THE NEW ORLEANS HURRICANE PROTECTION SYSTEM:

What Went Wrong and Why

A Report by the American Society of Civil Engineers Hurricane Katrina External Review Panel

ASCE

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Christine F. Andersen, P.E., M.ASCE

Jurjen A. Battjes, Ph.D.

David E. Daniel, Ph.D., P.E., M.ASCE (Chair)

Billy Edge, Ph.D., P.E., F.ASCE

William Espey, Jr., Ph.D., P.E., M.ASCE, D.WRE

Robert B. Gilbert , Ph.D., P.E., M.ASCE

Thomas L. Jackson, P.E., F.ASCE, D.WRE

David Kennedy, P.E., F.ASCE

Dennis S. Mileti, Ph.D.

James K. Mitchell, Sc.D., P.E., Hon.M.ASCE

Peter Nicholson, Ph.D., P.E., F.ASCE

Clifford A. Pugh, P.E., M.ASCE

George Tamaro, Jr., P.E., Hon.M.ASCE

Robert Traver, Ph.D., P.E., M.ASCE, D.WRE

ASCE Staff:

Joan Buhrman

Charles V. Dinges IV, Aff.M.ASCE

John E. Durrant, P.E., M.ASCE

Jane Howell

Lawrence H. Roth, P.E., G.E., F.ASCE

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Executive Summary

On the morning of August 29, 2005, Hurricane Katrina — one of the strongest storms ever to hit the coast of the United States — brought intense winds, high rainfall, waves, and storm surge to the Gulf of Mexico shores of Louisiana, Mississippi, and Alabama. Communities in all three states suffered damage, but this report focuses on the devastation to New Orleans and southeast Louisiana.

New Orleans was built on low-lying marshland along the Mississippi River. Levees and floodwalls were built around the city and adjacent parishes to protect against flooding. During and after Hurricane Katrina, many of those levees and floodwalls were overtopped and several were breached, allowing billions of gallons of water from the Gulf of Mexico, Lake Borgne, and Lake Pontchartrain to flow into New Orleans and flood major portions of the city.

As of August 2, 2006, 1,118 people were confirmed dead in Louisiana as a result of Hurricane Katrina. Another 135 people are still missing and presumed dead. Thousands of homes were destroyed. Direct damage to residential and non-residential property is estimated at $21 billion, damage to public infrastructure another $6.7 billion. Nearly half the region's population has not yet returned after evacuating. Nearly 124 thousand jobs were lost, and the region's economy was crippled.

The catastrophic failure of New Orleans's hurricane protection system represents one of the nation's worst disasters ever. The members of the American Society of Civil Engineers (ASCE) Hurricane Katrina External Review Panel have conducted an in-depth review of the comprehensive work of the United States Army Corps of Engineers (USACE) Interagency Performance Evaluation Taskforce (IPET) — at the USACE's request. The ASCE Hurricane Katrina External Review Panel's findings and conclusions are presented in this report.

A storm of Hurricane Katrina's strength and intensity is expected to cause major flooding and damage. A large portion of the destruction from Hurricane Katrina was caused not only by the storm itself, however, but also by the storm's exposure of engineering and engineering-related policy failures. The levees and floodwalls breached because of a combination of unfortunate choices and decisions, made over many years, at almost all levels of responsibility.

There were two direct causes of the levee breaches: collapse of several levees with concrete floodwalls (called I-walls) because of the way they were designed, and overtopping, where water poured over the tops of the levees and floodwalls and eroded the structures away. Furthermore, the many existing pump stations that could have helped remove floodwaters were inoperable during and after the storm.

The I-walls failed because the margin of safety used in the design process was too low — especially considering that the hurricane protection system was a critical life-safety structure. The engineering design did not account for the variability in the strength of soft soils beneath and adjacent to the levees. The designers failed to take into account a water-filled gap that developed behind the I-walls as they bowed outward from the forces exerted by the floodwaters.

Some overtopping of levees is to be expected in a major storm. However, the levees were not armored or protected against erosion — an engineering choice of catastrophic consequences because this allowed the levees, some constructed of highly erodible soil, to be scoured away, allowing water to pour into New Orleans.

In addition to these direct causes of the levee breaches, a number of other factors also contributed to the catastrophe:

- The risk to New Orleanians (i.e., the probability of failure combined with the consequences to human health and safety if that failure were to occur) was much higher than many people are generally willing to accept. Because these risks were not well understood or communicated effectively to the public, the importance of evacuating people and protecting property was under-estimated.

- The hurricane protection system was constructed as individual pieces — not as an interconnected system — with strong portions built adjacent to weak portions, some pump stations that could not withstand the hurricane forces, and many penetrations through the levees for roads, railroads, and utilities. Furthermore, the levees were not designed to withstand overtopping.

- The hurricane protection system was designed for meteorological conditions (barometric pressure and wind speed, for example) that were not as severe as the Weather Bureau and National Weather Service listed as being characteristic of a major Gulf Coast hurricane.

- Levee builders used an incorrect datum to measure levee elevations — resulting in many levees not being built high enough. Some levees were built 1 to 2 feet lower than the intended design elevation. Furthermore, despite the acknowledged fact that New Orleans is subsiding (sinking), no measures were taken into account in the design to compensate for the subsidence by monitoring the levees and raising them up to the pre-subsidence design elevation.

- No single agency was in charge of hurricane protection in New Orleans. Rather, responsibility for the maintenance and operation of the levees and pump stations was spread over many federal, state, parish, and local agencies. This lack of inter-agency coordination led to many adverse consequences from Hurricane Katrina.

- The hurricane protection system was funded on a project-by-project basis over many years. As a result, the system was constructed in a piecemeal fashion. In addition, there were pressures for tradeoffs and low-cost solutions that compromised quality, safety, and reliability.

- The design of the New Orleans hurricane protection system was not subject to the rigorous external review by senior experts that is often conducted for similar life-safety structures and systems.

The first of ASCE's Fundamental Canons in its Code of Ethics states, "Engineers shall hold paramount the safety, health and welfare of the public…." Serious deficiencies in the southeast Louisiana hurricane protection system must be corrected if the New Orleans area is to avoid a similar catastrophe when the next major hurricane strikes.

The ASCE Hurricane Katrina External Review Panel strongly urges that organizations responsible for critical life-safety facilities be organized and operated to enable, not to inhibit, a focus on safety, and that engineers continually evaluate the appropriateness of design criteria, always considering how the performance of individual components affects the overall performance of a system. Specific recommendations include:

- Keep safety at the forefront of public priorities by having all responsible agencies re-evaluate their policies and practices to ensure that protection of public safety, health, and welfare is the top priority for infrequent but potentially devastating impacts from hurricanes and flooding. Also, encourage Congress to establish and fund a mechanism for a nationwide levee safety program, similar to that which is in place for dams.

- Quantify and periodically update the assessment of risk. This approach should be extended to all areas in the United States that are vulnerable to major losses from hurricanes and flooding.

- Determine the level of acceptable risk in the community through quality interactive public risk communication programs in New

Orleans and other areas threatened by hurricanes and flooding. Once determined, manage the risks accordingly.

- Correct the system's deficiencies by establishing mechanisms to incorporate changing information, making the levees survivable if overtopped, strengthening the I-walls and levees, and upgrading the pumping stations.

- Assign to a single entity or individual (a licensed engineer) the responsibility of managing critical hurricane and flood protection systems such as the one in New Orleans.

- Implement more effective mechanisms for coordination and cooperation. (For example, those responsible for maintenance of the system must collaborate with system designers and must upgrade their inspection, repair, and operations processes to ensure that the system is hurricane- and flood-ready.)

- Upgrade engineering design procedures and practice to place greater emphasis on safety.

- Engage independent experts in high-level reviews of all critical life-safety structures, including hurricane and flood-protection systems.

In a very real sense, the findings and conclusions in this report extend far beyond the New Orleans hurricane protection system. The lessons learned from the engineering and engineering-related policy failures triggered by Hurricane Katrina have profound implications for other American communities and a sobering message to people nationwide: ***we must place the protection of safety, health, and welfare at the forefront of our nation's priorities***. To do anything less could lead to a far greater tragedy than the one witnessed in New Orleans.

CHAPTER 1

Introduction

On the morning of August 29, 2005, Hurricane Katrina struck southeast Louisiana and triggered what would become one of the worst disasters ever to befall an American city. The storm overtopped levees and floodwalls throughout southeast Louisiana and also caused the levees and floodwalls in the New Orleans area to fail or breach in more than 50 locations. Water rushed into New Orleans and flooded over 80 percent of the city—more than 10 feet deep in some neighborhoods.

One thousand one hundred eighteen (1,118) people lost their lives in the New Orleans area, and 135 more are still missing and presumed dead. Tens of billions of dollars worth of property was damaged. More than 400,000 people fled the city. Many have not returned. The educational and health care systems of the New Orleans area have been crippled. The devastation was so extensive, and the residual risk looms so ominous, that, more than a year and a half later, the future of New Orleans remains clouded.

The members of the American Society of Civil Engineers (ASCE) extend their sincere condolences to the families and friends of those who lost their lives during and after Hurricane Katrina. Our heartfelt sympathy goes out to the people of the New Orleans area who are left without homes, communities, and jobs, and to those who face an uncertain future.

The members of the ASCE Hurricane Katrina External Review Panel have conducted an in-depth review of the comprehensive work of the United States Army Corps of Engineers (USACE) Interagency Performance Evaluation Taskforce (IPET). We are indebted to the dedicated efforts of more than 150 engineers and scientists who have, in the year and a half following Hurricane Katrina, evaluated the causes of the New Orleans area hurricane protection system failures.

As a result of this excellent work, we now better understand what went wrong and why. The ASCE Hurricane Katrina External Review Panel has an obligation to share its findings and insights, which go beyond the scope of the IPET review, so that others may learn from this tragedy and prevent similar disasters from happening again, not only in New Orleans, but in other communities throughout the United States that are also vulnerable to hurricanes and flooding.

Interagency Performance Evaluation Taskforce

In the aftermath of the storm and flooding, Lieutenant General Carl A. Strock, P.E., Chief of Engineers, USACE, ordered an investigation to provide credible, objective engineering and scientific answers to fundamental questions about the operation and performance of the hurricane protection system in southeast Louisiana. The results of the performance evaluation were intended to answer the following four questions:

1. What were the storm surges and waves generated by Hurricane Katrina and did overtopping occur?
2. How did the floodwalls, levees, and drainage canals, acting as an integrated system, perform and breach during and after Hurricane Katrina?
3. How did the pumping stations, canal gates, and road closures, acting as an integrated system, operate in preventing and evacuating the flooding due to Hurricane Katrina?
4. What was and what is the condition of the hurricane protection system before and after Hurricane Katrina and, as a result, is the New Orleans protection system more susceptible to flooding from future hurricanes and tropical storms?

The objectives of the IPET work included identifying lessons learned and ways to potentially improve the performance of the existing hurricane protection system at the authorized level of protection. The IPET's work is documented in a comprehensive final report that is available at https://ipet.wes.army.mil/.

ASCE's Hurricane Katrina External Review Panel

The Chief of Engineers requested that ASCE form an external review panel to review and comment on IPET's work. ASCE brought together 14 experts in the key engineering and scientific disciplines related to the hurricane protection system failure to form the ASCE Hurricane Katrina External Review Panel.

The ASCE Hurricane Katrina External Review Panel's scope of work was to provide an ongoing, real-time, and objective technical review of the IPET report findings on the performance of the hurricane protection system in New Orleans and surrounding areas. ASCE Hurricane Katrina External Review Panel members visited New Orleans, examined the damaged areas, and had access to large amounts of information about the catastrophe and its causes. Beginning with the formulation of IPET's scope of work, the ASCE Hurricane Katrina External Review Panel members have been in close contact with IPET investigators, have actively submitted informal comments to the IPET, and have reviewed each IPET report in detail.

The factual and technical foundation for the findings presented in this report is the extensive work by IPET, although this report also draws from ideas expressed by others. Even though IPET's work formed the basis of the technical analysis, this report was prepared independently of IPET and the USACE, and solely reflects the views of the ASCE Hurricane Katrina External Review Panel members.

Other Teams of Investigators

Among the first groups of engineers to visit New Orleans after Hurricane Katrina was a levee assessment team from ASCE. This team examined and documented post-flood conditions to aid in investigating the causes of the failure. The results are presented in Report No. UCB/CITRIS–05/01, "Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005," November 17, 2005. Two of the members of the ASCE levee assessment team are members of the ASCE Hurricane Katrina External Review Panel.

The National Research Council of the National Academies performed a review of both IPET's and the ASCE Hurricane Katrina External Review Panel's work under NRC/NAE project DEPS-L-05-02-A, "New Orleans Regional Hurricane Protection Projects." The scope of the National Academies review was:

1. Review the data gathered by the IPET and the ASCE teams and provide recommendations regarding the adequacy of those data, as well as additional data that will be important to the IPET study and which should be gathered.

2. Review the analyses performed by the IPET and ASCE to ensure their consistency with accepted engineering approaches and practices.

3. Review and comment upon the conclusions reached by the IPET and ASCE teams, and;

4. Seek to determine lessons learned from the Katrina experience and identify ways that hurricane protection system performance can be improved in the future at the authorized level of protection.

This Report

Through this report, the ASCE Hurricane Katrina External Review Panel offers an assessment of what happened to the New Orleans hurricane protection system as a result of Hurricane Katrina—and why it happened. This report focuses on the direct physical causes and contributing factors to the hurricane protection system failures. This report was developed not to repeat the IPET information but, rather, to interpret the broader significance of the findings. In the broadest sense, the lessons learned from this catastrophe are not limited to

New Orleans or to levees and floodwalls: they are applicable to all engineering projects where public health, safety, and welfare are at risk. Issues pertaining to pre- or post-hurricane evacuation, rescue operations, or recovery efforts were not part of the scope of this study, although all of these issues have an impact on the ultimate consequences of the hurricane protection system failures.

The report is written for both the scientist/engineer and the layperson. The scientist/engineer will glean valuable information related to the science and technology of hurricane flood protection. The layperson will gain a broad understanding of exactly what caused the disaster.

Perhaps the most difficult question is not so much "What went wrong and why?" but "What must we do next?" to avoid a similar catastrophe in the future—in New Orleans and in other hurricane- and flood-prone areas of the country. The ASCE Hurricane Katrina External Review Panel believes strongly that if lives and public safety are to be protected, significant changes will be required in the way hurricane and flood protection systems are funded, designed, managed, and maintained.

CHAPTER 2

New Orleans

New Orleans is located in southeastern Louisiana near where the Mississippi River flows into the Gulf of Mexico *(Figure 2.1)*. The busy Port of New Orleans provides a gateway for imports including petroleum, steel, copper, rubber, cement, coffee, and containerized goods. The chief exports are grain and other foods from the midwestern United States and petroleum products. Thousands of ocean vessels from Europe, Asia, Latin America, and Africa move through New Orleans on the Mississippi River every year.

Figure 2.1 Satellite Photo of New Orleans Area

New Orleans, Louisiana, located near where the Mississippi River flows into the Gulf of Mexico, is one of the nation's most important ports.

From New Orleans, products reach Americans either via a 14,500-mile inland waterways network including the Mississippi, Missouri, and Ohio Rivers, or via other transportation modes, including six railroad lines, 50 ocean carriers, 16 barge lines, and 75 truck lines with access to the port. In addition to cargo, cruise ships and riverboats transport more than 700,000 passengers through the port annually.

