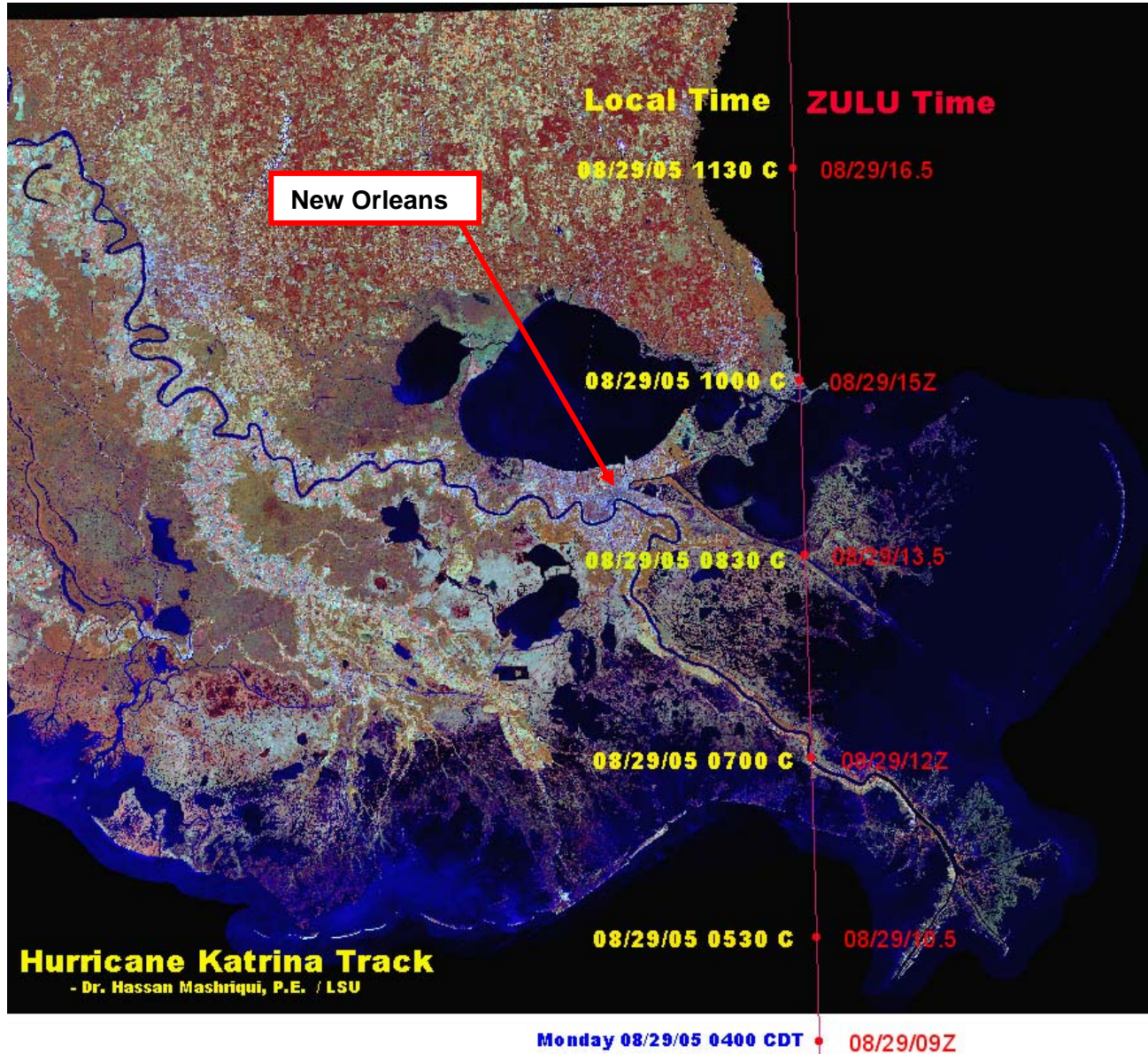
2.4 References

- Interagency Performance Evaluation Task Force, (2006), “Performance Evaluation, Status and Interim Results, Report 2 of a Series, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System,” Interim Report No. 2, March 10, 2006.
- Interagency Performance Evaluation Task Force, (2006), “Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System ”, Draft Final Report, June 1, 2006.
- Louisiana State University Hurricane Center, (2005), “Hurricane Katrina Advisory #22,” available from: <http://hurricane.lsu.edu/floodprediction/katrina22/>; date accessed: November 10, 2005.
- United States Army Corps of Engineers, (1967), “Lake Pontchartrain, LA, and Vicinity, Chalmette Area Plan, Hurricane Protection Levee First Lift, Sta. 594+00 – Sta. 770+00 (Not Continuous),” File No. H-8-24100, May 11, 1967.
- United States Army Corps of Engineers, (1966), “Lake Pontchartrain, LA. and Vicinity, Chalmette Area Plan, Design Memorandum No. 3, General Design,” November, 1966.



Source: <http://flhurricane.com/googlemap>

Figure 2.1: Location of New Orleans, and map of the path of the eye of Hurricane Katrina.



Source: Mashriqui, 2006

Figure 2.2: Traced path of the eye of Hurricane Katrina at landfall in the New Orleans area.