New Orleans is a part of Louisiana's extensive petroleum infrastructure that provides oil and other petroleum products to the nation. Louisiana ranks fifth in United States oil production, and is home to a network of pipelines and storage facilities plus 17 petroleum refineries, as well as to two of the nation's four Strategic Petroleum Reserves, which encompass the world's largest business center supply of emergency crude oil *(Figure 2.2)*. New Orleans also serves as a business center for energy companies such as BP, Shell Oil, Chevron, and ConocoPhillips.

Figure 2.2 Flooded Petroleum Storage Tank Farm

New Orleans is a major hub of regional petroleum production and refining operations providing up to 30 percent of the nation's oil. Damage to the petroleum complex from Hurricane Katrina was extensive.

A City on the River

Over the millennia, the Mississippi River has carried billions of tons of sediment from its headwaters toward the Gulf of Mexico. As the water flowed into the gulf, the sediment was deposited in the river delta, creating the land on which New Orleans and surrounding areas is now built. Within the river delta, high ground tends to be close to the Mississippi River due to natural river processes. New Orleans was established in the early 1700s on high ground adjacent to the Mississippi River.

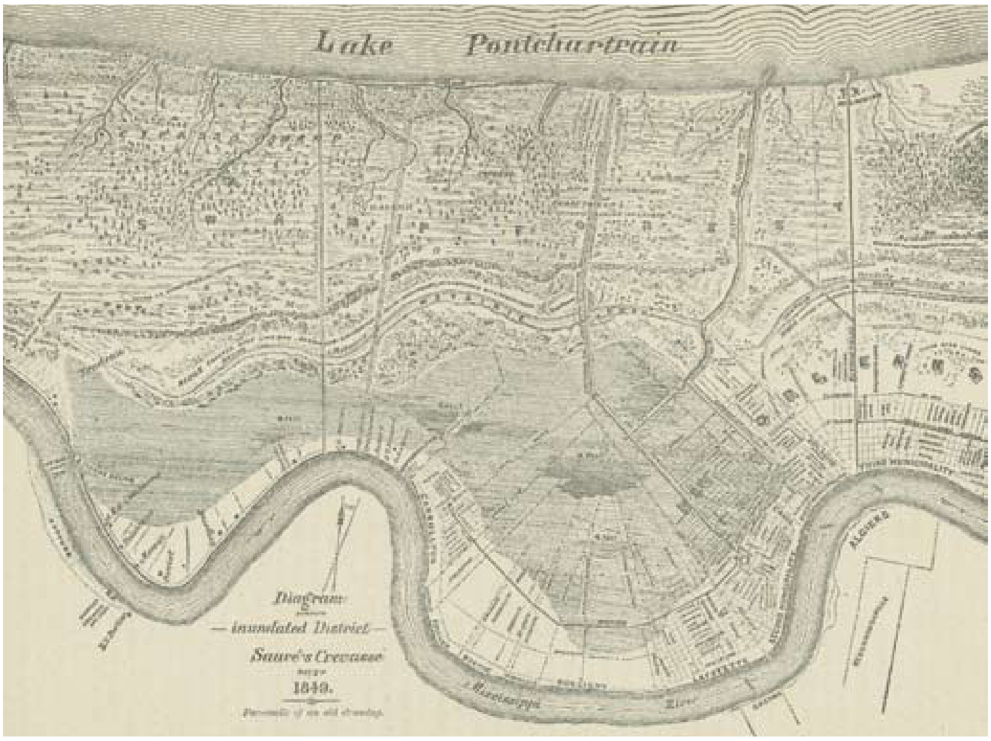
When floods occur on a major river, water mixed with sediment spills over the banks. The coarsest sediments (sand and gravel) settle out first, close to the river, forming natural levees near the river banks. Fine sediments (silt and clay) settle out further away into the swampland.

Over many floods and many alterations in the course of the river channel, this natural process has created a complex, highly variable geology. Layers of gravel, sand, silt, and clay are inter-fingered with layers of organic marsh deposits (often called peat) at various locations.

Development on the Marshes

A map of the east bank of New Orleans from 1849 *(Figure 2.3)* shows developed areas adjacent to the river, with cypress swamps, marshes, and bayous flanking the city to the north and east. The bayous naturally flowed northward into Lake Pontchartrain and eastward into Lake Borgne; Lake Borgne opens directly to the Gulf of Mexico. As New Orleans grew and prospered, levee systems were built around segments of the low swamplands to the north of the city, and the land was drained and developed.

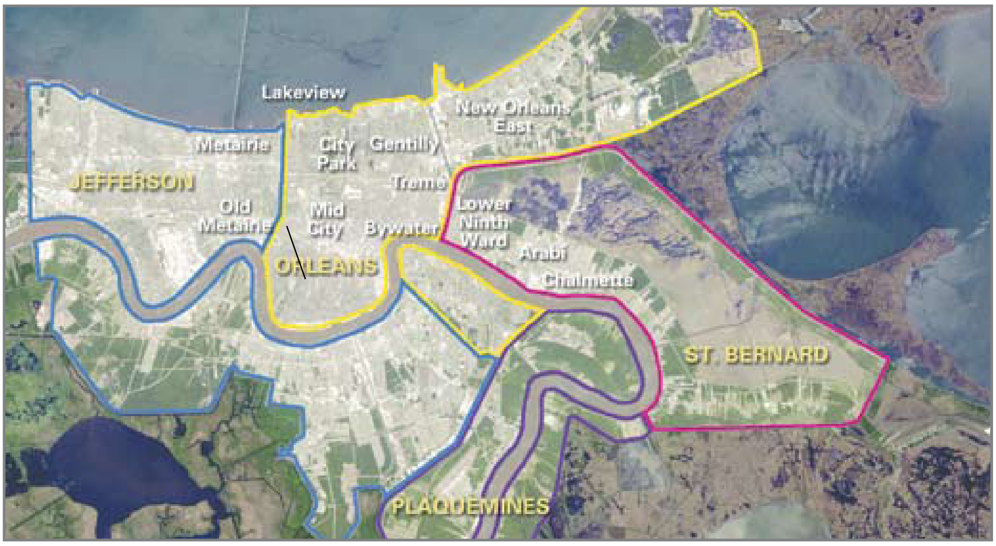
Figure 2.3 New Orleans in 1849



An 1849 map shows New Orleans built adjacent to the Mississippi River, with marshlands and bayous to the north.

The parishes of New Orleans and the neighborhoods within the parishes are shown in *Figure 2.4*. (Parishes are equivalent to counties in other parts of the United States.) Of primary significance to this report are Orleans and St. Bernard parishes. Significant flooding occurred in both due to failures in New Orleans's hurricane protection system.

Figure 2.4 The Parishes and Neighborhoods of New Orleans



St. Bernard, Plaquemines, and Orleans parishes were the most affected by flooding after Hurricane Katrina.

Levees and floodwalls were also built on the banks of several of the former bayous from Lake Pontchartrain into New Orleans. Waterways of significance to this report (as shown in *Figure 2.5*) include:

- 17th Street Canal
- Orleans Canal
- London Avenue Canal
- Inner Harbor Navigation Canal (also called the Industrial Canal)
- Gulf Intracoastal Waterway
- Mississippi River Gulf Outlet

New Orleans is Sinking

Large portions of Orleans, St. Bernard, and Jefferson parishes are currently below sea level—and continue to sink. New Orleans is built on thousands of feet of soft sand, silt, and clay. Subsidence, or settling of the ground surface, occurs naturally due to the consolidation and oxidation of organic soils (called "marsh" in New Orleans) and local groundwater pumping. In the past, flooding and deposition of sediments from the Mississippi River counterbalanced the natural subsidence, leaving southeast Louisiana at or above sea level.

However, due to major flood control structures being built upstream on the Mississippi River and levees being built around New Orleans, fresh layers of sediment are not replenishing the ground lost by subsidence. The natural subsidence has also been exacerbated by groundwater withdrawals, petroleum production, development, and other factors. Based on data collected by the United States Geological Survey from benchmarks located primarily in Orleans Parish (1951-1995), subsidence has been estimated to occur at an average rate of about 0.15 to 0.2 inches per year, although rates in excess of 1 inch per year occur in some locations.

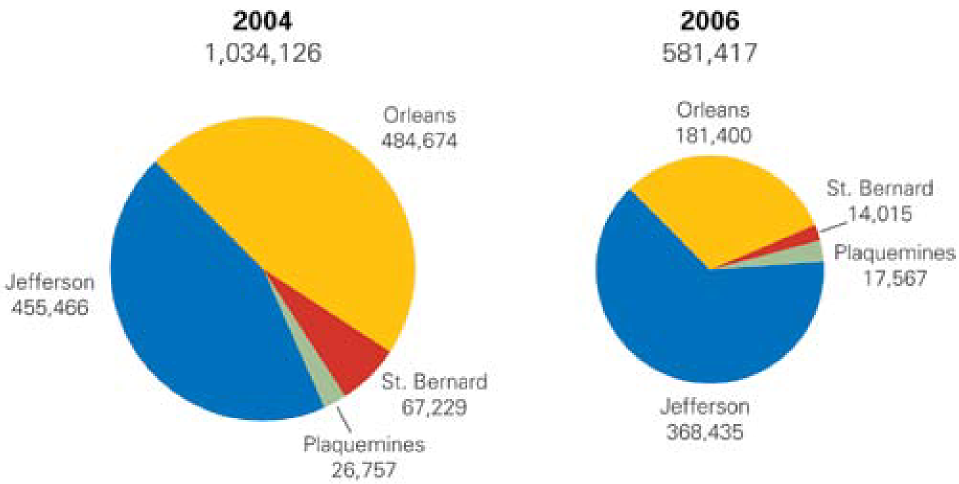
Figure 2.5 The New Orleans Waterways

New Orleans is surrounded by – and inter-fingered with – water: lakes, rivers, bayous, and canals.

The People of New Orleans

According to the 2004 United States Census, the population of the greater New Orleans metropolitan area affected most by Hurricane Katrina was approximately one million—67 percent African American, 28 percent Caucasian, and small percentages of Hispanics and Asians (3 percent and 2 percent, respectively). Studies attempting to estimate the city's post-Katrina population have set the 2006 population at around 580,000—a 44 percent decrease *(Figure 2.6)*.

Figure 2.6 Population of the New Orleans Region



The combined populations of Jefferson, Orleans, St. Bernard, and Plaquemines parishes dropped by 44 percent after Hurricane Katrina. Orleans Parish's population dropped 63 percent.

A Cultural Treasure

New Orleans fell under French, Spanish, and—following the Louisiana Purchase—American control, all within 100 years. Influences from the ruling nations blended with contributions from others entering the port city: African slaves, Caribbean islanders, and several waves of Italians, Germans, and Irish fleeing famine or simply seeking a new life in America. As a result, celebrations of Mardi Gras, St. Patrick's Day, St. Joseph's Day, and voodoo rituals all find a welcome home in New Orleans. The blend of languages also created words and phrases unheard in any other part of the country.

Some of the nation's oldest and most historic structures are located in New Orleans. Lacy ironwork and French- and Spanish-style architecture lend the city a European flavor. New Orleans's most famous export, jazz, also grew out of the city's mesh of cultures as European music styles gradually fused with ragtime, blues, and gospel *(Figure 2.7)*.

Creole cuisine, essentially classic French cooking incorporating local ingredients, is served in homes and restaurants, as is Cajun food, which was introduced to New Orleans by French-Canadian settlers in Louisiana.

Figure 2.7 A New Orleanian Leaving the City after the Hurricane

New Orleans is one of the most culturally rich and diverse cities in the U.S. in terms of music, architecture, food, and language. New Orleans is the home of jazz, America's most widely recognized indigenous musical art form.

CHAPTER 3

Hurricane Katrina

Hurricane Katrina was one of the strongest storms ever to hit the coast of the United States; New Orleans was directly in Hurricane Katrina's path. Hurricane Katrina brought intense winds, rainfall, waves, and storm surges that caused widespread devastation in New Orleans and along the coasts of Louisiana, Mississippi, and Alabama.

Hurricanes are not new to the Gulf Coast. Major hurricanes to have hit the Gulf Coast in the vicinity of southeast Louisiana are listed in *Table 3.1*:

Table 3.1 Major Hurricanes to Have Crossed Southeast Louisiana or Vicinity (1851-2004)

HURRICANE	YEAR	CATEGORY AT FIRST LANDFALL	CENTRAL PRESSURE AT FIRST LANDFALL (millibars)
CAMILLE	1969	5	909
KATRINA	2005	3	920
ANDREW	1992	5*	922
LA (NEW ORLEANS)	1915	4	931
LA (LAST ISLAND)	1856	4	934
SE FL/SE LA/MS	1947	4	940
AUDREY	1957	4	945
LA (CHENIER CAMINANDA)	1893	3	948
BETSY (SE FL/SE LA)	1965	3	948
LA/MS	1855	3	950
LA/MS/AL	1860	3	950
LA	1879	3	950
LA (GRAND ISLE)	1909	3	952

Source: National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NWS TPC-4, "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2005 (and Other Frequently Requested Hurricane Facts)"
**Hurricane Andrew was a Category 5 hurricane in Florida but a Category 3 hurricane as it reached Louisiana.*

The Storm

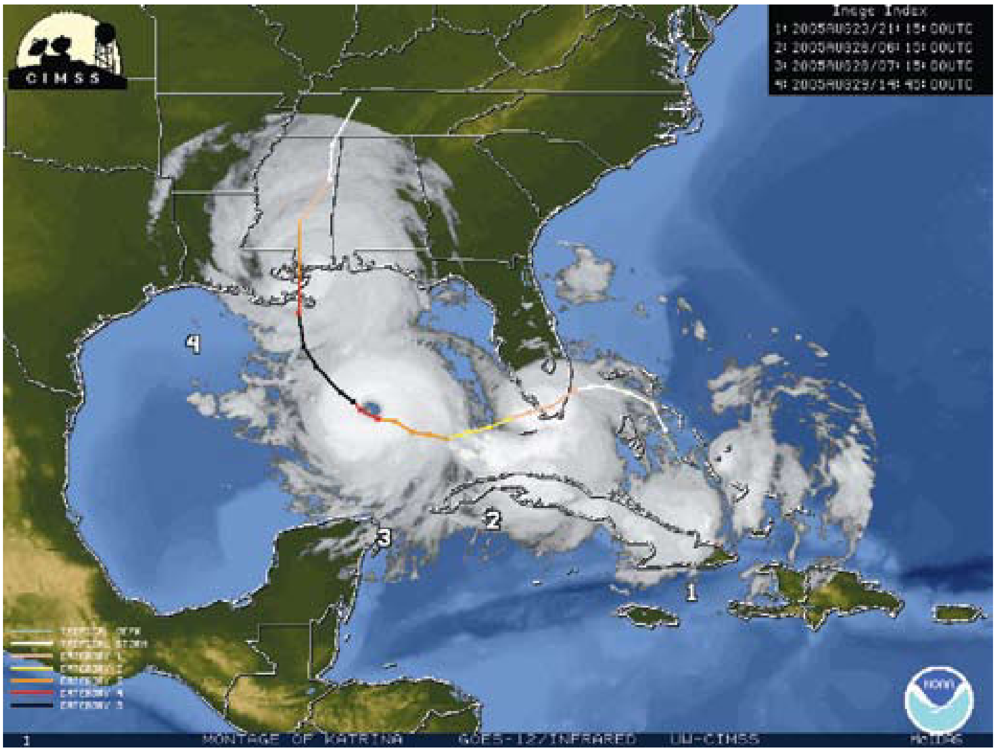
Hurricanes are intense low-pressure areas that form over warm ocean waters in the summer and early fall. As warm, moist air rises from the ocean surface into cooler air above, the water vapor condenses to form droplets and clouds. This condensation releases heat, boosting the rise of the air, lowering the central pressure, and drawing more warm, moist air into the storm. In this manner, the energy builds up and the wind speed increases. The low pressure causes wind to spiral inward toward the center of the low-pressure area, creating the hurricane. In the northern hemisphere, hurricane wind rotation around the eye of a hurricane is counter-clockwise. Hurricanes are categorized based on maximum wind speed according to the Saffir-Simpson Hurricane Scale, as summarized in *Table 3.2*.