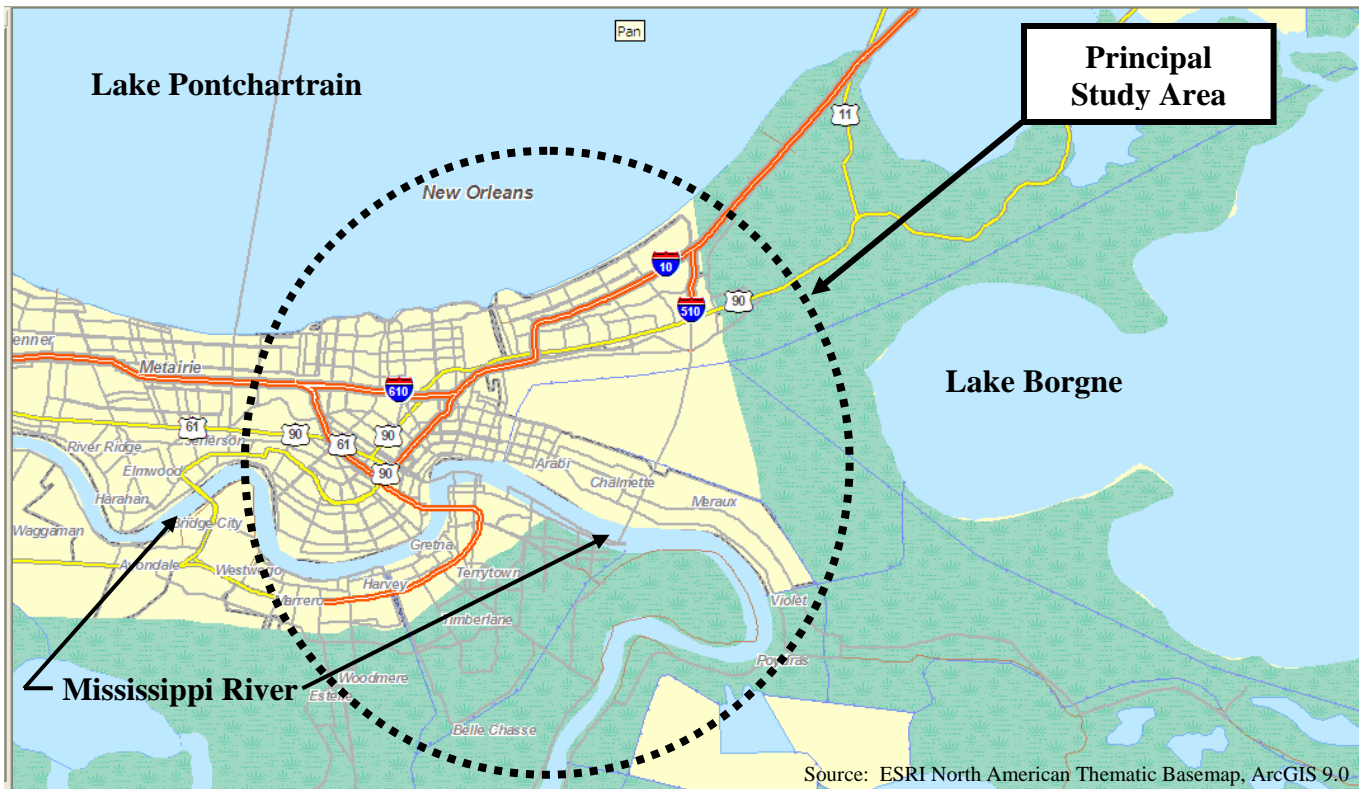
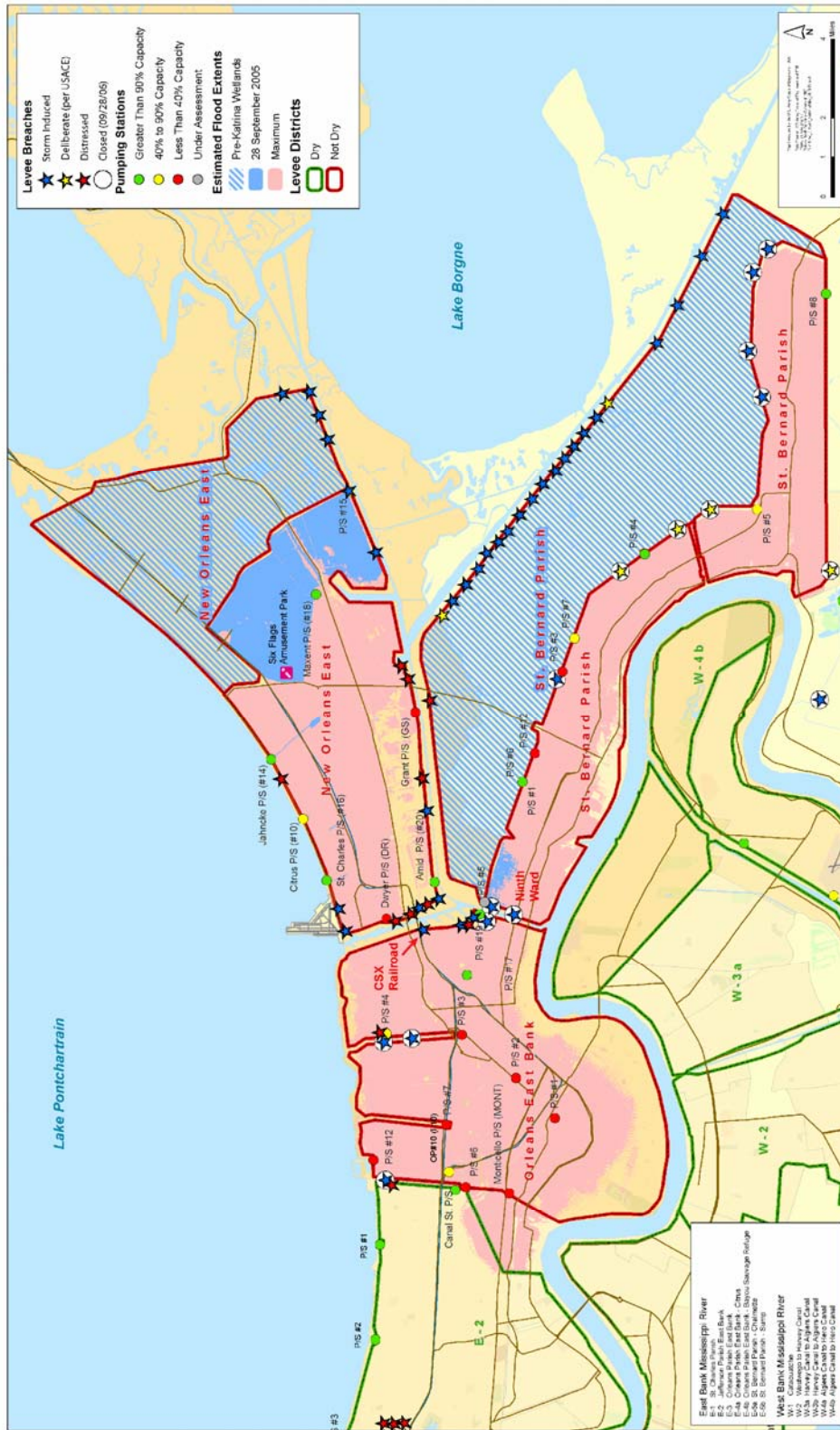
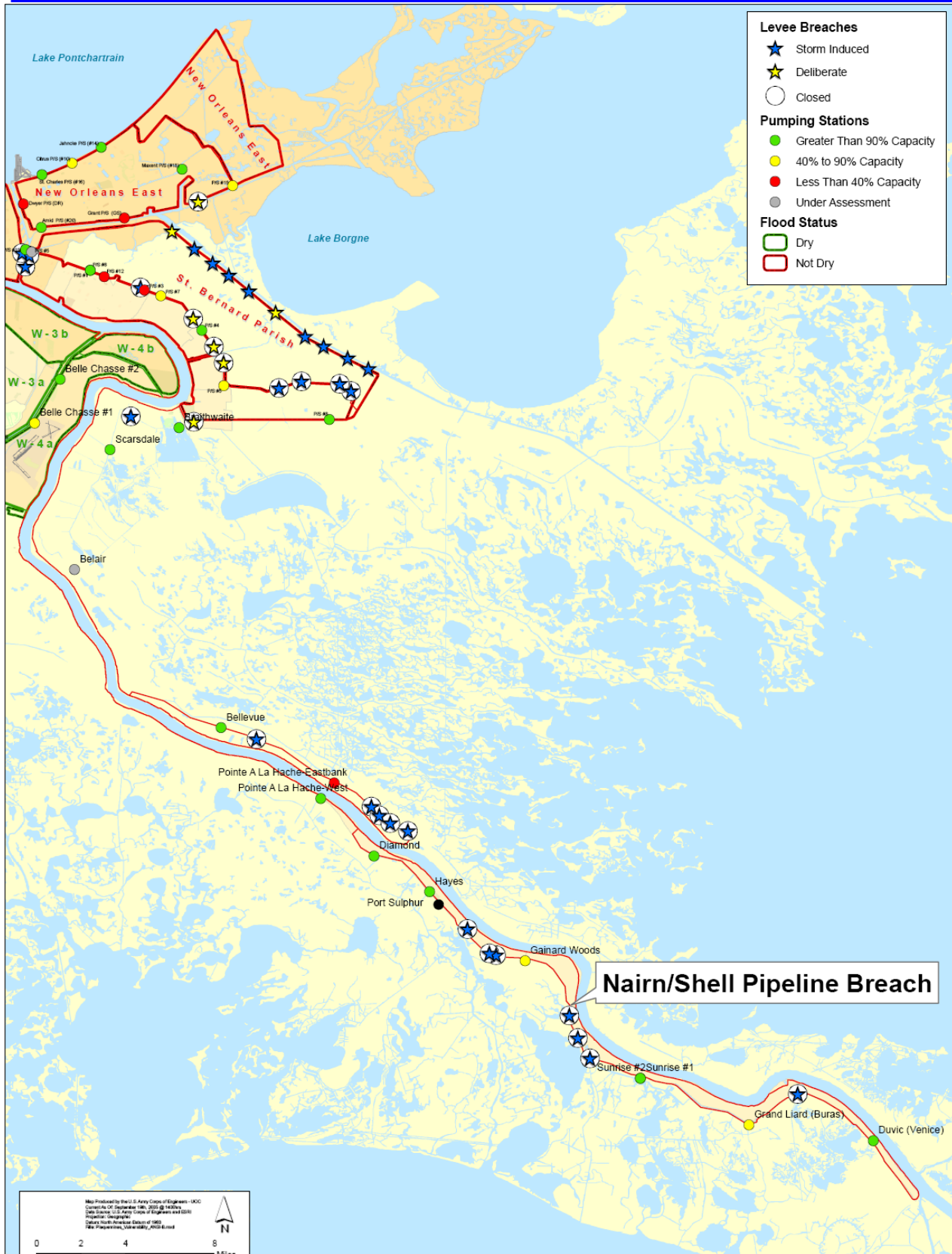