Table 3.2 The Saffir-Simpson Hurricane Scale

CATEGORY	WIND SPEED (mph)	TYPICAL STORM WATER SURGE (ft)
1	74 - 95	4 - 5
2	96 - 110	6 - 8
3	111 - 130	9 - 12
4	131 - 155	13 - 18
5	> 155	> 18

The path of and intensity history of Hurricane Katrina are shown in *Figure 3.1*. The storm started as a tropical depression in the Bahamas on August 23, 2005. It crossed south Florida on August 25 as a Category 1 hurricane, and then entered the Gulf of Mexico. The storm intensified as it tracked westward.

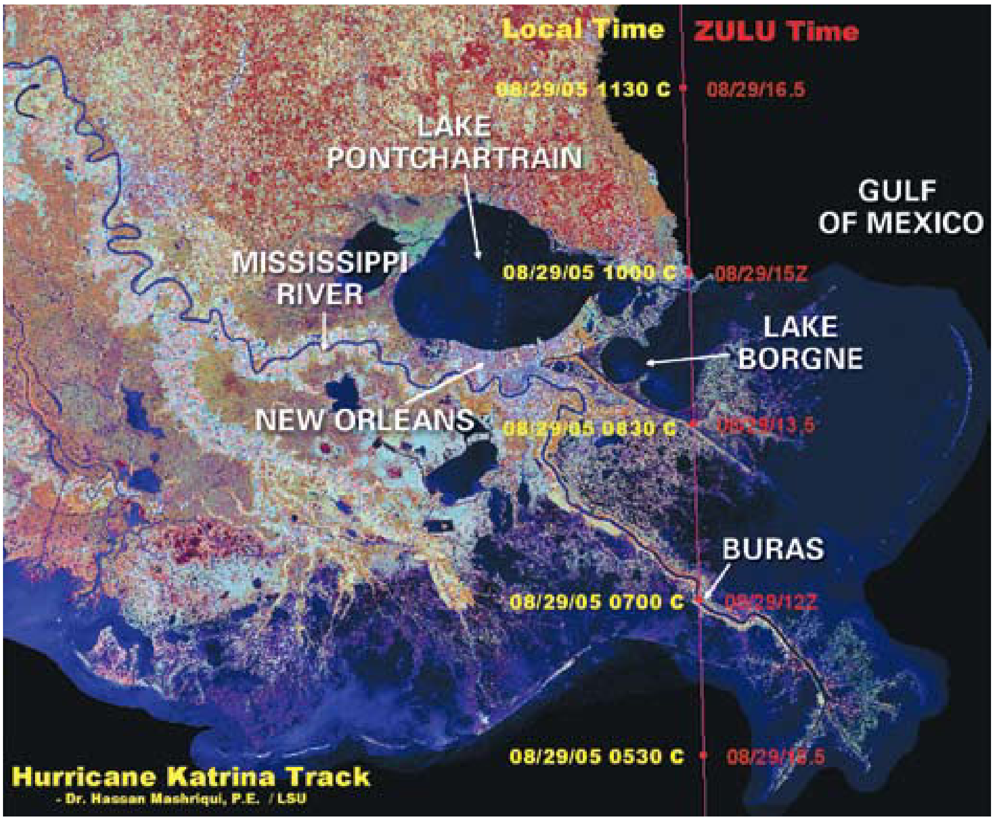
Figure 3.1 Path and Intensity History of Hurricane Katrina



This image is a montage of four satellite photographs taken in late August 2005, as Hurricane Katrina made its way from the Bahamas through the Gulf of Mexico, gaining strength.

On August 28, the storm began tracking toward the northwest, and intensified from a Category 2 to a Category 5 storm in just 12 hours. As it approached land, the warm, moist air and energy that Hurricane Katrina could draw from the Gulf of Mexico decreased, and Hurricane Katrina was degraded to a Category 3 storm. The path of the storm as it crossed into Louisiana is shown in *Figure 3.2*.

Figure 3.2 Traced Path of Hurricane Katrina over New Orleans



The eye of Hurricane Katrina tracked nearly due north across southern Louisiana, about 30 miles east of downtown New Orleans.

Wind, Water, and Waves

The strong wind and low atmospheric pressure of a hurricane causes storm surges. Storm surges typically cause the most damage near the coast, whereas winds cause the most damage away from the coast. Three factors contribute to the formation and intensity of a storm surge:

1. **Wind-induced motion of water.** The wind drags along the ocean's surface and causes the water to pile up as a surge higher than tide level. This is the main contributor to high water from a major hurricane. As the water and waves reach the shore, flooding typically occurs. Wind also generates waves on the water's surface, increasing the momentum of the surge toward land and adding to the water height on top of the surge. As Katrina crossed the Gulf, easterly winds blowing for several days caused water to

pile up against the east bank of the Mississippi River that juts out into the Gulf.

2. **Reduced pressure from the storm.** Atmospheric pressure is roughly 30 inches of mercury. Hurricane Katrina had a minimum central pressure of about 27 inches, or 3 inches below atmospheric pressure. Typically, water will rise about 1 foot of water for every inch drop of mercury. Therefore, sea level was about 3 feet above normal because of the low pressures of Hurricane Katrina.

3. **Favorable or unfavorable timing with high and low ocean tides.** The worst combination is when a hurricane-induced storm surge occurs during high tide which was, indeed, the case when Hurricane Katrina hit land.

A satellite view of Hurricane Katrina taken at 10:15am on August 29, 2005 is shown in *Figure 3.3*. At its peak strength about 200 miles off the Louisiana coast (24 hours prior to landfall), Hurricane Katrina generated winds with speeds of up to 160 miles per hour (mph) (1-minute average). Hurricane Katrina also reached a minimum central pressure of 902 millibars (27 inches of mercury) at its peak, ranking fourth lowest on record for all Atlantic basin hurricanes, and produced offshore individual waves approximately 100 feet high in the Gulf of Mexico, which are some of the largest waves for any hurricane over the past century.

Figure 3.3 The Eye of Hurricane Katrina as seen from a NOAA Satellite

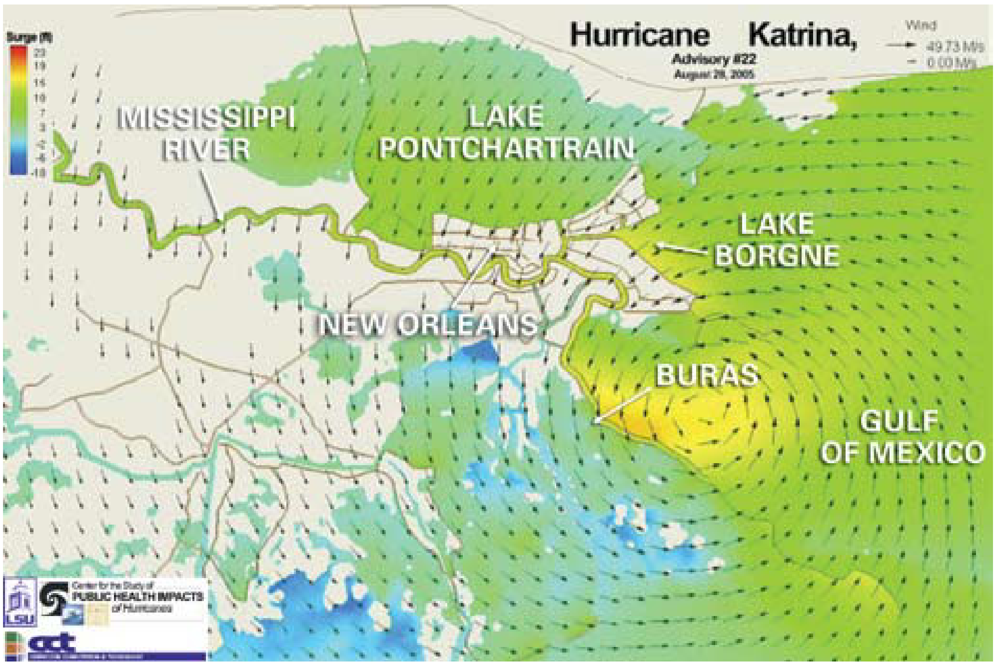
Hurricane Katrina was one of the strongest storms to hit the coast of the United States. The eye of Hurricane Katrina is shown in the center of the photo. The maximum wind speeds estimated during Hurricane Katrina were 160 miles per hour.

The leading edge of Hurricane Katrina made landfall at Buras, Louisiana, at 6:10am, August 29, 2005. The central pressure at landfall was 920 millibars, which ranked third lowest on record for United States land-falling storms. Although Katrina struck Louisiana as a Category 3 storm, its earlier status as a massive Category 5 storm added to the magnitude of the storm surge as Katrina approached the coast with ever greater intensity. When the eye of Hurricane Katrina struck at Buras at 6:30am, winds were approximately 127 mph.

Figure 3.4 shows wind vectors and storm surge elevation at about 7:30am on August 29, when the eye of the storm was just southeast of downtown New Orleans. The eastern edge of the New Orleans area was pounded by wind and water from the east. The northern edge of the New Orleans area along Lake Pontchartrain was pounded by wind and waves from the north. An enormous storm surge of water from the Gulf of Mexico built up in Lake Borgne.

The Mississippi River delta, which juts out to the southeast of New Orleans, created a barrier of land just to the west of the eye against which the massive storm surge also piled up. In south Plaquemines Parish, peak water levels reached 20 feet above mean sea level along the hurricane protection levees.

Figure 3.4 Wind Vectors and Calculated Storm Surge about 7:30am on August 29, 2005

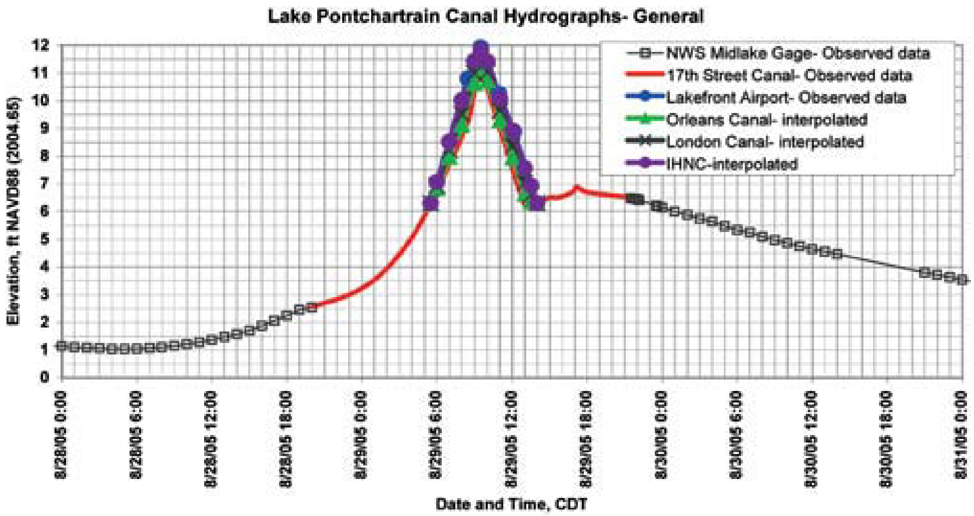


New Orleans was pounded by wind and water on the north and east. Wind drove water from the Gulf of Mexico into Lake Borgne. Water from Lake Pontchartrain was driven against New Orleans's lakeshore by winds blowing from the north.

The wind on Lake Pontchartrain was out of the north, piling up water along the southern shore of the lake. Peak water levels at the entrances to canals along the lakeshore of New Orleans were nearly 12 feet above sea level.

During a storm surge, the water level rises significantly above tide level for a few hours. After the hurricane passes and the direction of the wind shifts, water levels recede. A hydrograph, a graph of water level versus time, for the canal entrances at Lake Pontchartrain is shown in *Figure 3.5*. The highest water level occurred at approximately 9:30am on August 29, after which the water levels fell.

Figure 3.5 Hydrograph for the Canal Entrances at Lake Pontchartrain



On the lakeshore of New Orleans, water levels from the storm surge built up to a peak at 9:30am By 10:00am, the eye of the hurricane had passed slightly to the northeast of New Orleans, and the water levels began to fall.

In addition to the storm surges, Hurricane Katrina brought intense rainfall to the New Orleans area. Within Orleans Parish, for example, estimates of precipitation based on radar rainfall data indicate that up to 13.6 inches fell in some areas over the 24-hour period encompassing Hurricane Katrina. The 100-year rainfall (24-hour duration) for New Orleans is 12.58 inches, based on United States Weather Bureau Technical Paper 40 (1961). This means that there is a 1 in 100 probability in any given year that there will be 24-hour period where the accumulated rainfall will be greater than 12.58 inches.

CHAPTER 4

Hurricane Protection System

The USACE is responsible for the design and construction of most of the flood and hurricane protection levees along the Mississippi River and in the New Orleans area. Congress authorized the first major project to address hurricane-induced flooding in 1946. Since that time, as New Orleans's infrastructure and population has expanded, Congress has authorized a number of additional hurricane protection projects.

In addition, there are several other flood protection systems in and around New Orleans that are owned or operated by other agencies. These include:

- Interior drainage and pumping stations
- The Mississippi River Levee Flood Protection System
- Non-USACE levee features

The USACE's overall strategy to protect against flooding caused by hurricanes and storm surge was to build levees or floodwalls around segments of New Orleans. The USACE projects are generally grouped into three main units, as shown in *Figure 4.1*:

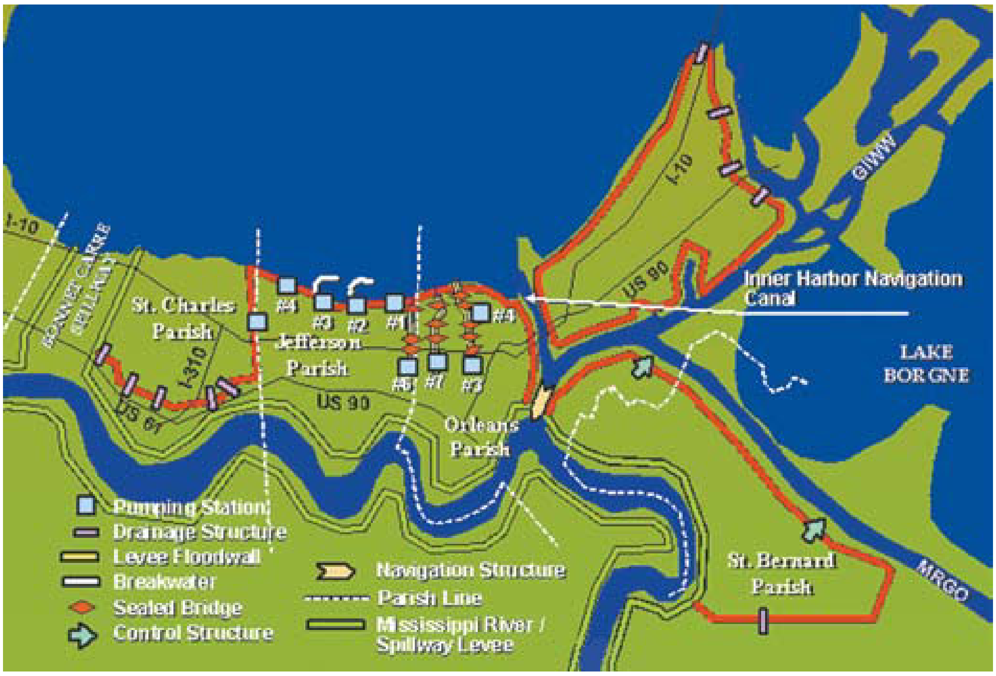
- Lake Pontchartrain, Louisiana and Vicinity Hurricane Protection Project
- West Bank and Vicinity, New Orleans, Louisiana, Hurricane Protection Project
- New Orleans to Venice, Louisiana, Hurricane Protection Project

Figure 4.1 Three USACE Hurricane Protection Systems in Southeast Louisiana

Over the past several decades, the USACE has designed and built three main hurricane protection systems to protect New Orleans and surrounding parishes from hurricane-induced flooding. The USACE designed and built the majority of the levees and floodwalls but they are maintained by local levee boards. Other levees and floodwalls are owned and operated by local levee boards. All of the pump stations are owned and operated by local agencies.