Figure 2.3: The greater New Orleans region levee and flood protection system Study Area.



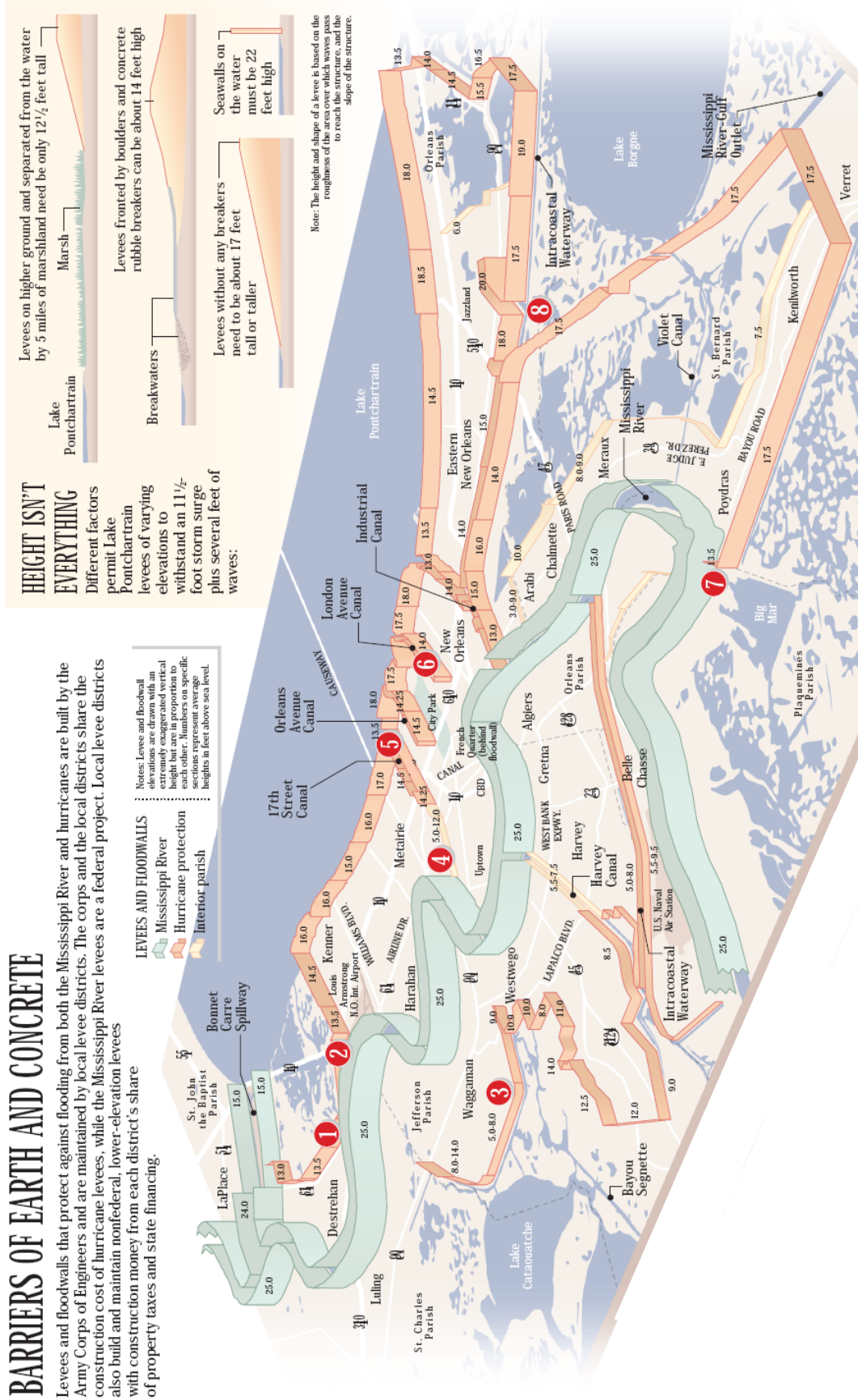
Source: Modified after USACE, 2005

Figure 2.4: Map showing principal features of the main flood protection rings or “protected areas” in the New Orleans area.