The Lake Pontchartrain, Louisiana and Vicinity Hurricane Protection Project *(Figure 4.2)* was intended to protect St. Bernard, Orleans, Jefferson, and St. Charles parishes between the Mississippi River and Lake Pontchartrain. The project generally included earthen levees with floodwalls along Lake Pontchartrain, the 17th Street Canal, the Orleans Canal, the London Avenue Canal, and the Industrial Canal.

Figure 4.2 Lake Pontchartrain, Louisiana and Vicinity Hurricane Protection Project



Failures within this hurricane protection system, comprised of earthen levees and floodwalls, caused the majority of the widespread flooding and damage during and after Hurricane Katrina.

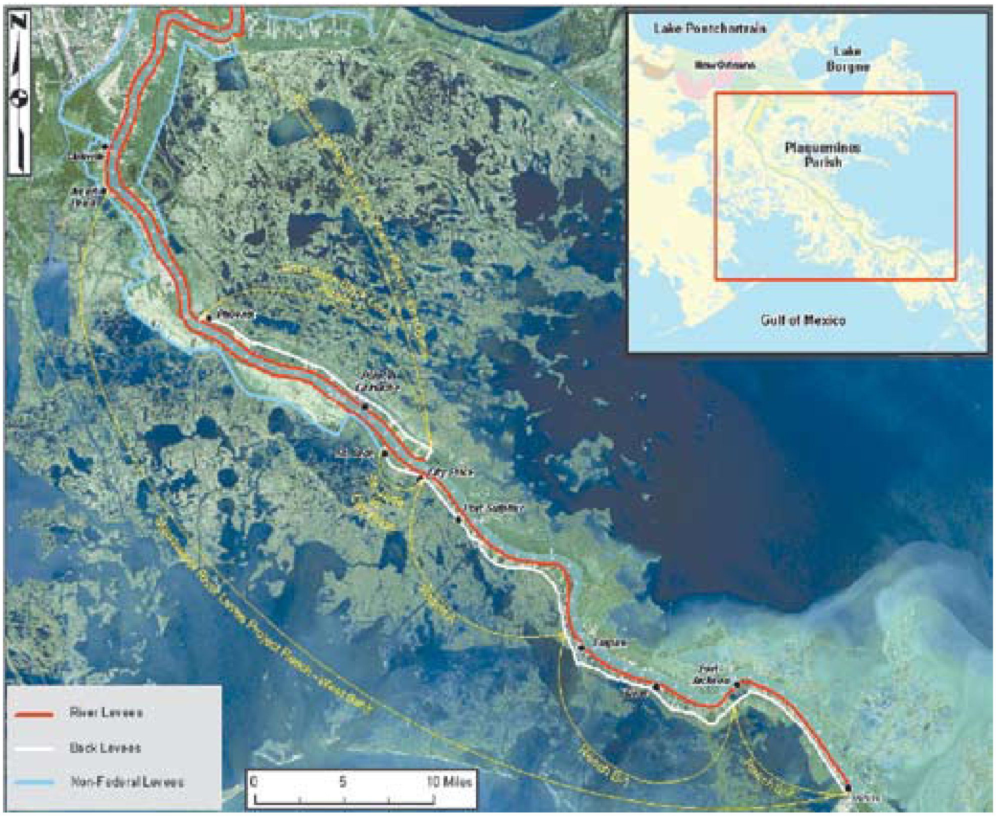
The West Bank and Vicinity, New Orleans, Louisiana, Hurricane Protection System *(Figure 4.3)* was intended to provide improved hurricane protection and flood control to portions of Jefferson Parish lying between the Mississippi River and Lake Salvador. The recommended plan included 22 miles of earthen levees and 2 miles of floodwalls extending from the canal to the V-levee near Jean Lafitte National Historical Park back north to the town of Westwego.

The New Orleans to Venice, Louisiana, Hurricane Protection Project is located along the east bank of the Mississippi River from Phoenix, Louisiana, (approximately 28 miles southeast of New Orleans) down to Bohemia, Louisiana, and along the west bank of the river from St. Jude, Louisiana, (approximately 39 miles southeast of New Orleans) down to the vicinity of Venice, Louisiana. As shown in *Figure 4.4*, the project generally consisted of earthen levees built along the Mississippi River.

Figure 4.3 West Bank and Vicinity, New Orleans, Louisiana, Hurricane Protection System

This hurricane protection system consists of earthen levees and floodwalls in New Orleans on the west bank of the Mississippi River.

Figure 4.4 New Orleans to Venice, Louisiana, Hurricane Protection Project



This hurricane protection system is intended to protect the low-lying land between the Mississippi River and the Gulf of Mexico from storm surge.

Standard Project Hurricane

The United States Congress directed the USACE to design the hurricane protection system for "the most severe combination of meteorological conditions that are considered 'reasonably characteristic' of the region." The approach historically taken by the USACE for design of Gulf Coast structures employs the concept of the "standard project hurricane," or SPH.

Following Hurricane Betsy in 1965, the USACE's selection of site-specific storm meteorological criteria was guided by the 1959 National Hurricane Research Project Report 33, "Meteorological Considerations Pertinent to Standard Project Hurricane, Atlantic and Gulf Coasts of the United States." In Project Report 33, the United States Weather Bureau (now the National Weather Service) recommended a single value for the central pressure index, three values each for forward speed and radius to maximum wind, one gradient wind speed value, and two values of surface wind speed. These criteria were based on historic hurricanes from 1900 to 1956.

In memoranda issued in 1959 and 1961, the USWB defined a probable maximum hurricane (PMH) as one that may be expected from the most severe combination of critical meteorological conditions that are "reasonably possible" for the region. The PMH had a lower central pressure index than the SPH.

At the outset of each hurricane protection project, the USACE chose design meteorological conditions that comprised the SPH based on the USWB recommendations. Facilities and structures were then designed to withstand the impacts of the SPH. The SPH meteorological criteria from Project Report 33 were used to design the Lake Pontchartrain and Vicinity and the New Orleans to Venice Hurricane Protection Projects.

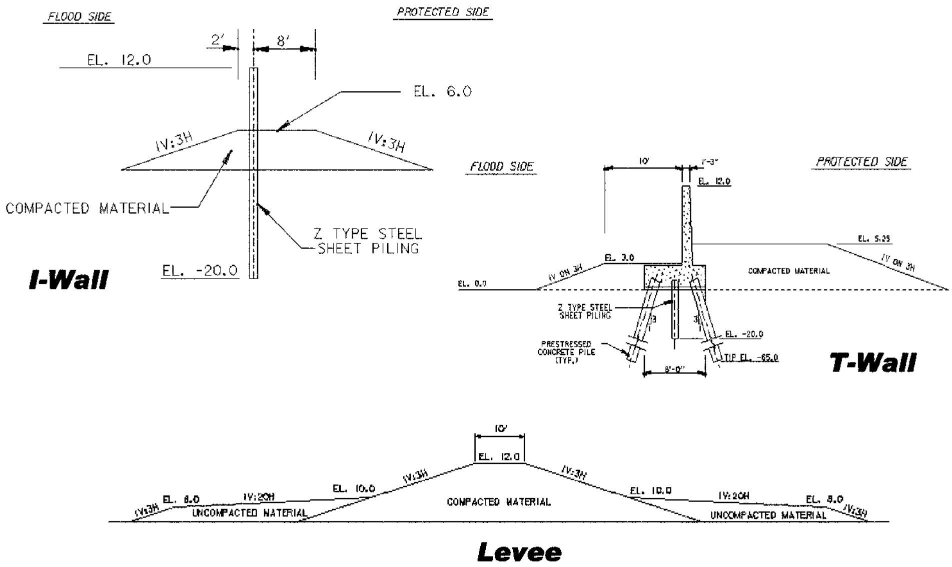
In 1979, NOAA issued Technical Report NWS 23, "Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Windfields, Gulf and East Coasts of the United States." This report contained revised criteria for the SPH, incorporating the characteristics of more recent hurricanes, including Hurricane Betsy, which directly hit New Orleans. Report NWS 23 also contained revised criteria for the PMH.

The West Bank and Vicinity Hurricane Protection Project was designed and constructed after Report NWS 23 was issued. It does not appear that the USACE used the updated SPH criteria, however.

Levees and Floodwalls

The USACE designed and built three types of flood protection structures in New Orleans's hurricane protection system, as shown in *Figure 4.5*. Earthen levees comprised the majority of the system.

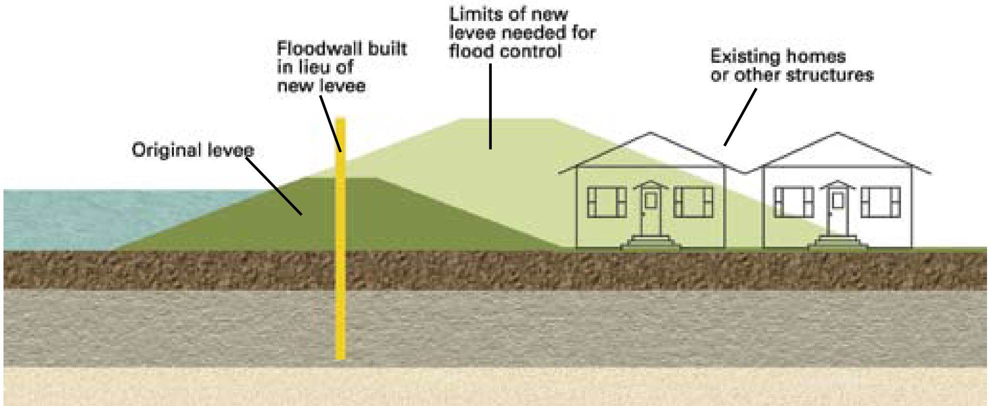
Figure 4.5 Typical USACE Flood Protection Structures



The USACE's levees and floodwalls followed a standard design, although the height of levees and walls varied throughout the hurricane protection system. In some places, hydraulic fill was used instead of compacted material to construct levees.

When an earthen levee is raised with additional earth fill, it can typically only be heightened by increasing the width at the base, as shown in *Figure 4.6*. In most urban areas of New Orleans, the land has been developed right up to the base of the levee. To raise and widen the levee would require private property to be purchased and buildings to be removed. Local opposition to such use of land is almost always considerable. A floodwall constructed in an existing levee allows the height of the levee to be raised without requiring the taking of adjacent property for levee expansion.

Figure 4.6 Increasing the Top Elevation of an Earthen Levee



Raising the top elevation of an existing earthen levee with additional earth fill also involves increasing its width. Where an existing levee was located adjacent to buildings, canals, or other structures, the USACE often resorted to using I-walls to avoid impacting adjacent development.

Some levee segments—particularly at gated closure structures where the levee alignment crosses roads or railroads—were constructed of T-walls instead of I-walls. T-walls are concrete structures shaped like an inverted T, supported on pre-cast pre-stressed concrete piles or steel H piles. Although T-walls are more robust than I-walls, they also cost much more to construct.

Datums and Elevations

The USACE authorized, designed, and modeled flood control structures in southeast Louisiana relative to a water level reference datum (e.g., Mean Sea Level (MSL); local MSL). MSL was assigned an elevation of zero. However, the structures were constructed relative to a geodetic (land-based) vertical datum that was incorrectly assumed as being equivalent to, or constantly offset from, the water level datum. This resulted, in the case of the outfall canals, in structures built approximately 1 to 2 feet below the intended elevation.

Each of the hurricane protection projects was designed and constructed on a project-by-project basis over the course of many years as funding became available. At the time of Hurricane Katrina, segments of the levee system were not yet complete, or the top elevations had not been raised to the authorized protective levels. Furthermore, because of regional subsidence, the hurricane protection structures had subsided as well, so that their top elevations were lower than originally designed or constructed. The Industrial Canal structures, for example, are more than 2 feet below their intended design elevations, mostly from subsidence over the 35-year life of the project.

Interior Drainage and Pump Stations

The average annual rainfall for the New Orleans area is 60 inches. Because much of New Orleans is below sea level (in effect, a series of large "bowls" surrounded by levees), nearly all runoff must be pumped out to prevent flooding. The interior drainage system was designed to remove stormwater runoff from rainfall events, not to remove water that enters the area from levee or floodwall overtopping or breaches.

New Orleans's interior drainage system consists of overland flow, storm sewers, roadside ditches, collector ditches, interior canals, interior pump (lift) stations, outfall pump stations, and outfall canals -- all designed to work together to gather runoff and then pump it into Lake Pontchartrain, Lake Borgne, or other nearby bodies of water. In Orleans Parish, this water is pumped out via major canals such as the 17th Street, Orleans, and London Avenue Canals. In a few locations, the pump stations discharge directly into the Industrial Canal and Intracoastal Waterway.

New Orleans's pumping system is one of the largest in the world. There are nearly 100 pumping stations in the greater New Orleans area. Some have been recently completed; others are approaching 100 years of age. Most of the pump stations appear to have been designed to handle flows from a 10-year, 24-hour storm, or around 9 inches of rainfall. For purposes of pump station design, each of the four parishes in the New Orleans area was divided into drainage subbasins. The basins usually follow natural topographical lines. They are often bordered by levees or ridges of relatively higher elevation.

Operational power is provided by various means. Some stations use pumps directly connected to diesel engines. For many stations, power is normally provided by the electrical grid, with back-up diesel generators or direct-drive diesel engines available when the electrical grid is out of service. Some of the older stations use 25 Hertz (Hz) power provided by a central generating plant to run the pumps. These stations use frequency changers to change 25 Hz power to 60 Hz power for the operation of their station service system.

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CHAPTER 5

The Levees Fail

The Lake Pontchartrain and Vicinity Hurricane Protection Project system experienced the worst damage during and after Hurricane Katrina and resulted in the most serious consequences to the city and people of New Orleans. The massive, destructive flooding of New Orleans was caused by ruptures at approximately 50 locations in the city's hurricane protection system. Of the 284 miles of federal levees and floodwalls—there are approximately 350 miles in total—169 miles were damaged.