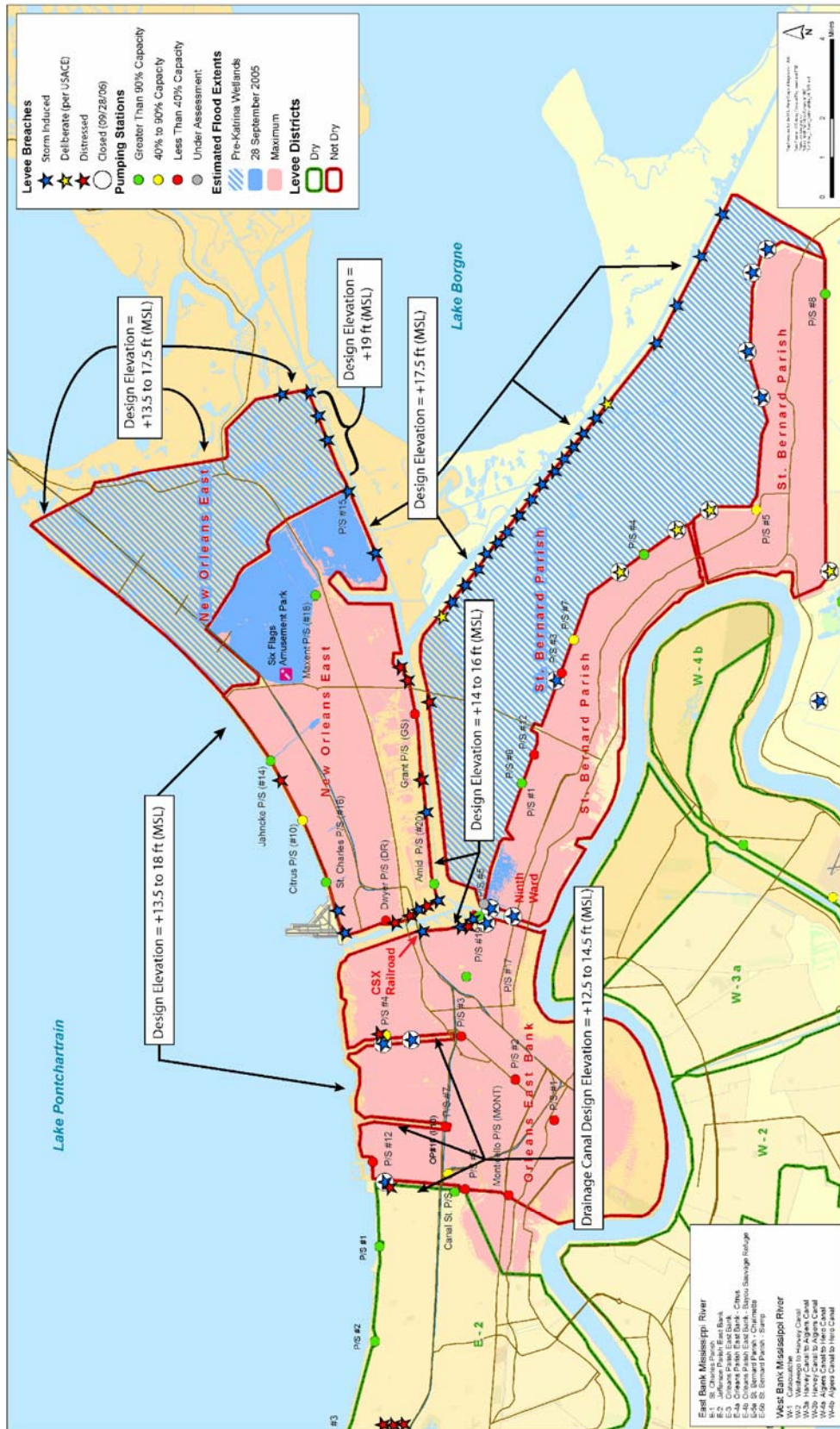
Source: Modified after USACE, 2005

Figure 2.5: Map showing the levee protected areas along the lower reaches of the Mississippi River (in the Plaquemines Parish Area.)



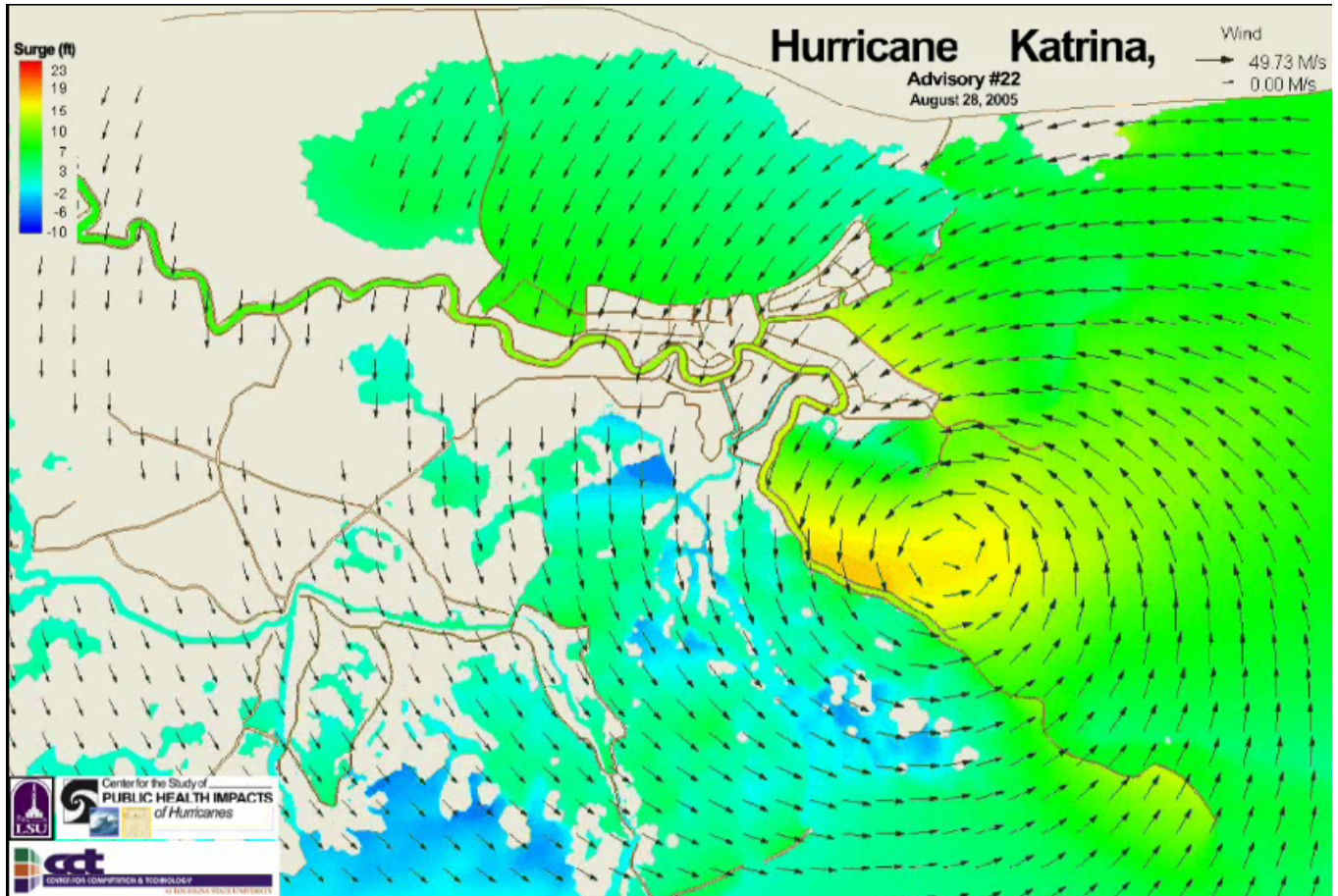
Source: Graphic by Emmet Mayer III/emayer@timespicayune.com (2005)

Figure 2.6: Map showing design flood stage elevations throughout the New Orleans region.



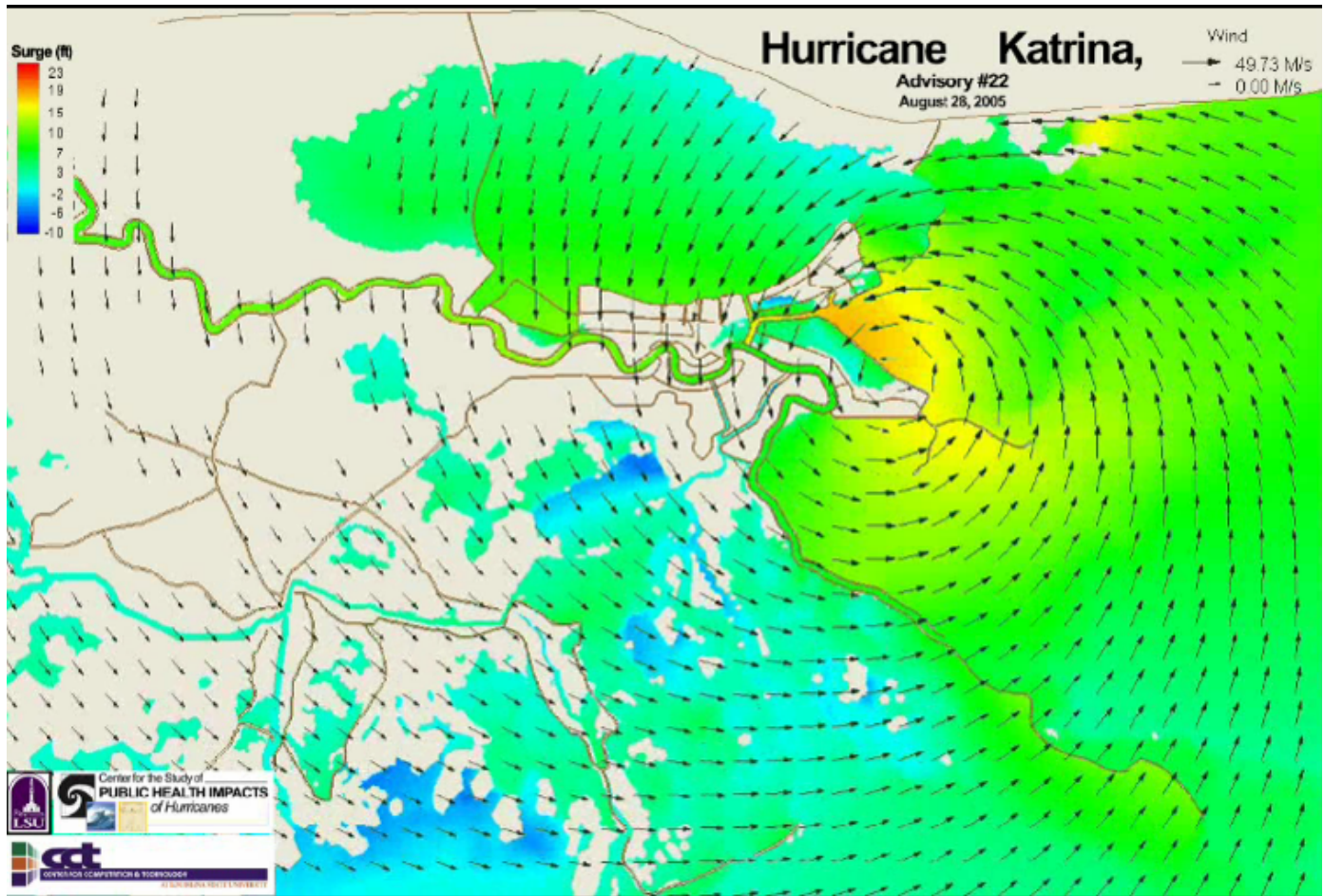
Source: Modified after USACE, 2005

Figure 2.7: Map showing the design flood stage levels for selected locations in the New Orleans Area.



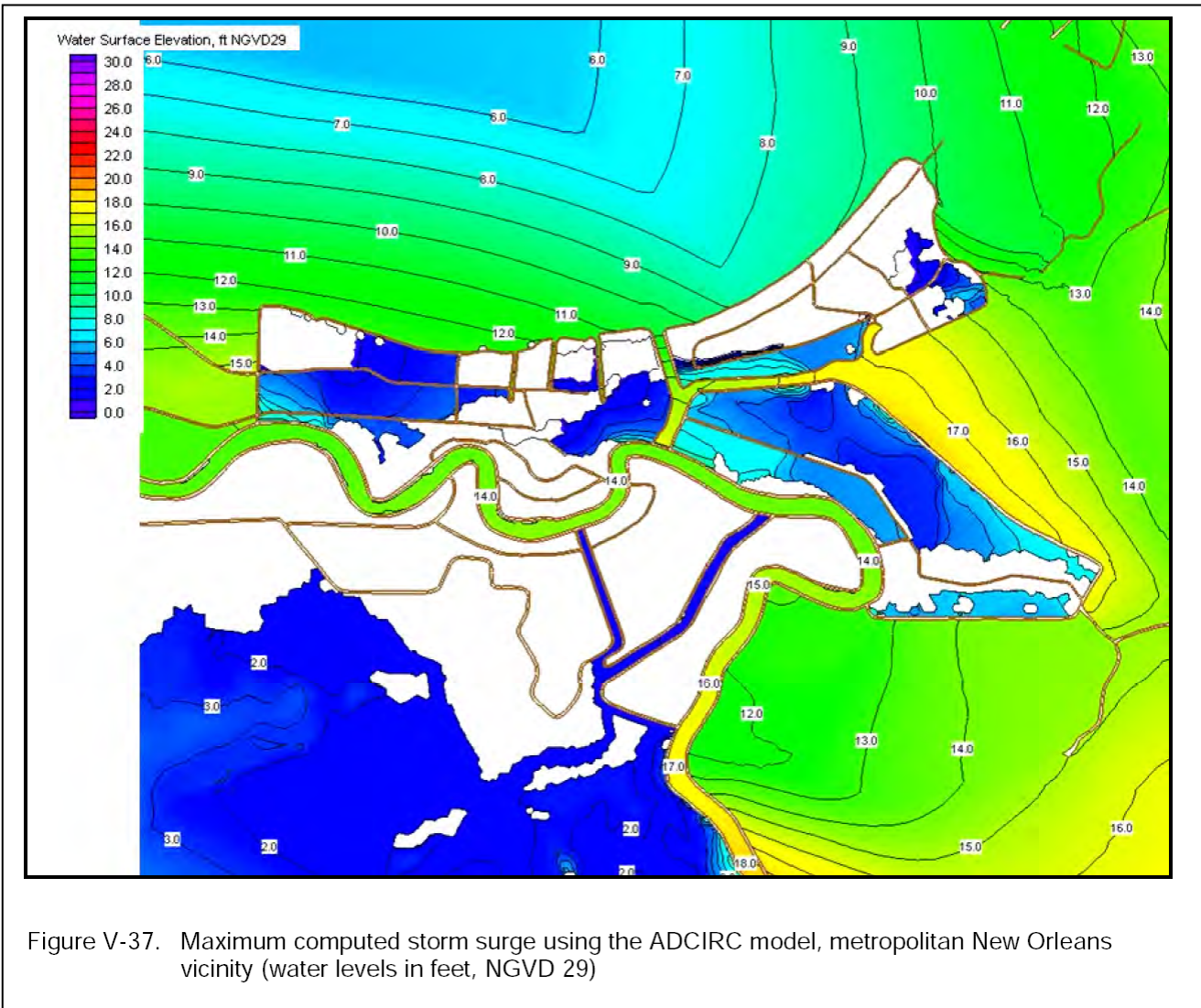
Source: <http://hurricane.lsu.edu/floodprediction/>

Figure 2.8: Calculated storm surge against the coast at about 7:30 am (CDT), August 29, 2006.