Levees in the USACE's New Orleans to Venice Hurricane Protection Project sustained significant damage caused by powerful flood waters overtopping and breaching the levees.

The levees in the USACE's West Bank and Vicinity Hurricane Protection Project experienced the least amount of damage.

Storm Surge Damage

Even before Hurricane Katrina made landfall, storm surge energized by the storm's outer bands began to creep into low-lying areas around Lake Borgne. Before dawn on August 29, rising water levels reached the Industrial Canal. Waves, in conjunction with high storm surge, overtopped and eroded the Mississippi River-Gulf Outlet levees *(Figure 5.1)* and flooded portions of St. Bernard Parish.

Figure 5.1 Storm Surge under the Paris Road Bridge in New Orleans East

Entergy Corporation personnel took this photo of storm surge waters cascading over a levee near the Entergy power plant in the New Orleans East area.

At 6:10am, Hurricane Katrina made landfall at Buras, east of New Orleans, and storm surge flooded most of Plaquemines Parish *(Figure 5.2)*. Strong east-west winds built up a significant surge level at the Intracoastal Waterway. By 6:30am, levees lining the south side of the New Orleans East neighborhood were overtopped and breached, flooding the area. Within an hour of the hurricane's landfall, wind-generated waves reached heights of at least 4 feet in the Industrial Canal, causing overtopping into portions of the Gentilly and Bywater neighborhoods.

Figure 5.2 Hurricane Damage in Plaquemines Parish

The storm surge from Hurricane Katrina overtopped levees (seen in this photo adjacent to the water) in Plaquemines Parish and knocked hundreds of homes off their foundations. (This photo was taken after flood waters had receded.)

Cracks in the System

Before and during Hurricane Katrina's landfall, ruptures (or breaches) in four I-walls developed *(Figure 5.3)*—all before water levels in the adjacent canals overtopped them .

Figure 5.3 Major Breaches in the New Orleans Hurricane Protection System

Failures of several I-walls and levees along the canals that finger into New Orleans allowed massive amounts of water to flood New Orleans.

At about 5am, a breach in the east bank of the Industrial Canal I-wall contributed the first flow of floodwaters to the Lower Ninth Ward in St. Bernard Parish. At about 6:30am, a breach was observed in the I-wall on the Orleans Parish side of the 17th Street Canal, which flooded a portion of Lakeview.

At about 7:00am, a breach occurred in a London Avenue Canal I-wall near Mirabeau Avenue in Gentilly (South Breach). About an hour later, a second breach occurred on the London Avenue Canal near Robert E. Lee Boulevard (North Breach).

Flooding Ensues

Within a few hours of the initial breach observed at the Industrial Canal, rising water in the canal overtopped and eroded levees. Torrents of water rushed into city streets. Multiple levee failures inundated some neighborhoods from several sides with such speed that houses filled to their rooftops in minutes *(Figure 5.4)*. In other areas, the rise of water was slower, but constant, filling homes at a rate of 1 foot every 10 minutes. On the west side of the Industrial Canal, I-wall failures allowed water to flood into the Upper Ninth Ward, Bywater, and Tremé neighborhoods. Another large floodwall breach on the east side of the Industrial Canal quickly flooded the Lower Ninth Ward in what witnesses describe as a "wall of water." Floodwaters from this break (shown in *Figure 5.5)* reached other neighborhoods of St. Bernard Parish including Arabi and Chalmette.

As the hurricane moved north, flooding in St. Bernard Parish was compounded by storm surge overtopping the Forty Arpent Canal levee and filling the balance of the parish. Storm surge from Lake Pontchartrain added to floodwaters already filling New Orleans East. Storm surge also overtopped an embankment at the foot of the Orleans Canal and flooded the City Park neighborhood.

By 8:30am the breach at the London Avenue Canal *(Figure 5.6)* created a rush of water and sand into the already-flooded Gentilly area. Soon afterward, a floodwall failed at the 17th Street Canal, releasing a massive wave of water into Lakeview *(Figure 5.7)*.

Figure 5.4 Industrial Canal, East Bank, North Breach

Floodwater from the Industrial Canal (top) rushed through a breach in the east bank I-wall into the Lower Ninth Ward (bottom). Water from the Industrial Canal also flowed into the Upper Ninth Ward, Bywater, and Tremé neighborhoods from breaches on the west side of the canal. (This photo was taken after floodwaters began to recede and water flowed from the Lower Ninth Ward back into the Industrial Canal.)

Figure 5.5 Industrial Canal, East Bank, South Breach

Water cascading over the floodwall at this location scoured out the wall's support and caused the breach. Waters from the Industrial Canal (bottom) rushed into the Lower Ninth Ward (top) with great force. (This photo was taken after the floodwaters began to recede and water flowed from the Lower Ninth Ward back into the Industrial Canal.)

Figure 5.6 London Avenue Canal South Breach

An I-wall failure on the east side of the London Avenue Canal allowed water to spill into the Gentilly neighborhood of New Orleans.

Figure 5.7 17th Street Canal Breach

The 17th Street Canal breach began at approximately 6:30am. By 9:00am, torrents of water from Lake Pontchartrain were rushing in to flood the Lakeview neighborhood (top of photo) and, ultimately, much of midtown New Orleans and surrounding areas.

Figure 5.8 London Avenue Canal North Breach

The I-wall along the west side of the London Avenue Canal failed at about 8:00am, allowing water to flood into the City Park neighborhood of New Orleans.

Water from the 17th Street Canal's 450-foot long breach eventually filled New Orleans as far south as Mid-City and west to Old Metairie. City-wide flooding was further compounded by another I-wall failure on the west side of the London Avenue Canal *(Figure 5.8)*.

A City Under Water

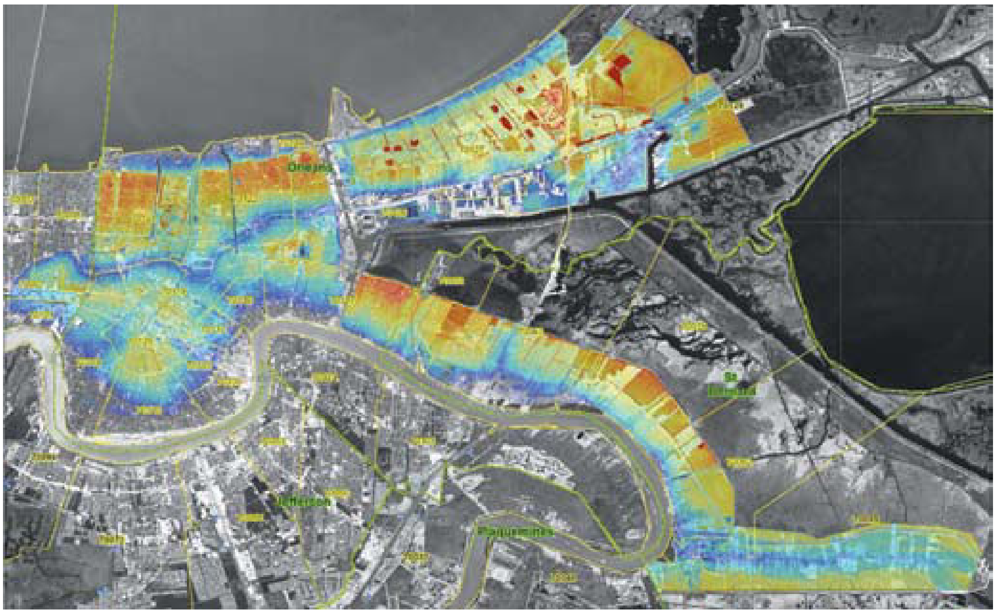
By the time the most significant I-wall failures had occurred, the peak of the surge levels was over. Though surge levels in the Gulf and in Lake Pontchartrain dropped, water continued to pour through the many damaged levees and floodwalls. This flooding continued until water in the city's bowl-shaped landscape equalized with the water level in Lake Pontchartrain.

By September 1, over 80 percent of the New Orleans metropolitan area was flooded as shown in *Figures 5.9 and 5.10,* with approximately two-thirds of the flooding attributed to water flowing through breaches. The remainder was attributed to overtopping and significant rain from the hurricane.

Figure 5.9 New Orleans Flooded

Overtopping and breaching at approximately 50 locations in the hurricane protection system led to destructive flooding that covered more than 80 percent of New Orleans.

Figure 5.10 Maximum Flooding Depth



By September 1, 2005, portions of Lakeview, Gentilly, New Orleans East, and the Lower Ninth Ward were submerged in more than 10 feet of water (orange and red colored areas). Significant portions of the city stood in water more than 6 feet deep (green and aqua colored areas).

Pump Stations Shut Down

During and after Hurricane Katrina, area pump stations could offer no relief to the flooding city because they were, themselves, left inaccessible and inoperable by the hurricane protection system failures. *Figure 5.11* shows one of the area's largest pump stations, Station No. 6, submerged in floodwaters.

Figure 5.11 Submerged Pump Station No. 6

Rapid and far-reaching flooding caused by the hurricane protection system failure left most pump stations, such as Station No. 6 (on the 17th Street Canal), inoperable.

CHAPTER 6

Consequences

The people who found themselves in New Orleans on the morning of August 29, 2005, not only witnessed history, they became a part of it. After many grueling days, survivors joined those who had evacuated before the storm in the largest mass migration in the United States since the Civil War. In the following weeks, receding floodwaters revealed billions of dollars in personal, public, and commercial property losses. With this massive property damage came the loss of 124,000 jobs.

More than a year and a half later, areas of New Orleans remain, in a practical sense, nearly unlivable. While many historic sites of the French Quarter and Garden District were, for the most part, spared, elements of every day life have been reduced to the bare minimum. Many homes are uninhabitable. Others, overrun with mold, require major repairs. Small businesses and restaurants remain shuttered, their proprietors unable to afford repairs or find housing for workers due to the dramatic loss of residential property. Medical care systems are compromised.

These losses, and the loss of people who will never return to New Orleans, bring further gaps in the city's economy as well as to its unique social and cultural foundation. As of August 2, 2006, 1,118 people were confirmed dead and 135 people are still missing and presumed dead, marking the grimmest consequence of the hurricane protection system failure.

Tragic Deaths

Floodwaters rose fast in some neighborhoods on August 29. While many people were able to evacuate either before or after the storm, many of the less fortunate drowned in the onslaught of water. Rapid flooding caused people to lose hold of family members as floodwaters rose. Some victims drowned in attempts to save others. In Orleans Parish, many people fled up into their attics to escape the rising waters, and then had to hack their way through the roofs to find a dry place to stand and wait for rescue. Some people evacuated their homes, only to die as they waited for food, water, or medical care. Dead bodies eventually floated to higher ground, where passersby mercifully covered them with stray tarps or soaked blankets.

Further from the breached levees and damaged floodwalls, water rose approximately 1 foot every 10 minutes. Some elderly or disabled residents could not reach their attics fast enough, leaving other family members to witness their deaths by drowning. One woman reportedly died of a heart attack while trying to escape through the roof. Others, trapped in their homes and attics, were found days, weeks, even months later. In St. Bernard Parish, many deaths were attributed to drowning in the storm surge.

Though the sick and the elderly were hardest hit *(Figure 6.1)*, causes of death were varied. Six deaths resulted from bacterial infection when new or existing wounds were immersed in floodwaters. Five people reportedly died of carbon monoxide poisoning from improperly using gasoline-powered generators during power outages. A bus accident during post-storm evacuation attempts killed one person, and one woman died when a helicopter cable failed during a rooftop rescue.

Figure 6.1 The Sick and the Elderly Were Hardest Hit

Above, many died when fast-rising floodwaters caught them off guard. Here, evacuees pass a drowning victim. Below, the sick and elderly were the most likely to be killed by the flooding and its aftermath. More than 30 people drowned when water levels nearly reached the ceiling at St. Rita's Nursing Home (left). Some residents already weak from illness died at evacuation centers (right).

Three people committed suicide. Only one person was murdered in the immediate aftermath, a remarkable number given New Orleans's extremely high homicide rate (10 times the national rate) prior to Hurricane Katrina.

However, the risk for additional homicides grew as rescue efforts stalled and residents took up arms against potential looting. Hospital pharmacies were threatened by armed assailants seeking drugs. The police, responding to shootings city-wide, fired on people, killing four.

Of the known fatalities, approximately 52 percent were African American, 40 percent were Caucasian, and 8 percent were of other or unknown race. Deaths were divided equally between men and women. As mentioned earlier, older residents were the hardest hit demographic group. Among all races, victims over the age of 70 accounted for 60 percent of all deaths.

Exposure, Injury, and Disease

The flood and its immediate aftermath were rife with potential for injury and illness. Throughout New Orleans, residents seeking safe haven waded through an opaque slush of mud, water, trash, and a mélange of chemicals—cleaners, solvents, and gasoline leached from flooded homes, businesses, and automobiles *(Figure 6.2)*. Added to the mix was output from seven major oil spills resulting from the flooding, plus runoff from up to 54 United States Environmental Protection Agency (USEPA) Superfund sites in the area.

Figure 6.2 Exposure to Toxic Chemicals

Survivors waded through a gruesome soup of mud and water plus chemicals and gasoline from flooded homes, businesses, and vehicles. Petroleum products left their telltale rainbow sheen on floodwaters.

Levels of *E. coli* and fecal *Coliform* bacteria in floodwaters were similar to typical stormwater runoff levels for the region, but much higher than standards for human contact. This exposure resulted in increased incidences of gastrointestinal illness, skin infections, and upper-respiratory infections.

Residents hurt themselves while hacking through their roofs or breaking windows to escape their flooded houses. People, such as those shown in *Figure 6.3*, sometimes waited on rooftops for days for rescue. Among them, several developed rashes from contact with hot roofing materials. Among rescue workers, a number of infections and non-infectious rashes were identified from contact with contaminated water, mite bites, and excessive chafing.

Figure 6.3 Rooftop Rescue

When floodwaters rose high and fast, residents had nowhere to go but up. Once water levels topped windows and doors, residents hacked through their roofs to await rescue.

Outbreaks of illness, exacerbated by person-to-person contact in close quarters, were reported in a Houston shelter where more than half the evacuees suffered acute diarrhea and vomiting for a week, and in Dallas, where an antibiotic-resistant strain of staph infection broke out. Fortunately, the Center for Disease Control and Prevention (CDC) reported no confirmed cases of dysentery, typhoid fever, or cholera.

Due to flooded hospitals and crowding at evacuation centers, the health of evacuees suffering from pre-existing conditions (such as diabetes and kidney failure) and those requiring prescriptions (for cancer, seizure illnesses, asthma, and psychiatric disorders) became compromised. Shortages of medication plagued shelters in the following weeks.

Catastrophic Financial Losses

To assess the financial losses in the New Orleans metropolitan area, researchers used the most recent inventories and field surveys of land use, properties lost, and estimated values. Assumptions made to determine expected personal property losses were based on reported flood depths in each neighborhood. Residential property throughout the New Orleans metropolitan area *(Figures 6.4 and 6.5)* was more than twice as likely as commercial property to be destroyed by the failure of the hurricane protection system.

Figure 6.4 Lower Ninth Ward after Floodwaters Were Removed

The force of the torrential waters raging through Industrial Canal East Bank North Breach (upper right) knocked some houses in the Lower Ninth Ward many feet off their foundations and completely obliterated others. (This photo was taken after floodwaters had been removed.)