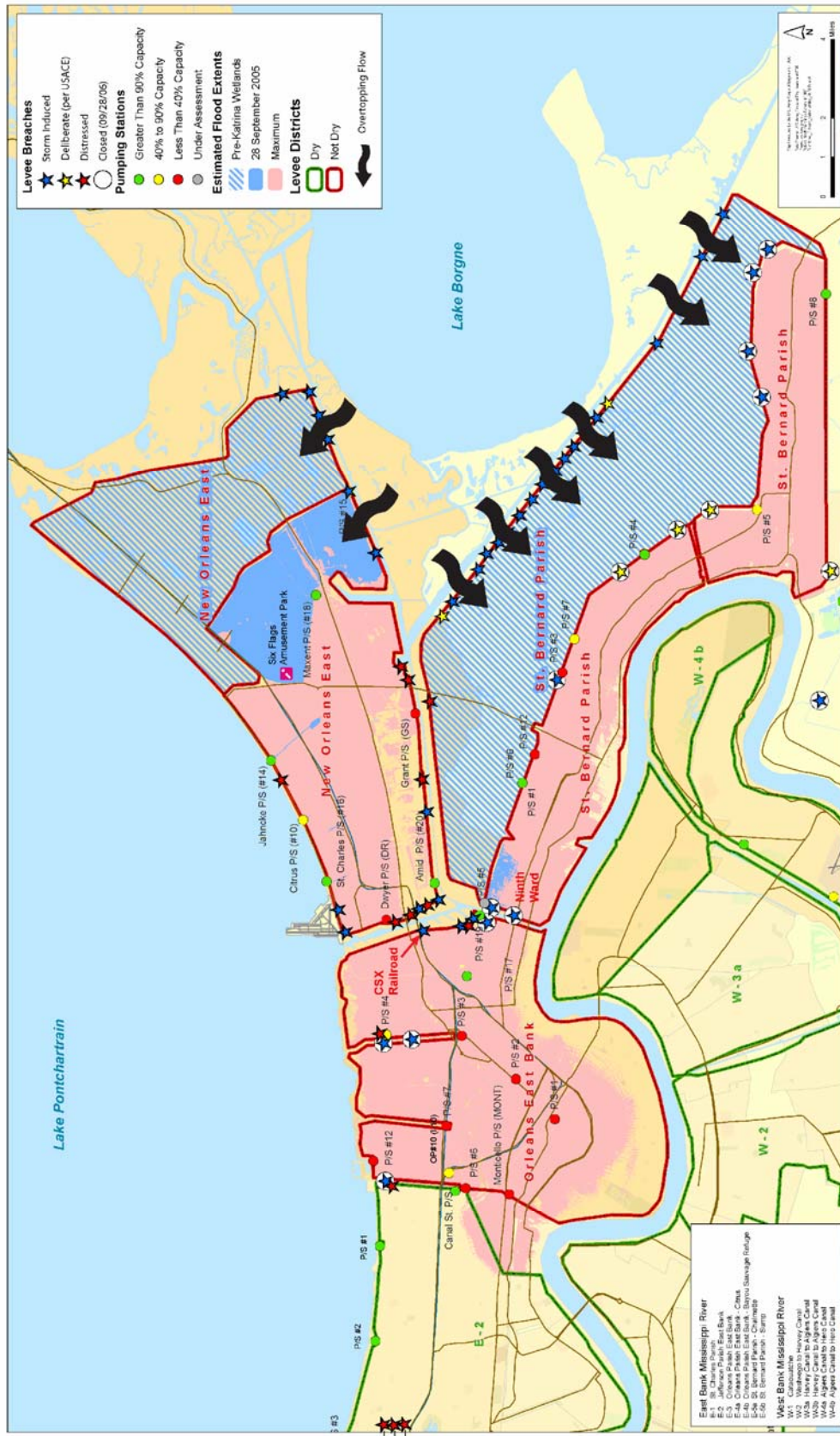
Source: <http://hurricane.lsu.edu/floodprediction/>

Figure 2.9: Map of calculated storm surge levels, at time when the eye of the storm passed close to the east of New Orleans at about 8:30 am (CDT).



Source: IPET Interim Report No. 2; April, 2006

Figure 2.10: Map showing calculated aggregate maximum storm surge levels (maximum values at any point in time).



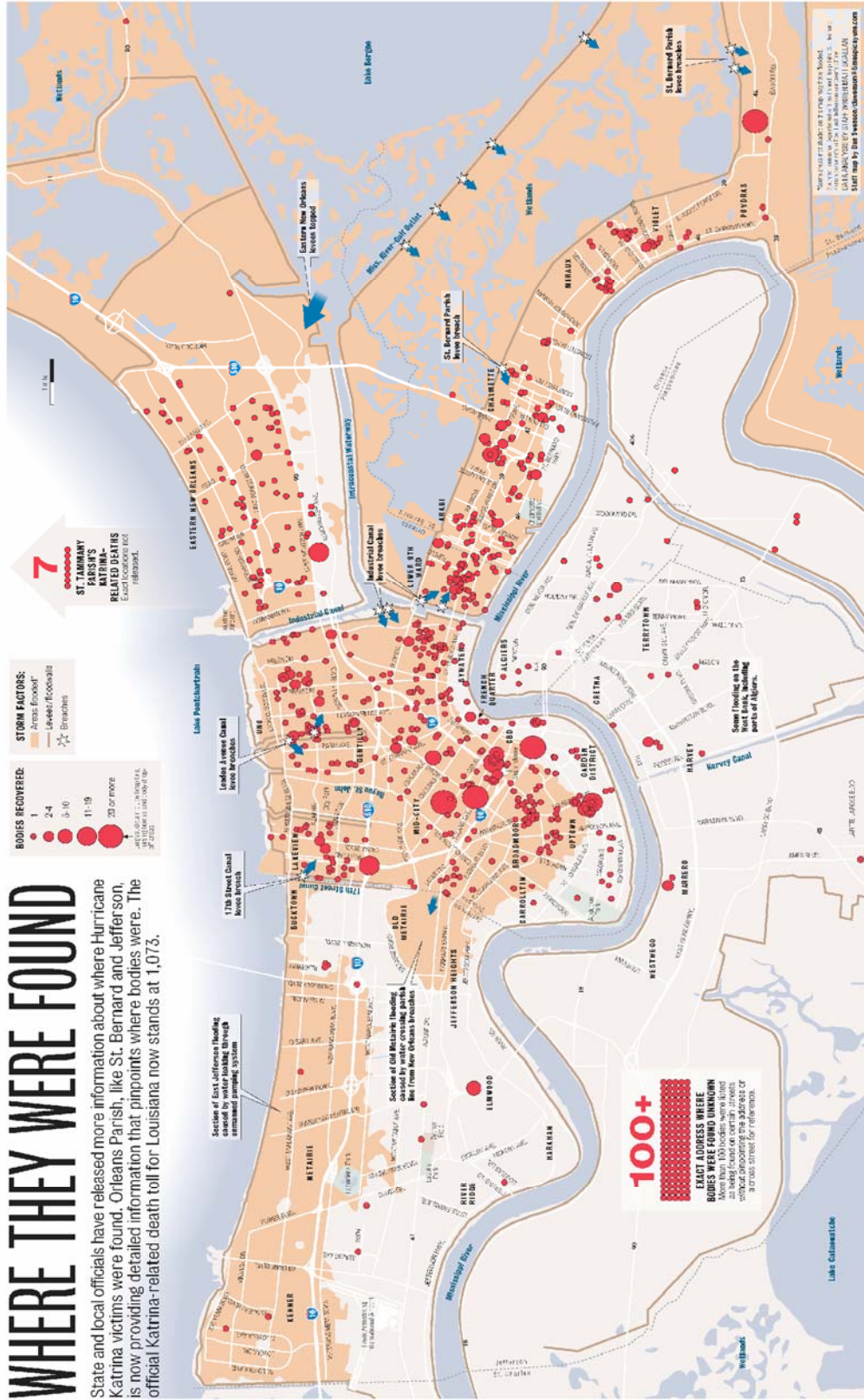
Source: Modified after USACE, 2005

Figure 2.11: Storm surge overtopping the eastern flank of the regional flood protection system at the northeast edge of the St. Bernard Parish and Ninth Ward protected areas.