Figure 6.5 Residential Property Decimated

The IPET estimates that single-family residential property sustained over $13.3 billion in direct losses. (These photos were taken after floodwaters had been removed.)

Direct damages to residential and non-residential capital (commercial, industrial, and public buildings) reached approximately $21 billion. Region-wide, 25 percent of the value of residential properties, including autos, was destroyed compared with 12 percent of the value of non-residential properties.

Losses to public structures and damages to infrastructure (roads, public transit systems, drainage and sewage systems, potable water service, telecommunications systems, and electrical utilities) reached between $6 billion and $6.7 billion. Damage to drinking water service resulted in an estimated leakage rate of 85 million gallons per day of treated water. The loss of electricity, which lasted for weeks, led to massive food spoilage and the ruin of more than 300,000 refrigerators, all of which required special handling prior to disposal. As floodwaters receded, widespread cleanup efforts began. *Figure 6.6* illustrates just a portion of the extensive public clean-up effort required to eliminate health hazards so residents could return to begin their own clean-up and rebuilding efforts.

Figure 6.6 Massive Cleanup Efforts

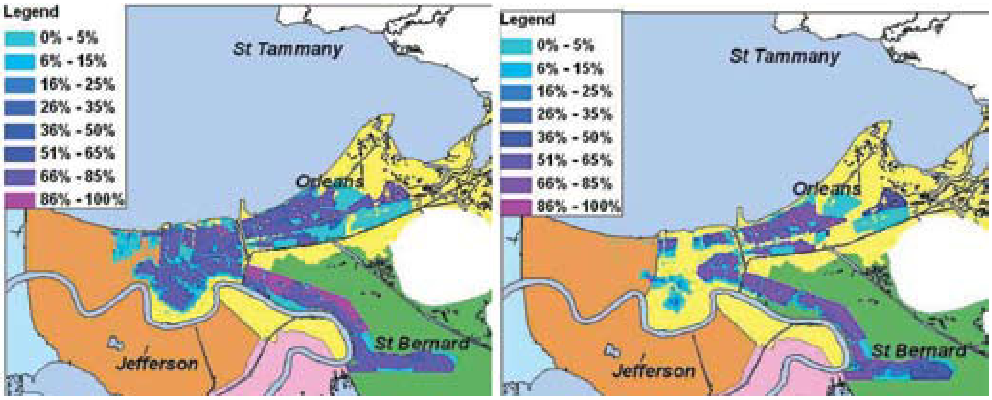
In Chalmette (top), workers vacuumed a thick layer of oil from city streets. More than 300,000 refrigerators (below), ruined by spoiled food after weeks of power outages, had to undergo hazardous materials removal before disposal.

Had the Hurricane Protection System Not Failed

For a storm the size of Hurricane Katrina, loss of life and property due to heavy rain, wind damage, and overtopping of levees is expected. A modeling exercise conducted by the USACE compared expected deaths from the hurricane protection system failure with scenarios in which the system did not fail. Results of this modeling indicate that had the levees and floodwalls not failed and had the pump stations operated, nearly two-thirds of the deaths would not have occurred.

Even without levee breaching, Hurricane Katrina's rainfall and levee overtopping would have caused the worst property loss ever experienced by New Orleanians. However, as pictured in *Figure 6.7*, less than half the actual property losses—an estimated $10 billion loss in residential and non-residential capital—would have occurred had the levees not failed and had the pump stations operated. This estimate did not consider damages to infrastructure and public utilities, which would have suffered far less damage had flooding not been as widespread.

Figure 6.7 Property Damage Modeling Results



Comparing regional property damage from the hurricane protection system failure (left) to a scenario in which the levees and pumping stations had not failed (right) indicates far less property loss would have occurred. Similarly, nearly two-thirds of deaths could have been avoided.

Cascading Financial Impacts

Researchers have compared data quantifying the pre-Katrina economic base for the New Orleans metropolitan area with anecdotal post-Katrina data. While limited, this preliminary assessment proves useful in estimating the indirect economic consequences brought on by the levee failures and the subsequent dislocation of hundreds of thousands of residents. However, household, business, and policy decisions yet to be made may have a profound impact on the region's long-term economic forecast.

As of June 2006, the population of New Orleans was still less than half the pre-Katrina population (more than a million people in 2004 versus just over half a million in 2006). Many jobs are still not available due to the reduced customer base and the destruction of business property, infrastructure, and residences. Total employment in the New Orleans metro area plummeted 25 percent (from 512,000 jobs to 388,000 jobs) between August (pre-Hurricane Katrina) and September 2005 (post-Hurricane Katrina).

The significant damage to infrastructure will likely slow the recovery of population and business activities. Repair work and labor force return has occurred unevenly, but predictably, across the area. Where flood water was shallow, more recovery has proceeded. In areas where flood water was deep, little recovery or reinvestment has taken place. *Figure 6.8* illustrates the contrast in rebuilding efforts between two neighborhoods—Lakeview, which was decimated by floodwaters as high as 10 feet, and a portion of Chalmette that saw lower flood levels.

Figure 6.8 Recovery is Slow

Rebuilding efforts vary directly with the level of flooding that occurred. In Lakeview (top), where floodwaters reached 8 to 10 feet, City officials have posted survey cards on abandoned houses to determine if residents plan to return. In areas where flood levels were lower, such as portions of Chalmette (bottom), residents have started repair work while they live in Federal Emergency Management Agency (FEMA) trailers.

Impacts to the economy of the State of Louisiana are significant, although impacts to the United States economy from the hurricane and flooding were short-lived. In the 2001/2002 fiscal year, combined general revenues for the five-parish region, including taxes and other income streams, totaled $3.4 billion, more than a third of local government general revenues in Louisiana. Since Hurricane Katrina this tax revenue has plummeted.

Prospects for Economic Growth

A regional economic forecasting model compiled for the IPET study presented economic forecasts for the New Orleans area, the rest of Louisiana, and the United States population following Hurricane Katrina. Economic outlooks reflecting pre-Katrina conditions were used as control values, and two scenarios were examined—flat population growth and a more brisk population growth.

Both scenarios yielded some economic growth, but not enough growth to reach levels anticipated, pre-Katrina, by 2010. According to the model, the economic growth of the New Orleans area will impact the overall growth of the state, but has little effect on the Gulf Coast region and the remainder of the United States The flat population scenario does, however, have the expected impact of increasing growth in the nation, reflecting the contribution of evacuees who choose not to return to the New Orleans metro area.

Long Term Health and Safety

Almost every hospital in the New Orleans area was crippled in some way from the floodwaters. As of March 2006, only 456 staffed hospital beds were available, one-fifth the pre-Katrina number. Less than half the adult acute-care facilities remain open. The Medical Center of Louisiana at New Orleans sustained so much damage that it has closed. This leaves a significant gap in health-care services for Medicaid patients and the uninsured, and removes a Level I Trauma Center from the Gulf Coast region. Residents must seek emergency care and other treatment at temporary facilities, as pictured in *Figure 6.9*.

Workers who lost their jobs and medical insurance coverage may or may not qualify for Medicaid coverage. Many people may go untreated for minor or serious medical conditions. Thousands of doctors and other health-care providers remain dispersed throughout the country. As of April 2006, New Orleans's physicians-per-resident rate had dropped from a pre-Katrina rate of 9.6 physicians per 3,200 residents to less than one primary care physician per 3,200 residents and less than one psychiatrist per 21,000 residents.

Figure 6.9 Outposts for Care

Due to extensive damage to almost every New Orleans hospital, including the Medical Center of Louisiana at New Orleans and its trauma center, residents must seek care in temporary medical facilities. Above, an emergency care and dental facility operated out of the Ernest N. Morial Convention Center for a time, and was then set up in a gutted, downtown department store.

With the exception of mold issues, environmental health impacts—for instance, from contaminated air, water, or soil—are not expected to be far-reaching. Reports of "Katrina cough" thought to be brought about by the presence of higher levels of dust and mold have not been substantiated. Still, health officials advised protection for construction workers, waste-handlers, and residents during clean-up and rebuilding.

Mold, as shown in *Figure 6.10*, grew in most homes that remained flooded over several weeks, introducing a potential environmental health problem. While mold has no established exposure limits, it presents a risk of opportunistic fungal infection in immuno-compromised persons. The CDC's measurements of airborne endotoxins that result from molds indicate that typical mold growth has reached levels associated with respiratory symptoms and skin rash.

Figure 6.10 Overrun by Mold

Mold covering interior walls presents a significant challenge for homeowners determined to restore their houses.

Most people exposed to traumatic events, such as serious accidents, combat, assault, or natural disasters, will experience feelings such as fear, anger, uncertainty, and sorrow. A subset of those exposed will experience symptoms of post-traumatic stress disorder, the result of structural and functional changes in the brain. Mental health impacts have already been observed; the suicide rate in New Orleans is nearly triple the pre-Hurricane Katrina suicide rate. Up to 6 months after the hurricane, calls to a city suicide hotline had doubled from pre-hurricane rates, despite the significantly smaller population. Others exposed to trauma may experience depression and substance abuse.

Evacuees and Their Receiving Communities

Counting pre- and post-hurricane evacuations, Hurricane Katrina displaced more than one million people. Evacuees left the city in droves by airplane or bus, as shown in *Figure 6.11*, in the days following the extensive flooding. By early October 2006, displaced individuals were located in 369 different cities in every state of the nation, with thousands clustered in large southern cities such as Houston, Atlanta, Memphis, and Baton Rouge.

Figure 6.11 Mass Migration

The evacuation of New Orleanians before and after Hurricane Katrina represents the largest mass migration in United States history since the Civil War. Above, immediately following the hurricane, the Louis Armstrong New Orleans International Airport became a processing center for rescued people leaving the city. Below, thousands of evacuees left the area by bus.

Receiving communities quickly found their services over-burdened. Before Katrina, nearly one-half of New Orleans's residents were either on Medicaid or uninsured. These evacuees have created an unanticipated strain on other communities' health-care systems. In Baton Rouge, the addition of 100,000 evacuees to the city's pre-Katrina population of 225,000 residents has led to over-crowding, traffic jams, and long waits for services. In Houston, 33 of 189 homicides (17 percent) involved Hurricane Katrina evacuees, although they increased the population by only about seven percent.

Impacts to New Orleans's Culture

The failure of the hurricane protection system, massive infrastructure damage, and the lack of jobs and residential properties for residents to return to have caused a breakdown in New Orleans's social structure. Many victims have lost homes, schools, jobs, shops, places of worship, and networks of family and friends.

Of New Orleans's 73 neighborhoods, only eight neighborhoods did not flood. Thirty-four were completely inundated. Many neighborhoods remain uninhabitable because of damage to residential structures.

Most religious congregations, a key source of community connectedness in New Orleans, have not resumed services. Many churches flooded and sustained significant damages, and, in the most devastated neighborhoods, few parishioners have returned.

Following Hurricane Katrina, school enrollment (primary and secondary) was down 52 percent in the five-parish metro area and down 86 percent in Orleans Parish. Students attend schools in other parishes or in cities where they have relocated. Enrollment is limited at University of New Orleans and Dillard, Xavier, Loyola, and Tulane Universities.

Two of New Orleans's most famous commodities—fine food and live music—remain severely affected. The majority of the city's musicians have not returned to the city *(Figure 6.12)*, and many restaurants damaged by the flooding remain closed. Losses in these two areas affect economic recovery as well as the recovery of New Orleans's social norms.

Figure 6.12 Awaiting Music's Return

A piano is removed from music legend Fats Domino's destroyed home in the Lower Ninth Ward. Many musicians have not returned to New Orleans due to a lack of housing and damaged performance venues.

The Natural Environment

Although an estimated 295 square kilometers (114 square miles) of wetland loss has been attributed to Hurricane Katrina, the loss was independent of failures of the hurricane protection system. The observed loss in wetlands —and associated losses in plants and animals—is consistent with long-term wetland loss trends plus losses from the storm surge *(Figure 6.13)*.

Figure 6.13 Wetlands Loss

Approximately 114 square miles of wetland loss resulted from storm surge and typical wetland loss trends, not from the hurricane protection system failure.

CHAPTER 7

Direct Causes of the Catastrophe

What is unique about the devastation that befell the New Orleans area from Hurricane Katrina—compared to other natural disasters—is that much of the destruction was the result of engineering and engineering-related policy failures. The levees were engineered structures intended to protect people from high water—the very disaster that they failed to prevent. The pump stations were engineered structures intended to remove rainwater from the New Orleans bowl, but they weren't always designed to withstand a hurricane or levee breach and they failed to pump.

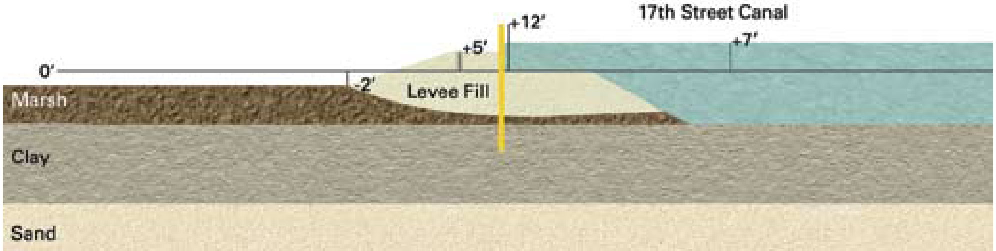
As outlined in Chapter 5, the levees in the New Orleans area breached at about 50 distinct locations. At least seven of the major failures were related to breaching of levees containing I-walls. The I-wall failures were particularly devastating because of the heavy residential development and low elevations they were attempting to protect. The rest of the levees breached when they were overtopped by the floodwaters, which eroded the levee material away.

17th Street Canal Breach

At about 6:30am on August 29, a 450-foot-long section of I-wall along the east side of the 17th Street Canal failed, sending torrents of water into New Orleans's Lakeview neighborhood. The water level in the 17th Street Canal at the time of failure was about 5 feet lower than the top of the wall, well below the design water level.

A cross-section of the levee and flood wall is shown in *Figure 7.1.* The levee and floodwall were built over a layer of organic soil called peat or marsh, which, in turn, overlays a layer of very soft clay. A principal concern with levees founded on soft soil is the possibility that the entire levee might slide either into the canal or away from the canal because of the low strength of the soft soil. This is a design problem that engineers deal with routinely. Indeed, the mechanism of failure was the levee sliding away from the canal.

Figure 7.1 Cross-Section of 17th Street Canal Levee and Floodwall



The levee and I-wall failed by sliding away from the canal along a failure surface in the weak soft clay below the levee.

Soil Strength Over-estimated

To prevent the failure of a levee or I-wall such as that along the 17th Street Canal, the "resisting forces" (i.e., the strength of the underlying soil) must be greater than the "driving forces" imposed upon it (i.e., the weight of the levee and the pressure of the canal water acting against the levee and the wall). The "factor of safety" against failure occurring is the ratio of the shear resistance of the soil divided by the shear force that develops along a potential sliding surface.

If the factor of safety is less than one, failure will occur. Because the factor of safety is directly proportional to the soil strength, determining the soil strength is one of the most important decisions that an engineer makes for levee design.

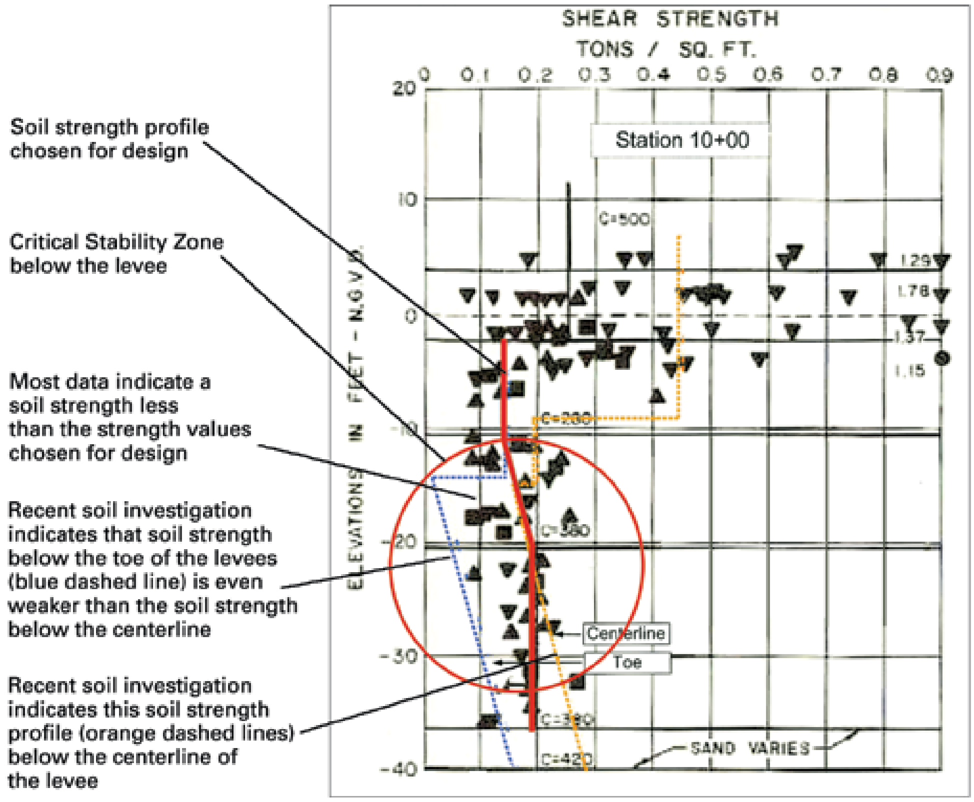
The engineers responsible for the design of the levee and I-wall over-estimated the soil strength—meaning that the soil strength used in the design calculations was greater than what actually existed under and near the levee during Hurricane Katrina.

Figure 7.2 illustrates how the soil data were mis-interpreted. During a soil investigation, samples are obtained from drill holes and tested in a laboratory to determine soil properties. From a plot of the soil strength data, conservative values should be selected for design.

For the 17th Street Canal failure, the critical zone for sliding was the soft clay between elevations -15 and -30 feet. The soil strength value chosen for design is highlighted by the red line. There are twice the number of data points to the left of (weaker than) the design shear strength profile than to the right (stronger than). The engineers made an unconservative (i.e., erring toward unsafe) interpretation of the data: the soil below the levee was actually weaker than that used in the I-wall design.

Two additional important factors led to an over-estimate of the soil strength below the 17th Street Canal. First, the data shown in *Figure 7.2* represent the values from *borings drilled along the centerline of the levee over a distance of 8,000 feet*—about 1½ miles. Lumping together data over distances is not uncommon. However, care must be taken in areas where there is geologic variability—such as in the New Orleans area—where the soil is stronger in some areas and weaker in others. Data from borings closest to the 17th Street Canal failure indicate that the actual average soil strength in the critical stability zone at the breach site is around 0.13 tons per square foot (tsf), compared to the engineer's design strength of 0.19 tsf—or approximately 32 percent lower.

Figure 7.2 Plot of Soil Strength beneath the 17th Street Canal Levee



Mis-interpretation of soil data below the 17th Street Canal levee was one of three primary reasons the I-wall failed.

Second, the data shown in *Figure 7.2* were obtained from borings drilled along the centerline of the levee; the key word here is the word "centerline." It is well understood that clay soil is consolidated and strengthened by the weight of overlying soil. The soft clay below the centerline of the levee was therefore stronger than the soil *below and beyond the edge* of the levee. Recent soil investigations by the USACE verify this: the orange-dashed line in *Figure 7.2* shows the average strength profile below the centerline of the levee, whereas the blue-dashed line shows the lower strength beneath and beyond the toe of the levee slope. The design engineers did not take this into account, and, accordingly, over-estimated the strength of the soil outside the footprint of the levee.

Factor of Safety

Over-estimating the soil strength below the levee set the stage, but was not the sole cause of the 17th Street Canal failure. The factor of safety for slope stability analyses such as these—the resisting forces divided by driving forces—must be greater than one. The higher the factor of safety above one, the less likely the levee will fail.

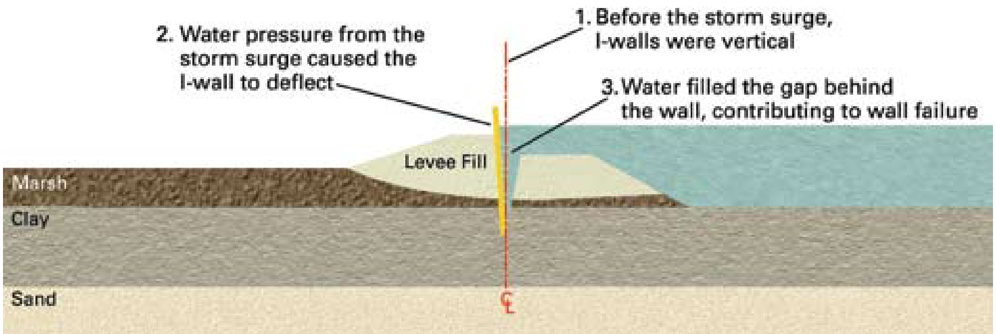
The target factor of safety chosen by the design engineers for the 17th Street Canal levee and floodwall design was 1.3. A target factor of safety of 1.3 is at the low end of generally accepted engineering values, and is inconsistent with current USACE standards. Key USACE design guidance documents call for a target factor of safety of at least 1.4 to 1.5 under long-term conditions.

The cumulative effect of using a target factor of safety of 1.3 and over-estimating the soil strength—a compounding error—was disastrous. The design was simply too close to the margin of safety, allowing little or no room to account for variables or uncertainties.

The Water-Filled Gap

Another critical engineering oversight that led to the failure of the 17th Street Canal involves not taking into account the possibility of a water-filled gap, which is illustrated in the diagram in *Figure 7.3.* The water-filled gap turned out to be a very important aspect of the failures of the I-walls around New Orleans.

Figure 7.3 The Water-Filled Gap

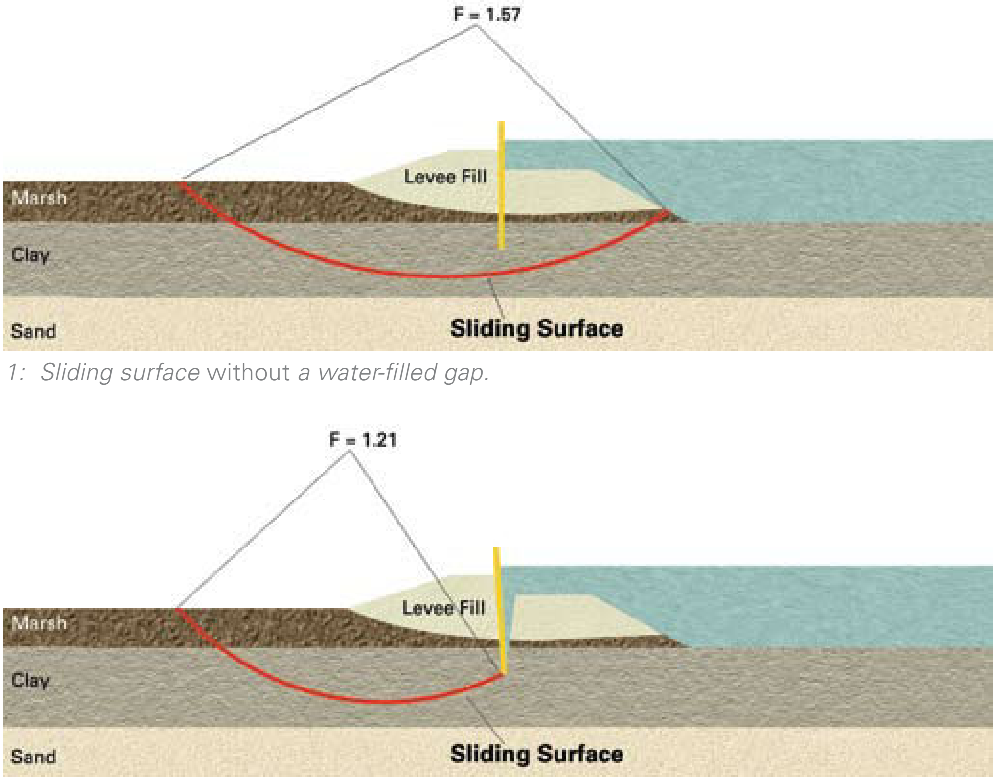


As floodwaters pushed against the I-wall and the I-wall leaned away from the canal, water flowed into the gap created between the wall and the soil behind it. The water-filled gap was an important factor in several I-wall failures.

Figure 7.4 illustrates the reason the water-filled gap led to failure of several I-walls. The first diagram in *Figure 7.4* shows the critical sliding surface passing beneath the 17th Street Canal I-wall and through soil between the wall and the canal—without a water-filled gap. The shearing resistance provided by this segment along the failure surface adds to the stability. In the second diagram of *Figure 7.4,* representing the actual situation with a gap, the critical sliding surface starts at the base of the water-filled gap. The sliding surface cuts through less soil, so that less resisting soil strength can be mobilized. In addition, the pressure on the wall generated by the water in the gap adds to the forces tending to slide the wall away from the canal.

Analyses indicate that, with the presence of a water-filled gap, the factor of safety is about 30 percent lower. Because a factor of safety of 1.3 was used for design, a reduction by 30 percent would reduce the factor of safety to approximately one: a condition of incipient failure.

Figure 7.4 17th Street Canal Failure Mechanism



1: Sliding surface without *a water-filled gap.*

2: Sliding surface with *a water-filled gap.*

Without the water-filled gap (top), the critical sliding surface is longer, which increases the stability of the wall. The wall with the water-filled gap (bottom) has a significantly lower factor of safety. As the water level rose in the canal, the factor of safety decreased from 1.21 to 1.0, or incipient failure.

In 1985, the USACE performed a full-scale field test on an I-wall to help verify design criteria for I-walls under high-water conditions. This field test, although focused on structural design criteria, also revealed the potential for large I-wall deflections. The observed deflections, nearly 3 inches at the ground surface, caused researchers to include the following statement in the report: "Although the test wall was not loaded to 'failure,' … failure may have been imminent." (USACE (1988), "E-99 Sheet Pile Wall, Field Load Test Report," Lower Mississippi Valley Division, Vicksburg, MS, 85 p.)

In the late 1990s, sophisticated computer modeling of the field test indicated that, "As the water level rises, the increased loading may produce separation of the soil from the pile on the flooded side (i.e., a tension crack develops behind the wall). Intrusion of free water into the tension crack produces additional hydrostatic pressures on the wall side of the crack…"

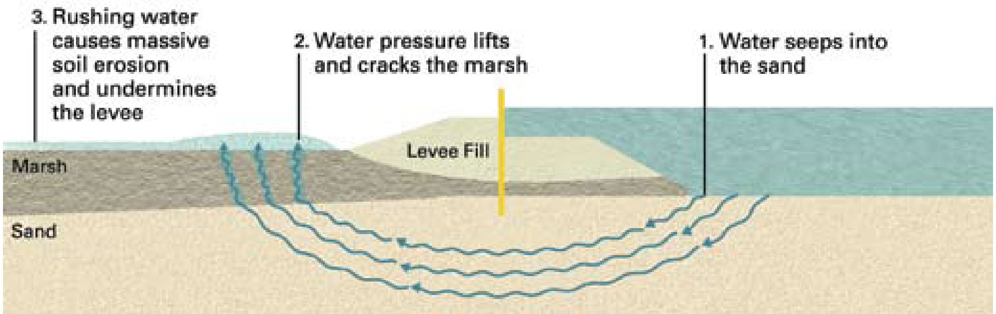
Thus, USACE researchers clearly recognized the potential for a water-filled gap to develop. This knowledge has now been found to be very important. As research and new information evolved in the 1980s and 1990s, the design of the existing I-walls was not checked for safety and stability in the light of new information.

London Avenue Canal South Breach

The London Avenue Canal South Breach occurred around 6 to 7am on August 29th, sending tons of sand and water into the New Orleans Gentilly neighborhood. As with the 17th Street Canal, the water level in the London Avenue Canal at the time of failure was about 5 feet lower than the top of the wall, well below the design water level.

The soil beneath the London Avenue Canal South Breach area is sand beneath the marsh layer, rather than soft clay, as was the case at the 17th Street Canal breach location. A cross-section describing the failure mechanism is shown in *Figure 7.5*.

Figure 7.5 Cross-Section of London Avenue Canal Levee and Floodwall



The levee and I-wall failed when pressure from the water seeping through the sand below the levee caused the marsh layer to crack. The sand then flowed out with the water, undermining the levee and I-wall.

As the water level rose in the canal, water seeped into the highly permeable sand, flowing under the levee toward the land-side of the wall. The water pressure acted upward on the bottom of the marsh layer. The stability of the levee under this type of condition hinges on whether the weight of the overlying material is great enough to resist the uplift water pressure acting upward on it. In well-designed structures, the uplift water pressure is never allowed to come close to the weight of the overlying soil. At the

London Avenue Canal South Breach, however, the water pressure exceeded the weight of the marsh layer and the topsoil above it.

The marsh layer was lifted up off the sand and cracked open, which allowed water to rush through the cracks. After the cracks developed, the upward-rushing water carried sand with it, gouging and scouring a hole that rapidly expanded and worked its way back under the levee, undermining and destroying it *(Figure 7.6)*.

Figure 7.6 Cars and Houses Partially Buried by Sand

Tons of sand were washed out from beneath the levee and floodwall at the London Avenue Canal South Breach and flowed into the adjacent neighborhood. (This photo was taken after floodwaters had been removed.)

Oversimplified Assumptions

The mechanisms of seepage and subsurface erosion have been well known for decades. Seepage beneath levees is discussed in depth in the USACE Engineer Manual EM1110-2-1913, "Design and Construction of Levees." Chapter 5, "Seepage Control," begins as follows:

> *"Without control, underseepage in pervious foundations beneath levees may result in (a) excessive hydrostatic pressures beneath an impervious stratum on the landside, (b) sand boils, and (c) piping beneath the levee itself. Underseepage problems are most acute where a pervious substratum underlies a levee and extends both landward and riverward of the levee and where a relatively thin top stratum exists on the landside of a levee."*

The design engineers of the London Avenue Canal levees and floodwalls did evaluate seepage. However, it was not apparent from the design information reviewed by the Hurricane Katrina External Review Panel that the potential uplift of the marsh layer was accounted for properly. Flow nets were drawn, but none included the marsh layer. The potential for uplift was assessed, but calculations used a critical hydraulic gradient value appropriate for soil, not for marsh.