VICTIMS OF KATRINA

WHERE THEY WERE FOUND

State and local officials have released more information about where Hurricane Katrina victims were found. Orleans Parish, like St. Bernard and Jefferson, is now providing detailed information that pinpoints where bodies were. The official Katrina-related death toll for Louisiana now stands at 1,073.



Source: Times Picayune (2005)

Figure 2.12: Map showing locations of confirmed deaths (as of December 2005) as a result of Hurricane Katrina.



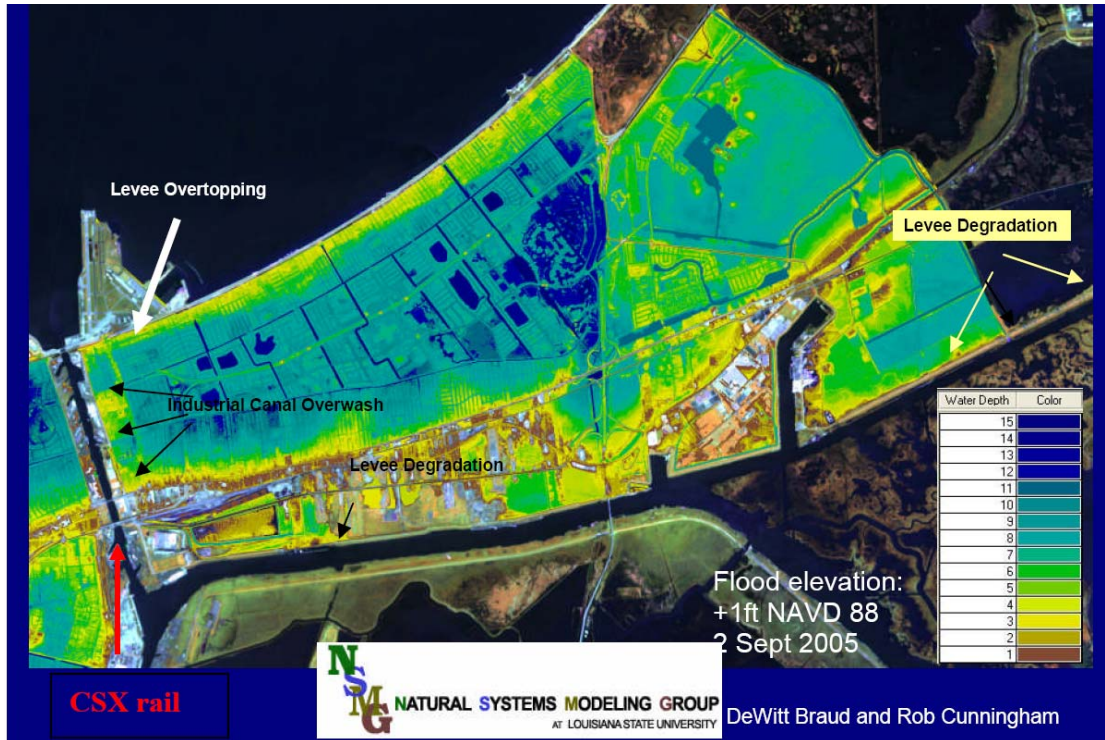
Photograph by Les Harder

Figure 2.13: Oblique view of the (south) levee break at the Inner Harbor Navigation Canal into the lower Ninth Ward.



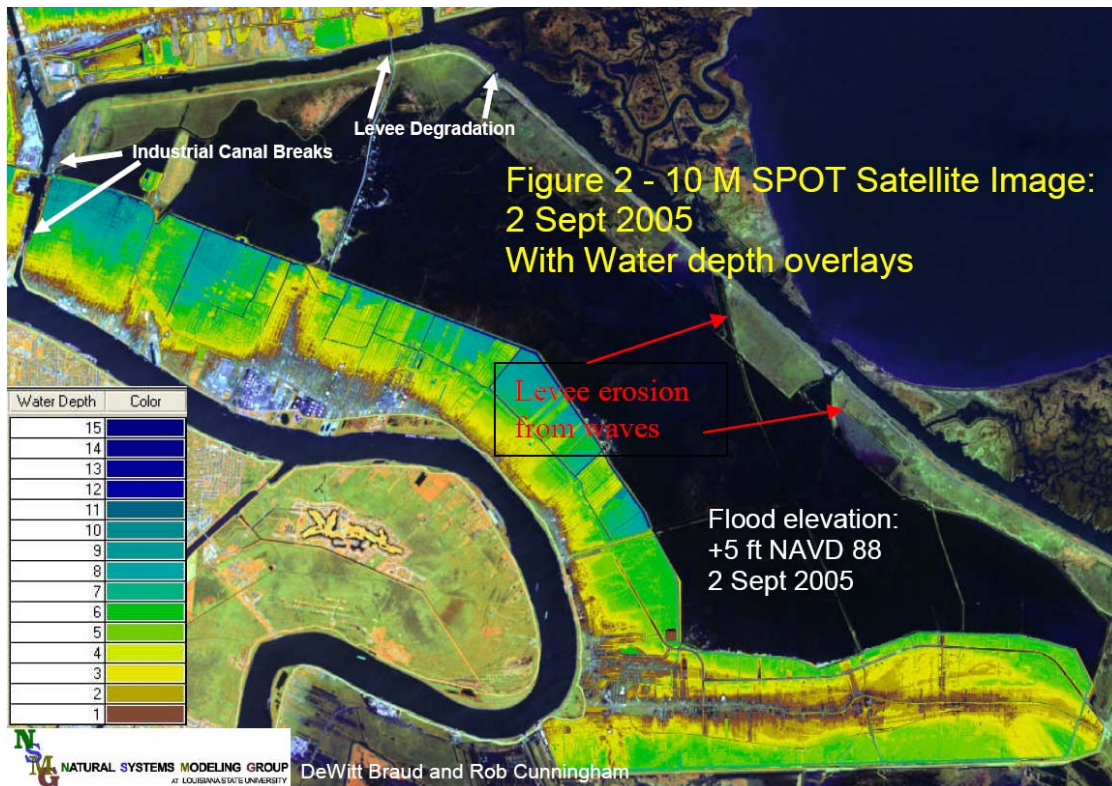
Photo courtesy of the U.S. Army Corps of Engineers

Figure 2.14: Initial closure of the large breach at the north end of the 17th Street Canal.



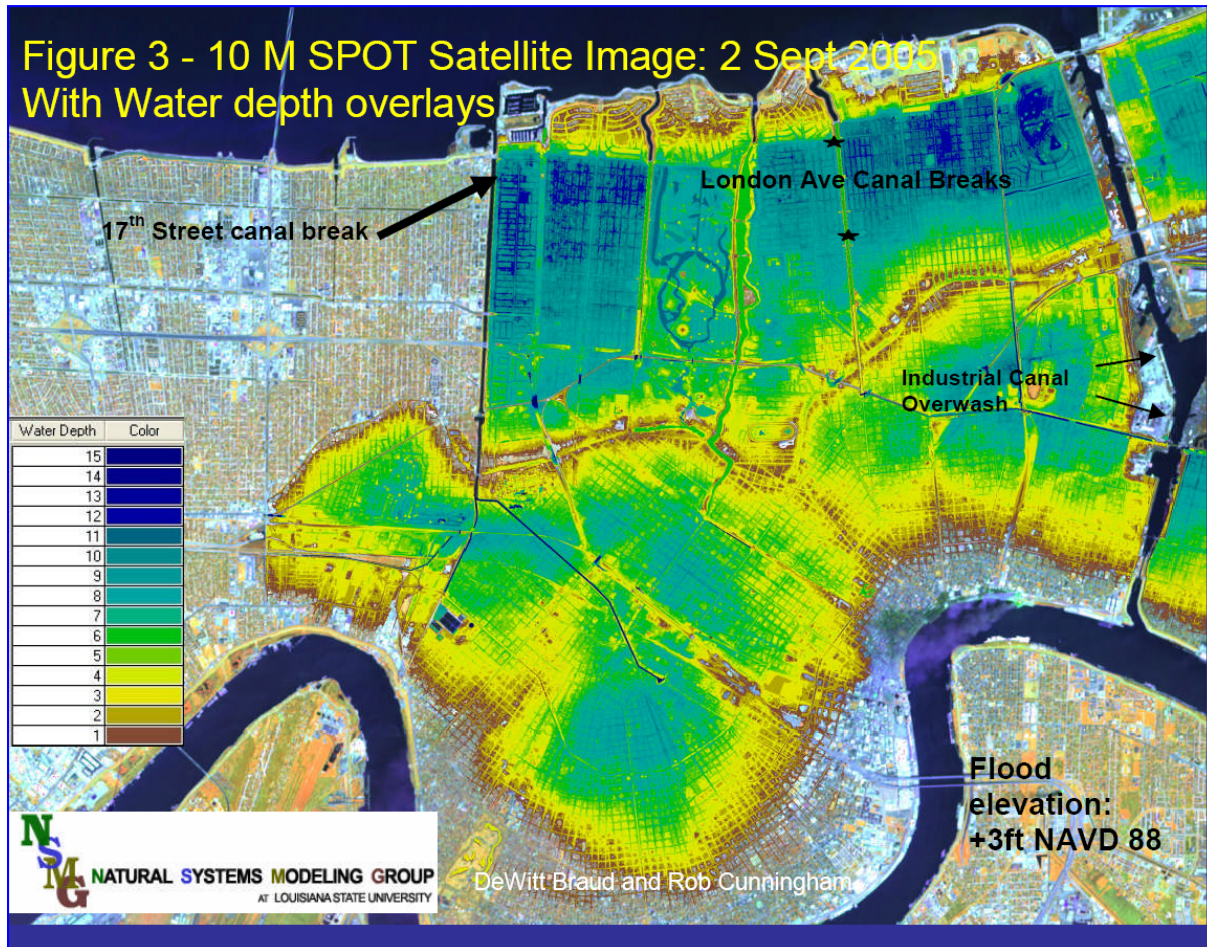
Source: LSU Hurricane Center, 2006

Figure 2.15: Depth of flooding of New Orleans East on September 2nd (4 days after Hurricane Katrina)



Source: LSU Hurricane Center, 2006

Figure 2.16: Depth of flooding of St. Bernard Parish and the Lower Ninth Ward on Sept. 2nd (4 days after Hurricane Katrina).



Source: LSU Hurricane Center, 2006

Figure 2.17: Depth of flooding of the Orleans East Bank (Downtown) protected area on September 2nd (4 days after Hurricane Katrina).



Photograph by Rune Storesund

Figure 2.18: High water marks remain on structures after temporary levee repairs have been completed and flood waters have been pumped out.



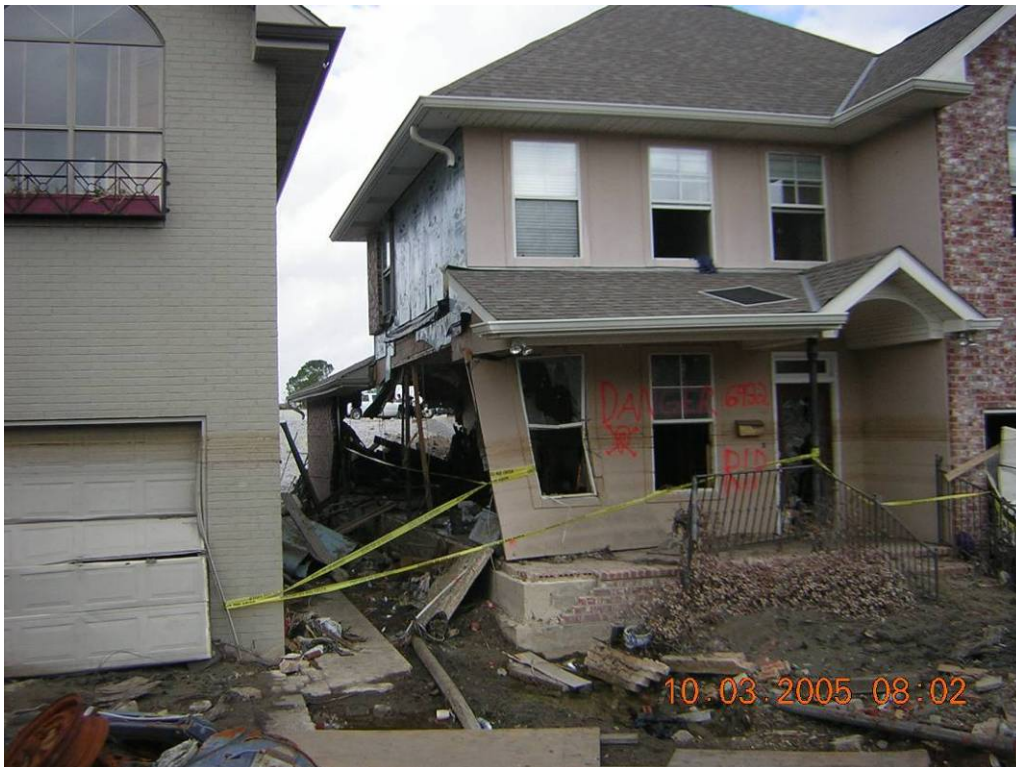
Photograph by Les Harder

Figure 2.19: Flooded neighborhood in St. Bernard Parish, showing homes floated off their foundations and transported by floodwaters.



Photograph by Les Harder

Figure 2.20: Homes in Plaquemines Parish carried from left to right in photo and strewn across the crown of the Mississippi Riverfront levee.



Photograph by Rune Storesund

Figure 2.21: Damage to a residential neighborhood in the 17th Street Canal area due to flooding.



Photograph by Rune Storesund

Figure 2.22: Search and rescue markings on a residence in the Canal District.



Photograph by Rune Storesund

Figure 2.23: Another view of flooding damage in the Canal District.



Photograph by Les Harder

Figure 2.24: Search and rescue team markings on a building in the lower Ninth Ward where three inhabitants died.



Photograph by Les Harder

Figure 2.25: View inside structure shown previously in Figure 2.21.



Photo Courtesy of http://www.wwltv.com/sharedcontent/breakingnews/slideshow/083005_dmnkatrina/7.html

Figure 2.26: Neighborhood in New Orleans East fully flooded.



Photo courtesy of http://www.wwltv.com/sharedcontent/breakingnews/slideshow/083005_dmnkatrina/7.html

Figure 2.27: View of the City of New Orleans at the peak of the flooding.