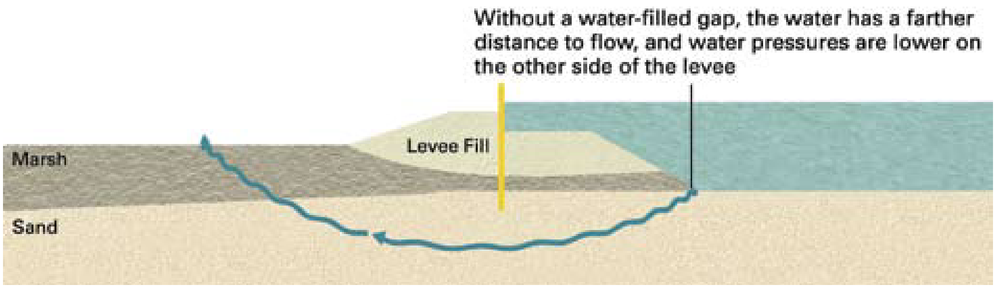
Because the problem with uplift for situations such as those existing at the London Avenue Canal is so well known, the Hurricane Katrina External Review Panel would have expected the design memoranda to contain a thorough, well-documented assessment of the potential for uplift of the marsh. No logical explanation for the lack of such information in the design memoranda could be identified.

Recent computer analyses of the London Avenue Canal South Breach indicate that the water pressures in the sand were sufficient to lift and rupture the marsh, and that the ensuing cracked condition would be expected to rapidly lead to erosion and collapse. The implication is that if a more rigorous analysis had been performed at the time of design, the potential problem would have been predicted and corrective action taken. Proactive measures to control the seepage—such as extending the depth of the sheet pile wall or installing relief wells—were not employed, leaving no redundancy or secondary means to protect from severe underseepage problems. Unfortunately, there was no second line of defense.

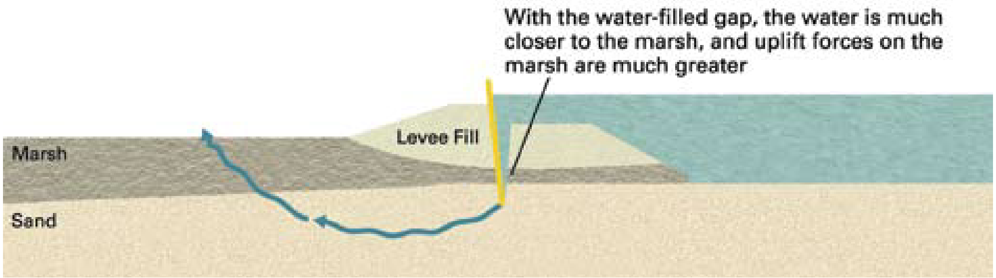
The Water-Filled Gap — Again

The failure of the London Avenue Canal I-wall was exacerbated by, and perhaps even caused by, the water-filled gap that developed behind the wall. Just as with the 17th Street Canal, the water in the London Avenue Canal pushed the I-wall away from the canal side, leaving a gap between the I-wall and the levee, which filled with water. As shown in *Figure 7.7*, the elevated water pressures were brought much closer to the land-side of the levee, significantly increasing the uplift forces on the clay and worsening the situation. As with the 17th Street Canal, a water-filled gap was not considered in the design of the London Avenue Canal levees and floodwalls.

Figure 7.7 London Avenue Canal South Breach Failure



1: Conditions without *a water-filled gap.*



2: Conditions with *a water-filled gap.*

Without the water-filled gap (top), there is less pressure on the underside of the marsh layer. The water in the water-filled gap (bottom) exerts significantly higher pressure on the marsh layer because it is closer.

London Avenue Canal North Breach

The London Avenue Canal North Breach occurred on the west side of London Avenue Canal around 7 or 8am on August 29th, allowing water to flood into the adjacent neighborhood. The upper 15 feet or so of soil beneath the London Avenue Canal North Breach consists of marsh underlain by a thick stratum of sand, similar to the conditions at the London Avenue Canal south failure. However, the sand at the North Breach was much looser and weaker than the sand at the South Breach.

The levee and I-wall probably failed in much the same way as the 17th Street Canal failure, in which the driving forces (the weight of the levee and the pressure of the canal water against the wall) exceeded the resisting forces (the strength of the underlying soil). The sliding failure was exacerbated by underseepage and associated water pressures.

Recent analyses of the London Avenue Canal North Breach indicate that the failure probably would not have occurred had a water-filled gap not developed. Factors of safety against stability failure without a crack were computed to be around 2.0. With a crack, the factor of safety was about 1.0 at the water elevation associated with failure.

Industrial Canal East Bank North Breach

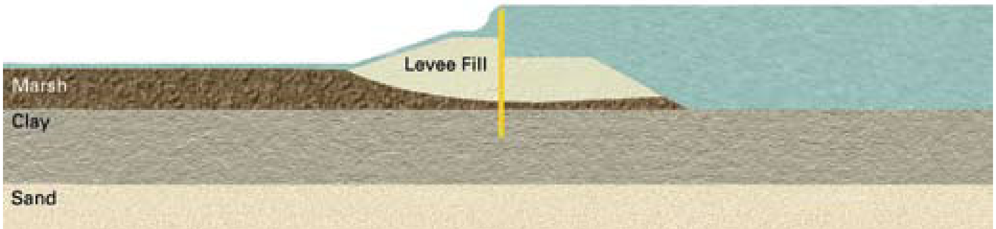
The failure of the Industrial Canal East Bank north I-wall was likely the source of the earliest flooding (observed at 5:00am) in the Lower Ninth Ward. The water level in the Industrial Canal was below the top of the floodwall. The soil conditions in this area consisted of marsh deposits overlying soft clay, which overlies sand.

The Industrial Canal East Bank north I-wall failed in much the same way as the 17th Street Canal I-wall failed: by slope failure along a sliding surface in the marsh. As with the 17th Street Canal, the presence of a water-filled gap (not considered during design) greatly reduced the factor of safety.

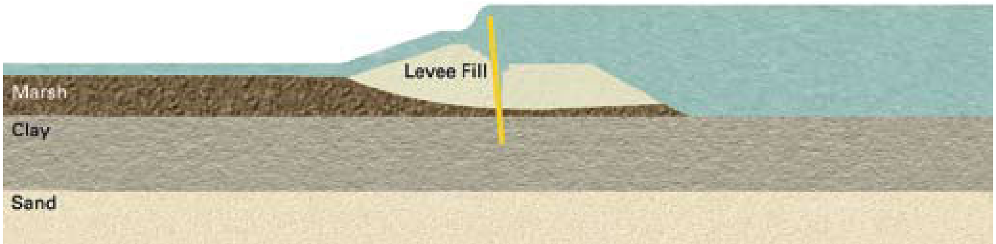
Industrial Canal East Bank South Breach and Industrial Canal West Bank Breach

Both the Industrial Canal East Bank south I-wall and Industrial Canal West Bank I-wall were overtopped by floodwaters from Hurricane Katrina. The peak water level was estimated to be 1.7 feet above the tops of the floodwalls and levees. The apparent failure mechanism is shown in *Figure 7.8* and *7.9*.

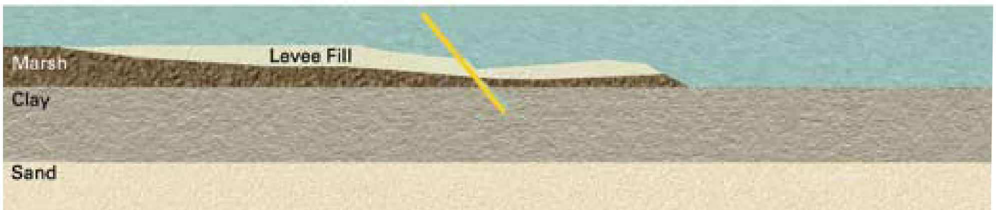
Figure 7.8 Overtopped I-wall Failure Mechanism



1: Floodwaters overtop the I-wall.



2: The water scours soil from the land-side of the I-wall and washes it away.



3: I-wall fails due to lack of foundation support.

Water flowing over the floodwalls scoured and eroded the land-side of the levee at the base of the walls. The sheetpiles that support the I-walls were undermined. In some locations, the sheetpile walls may have lost all of their foundation support, resulting in failure of the wall.

Figure 7.9 Industrial Canal East Bank South Failed I-wall

Cascading floodwaters gouged a deep trench on the land-side of the Industrial Canal. Without foundation support from the soil, the sheetpile wall (upper left) was tossed aside. (This photo was taken after floodwaters had been removed.)

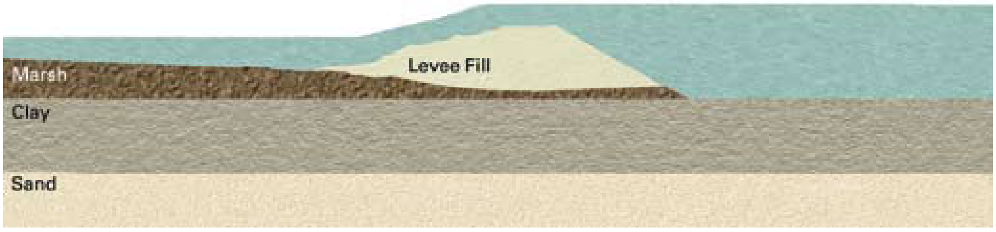
Industrial Canal West Bank South and All Other Levee Breaches

Earthen levees without I-walls all around New Orleans — including the levee at the Industrial Canal West Bank South breach — were overtopped by Hurricane Katrina's storm surge. Out of the 50 total estimated levee breaches system-wide, the majority can be attributed to overtopping and erosion. The failure mechanism from overtopping is shown in *Figure 7.10*.

Levees constructed with properly compacted clay with a good grass cover appeared to have withstood the storm the best, as shown in *Figure 7.11*. Levees with higher silt and sand content in the embankment material —or levees built with hydraulic fill (in which the levee material was mixed with water to create a slurry, then pumped or flowed into place)—sustained the worst erosion damage, and in some cases were completely washed away, as shown in *Figure 7.12*.

Figure 7.10 Overtopped Levee Erosion Failure Mechanism

1: Floodwaters overtop the levee.



2: The water scours soil from the crest and land-side of the levee and washes it away.

3: Some levees constructed of sand and silt washed away completely.

Water overtopping the levees caused serious scour and erosion. Some levees were completely washed away.

Figure 7.11 Levee Under the Paris Road Bridge in New Orleans East

Even though this earthen levee was overtopped (as was shown in Figure 5.1), it sustained relatively minor damage. (This photo was taken after floodwaters had receded.)

Figure 7.12 Obliterated Levee along the Mississippi River-Gulf Outlet

Many levees that were constructed with hydraulic fill severely eroded or washed away entirely. (This photo was taken after floodwaters had receded.)

Pumping System: Useless During Hurricane Katrina

The pumping stations throughout the New Orleans area could have been — but were not — an integral part of the hurricane protection system. Most hurricanes and tropical storms bring heavy rainfall, but the pump stations were designed only to remove stormwater runoff and routine seepage water from the interior drainage system and pump it into Lake Pontchartrain or other nearby bodies of water.

During Hurricane Katrina, more than 12 inches of rain fell on parts of New Orleans. During and after Hurricane Katrina, a few pump stations operated, but their output, approximately 18,000 cubic feet per second (about 16 percent of total pumping capacity for the region), played no significant role in lowering floodwaters because the pump stations were not located in the areas of worst flooding.

Pumping stations could not be operated for many reasons. Nearly all pump station operators in Jefferson and St. Bernard Parishes were evacuated when Hurricane Katrina threatened the area because the stations were not designed to withstand hurricane forces. Without operators, the pump stations lay idle. The storm knocked out electrical power early on, and many of the pump station engines cannot run without electricity. Pump stations themselves were flooded by water from levee overtopping and floodwall breaching, causing widespread equipment damage and failure. The buildings housing many of the older pump stations could not withstand the wind and water forces from the hurricane and sustained significant damage.

Even if the pumping system had survived the hurricane, it simply would not have been able to pump the huge amount of water that flooded into New Orleans because of overtopping and breaches. Ironically, the discharge from the stations was hard-piped into the same canals and waterways that had experienced significant breaches. Even if the pumps had continued to operate, they would have recirculated water back into the canals, only to have it flow back through the breaches.

Unintended reverse flow through some pumps in Jefferson Parish even *added* to the flooding. While methods were available to prevent reverse flow, they depended on human operators and electrical power, neither of which were present at the time. In the absence of automatic backflow preventers within the pump stations, water in the canals flowed through some idle pumps back *into* the city.

CHAPTER 8

Contributing Factors

Chapter 7 outlined the direct physical causes of the New Orleans hurricane protection system failures. This chapter describes the contributing factors. With the benefit of hindsight, we now see that questionable engineering decisions and management choices, and inadequate interfaces within and between organizations, all contributed to the problem.

Hurricane Katrina simply overwhelmed the hurricane protection system. The storm's forces exceeded the hurricane protection system's ability to withstand them. No one person or decision is to blame. The engineering failures were complex, and involved numerous decisions by many people within many organizations over a long period of time.

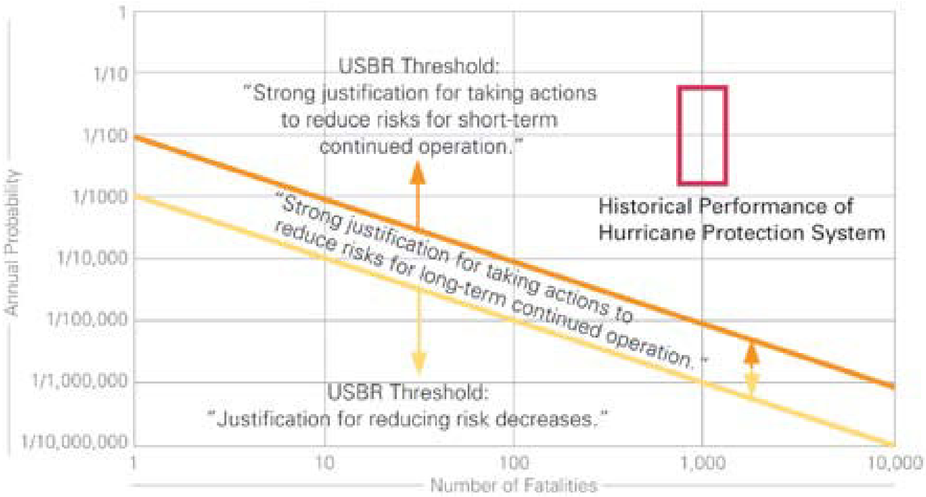
Risk to New Orleans Not Fully Appreciated

In terms of large engineered systems such as nuclear power plants or dams, the concept of "risk" captures both (a) the consequences to human health and safety if a failure were to occur, and (b) the probability of a failure. A hurricane protection system is a large engineered system like a nuclear power plant or a dam, and comprises the same complicated infrastructure and management issues. Therefore, it is helpful to look at risk through the lens of risk quantification for one of those structures.

A common approach for quantifying and comparing risks is to develop a risk evaluation chart, as shown in *Figure 8.1*, which is based on the United States Bureau of Reclamation's (USBR's) guidelines for public protection for major dams. "Thresholds" have been established—based on engineering judgment—that represent the level of risk that a society is willing to accept in order to benefit from accepting that risk. For combinations of fatalities and frequencies that plot above the upper line in *Figure 8.1*, there is "strong justification for taking actions to reduce risk for both long-term and short-term continued operations."

Relative to what people are generally willing to accept or tolerate for dams, the level of risk to the residents of New Orleans was very high. For instance, if the hurricane protection system had been treated as a major dam, it would have needed to be designed so that the likelihood of failure would occur roughly *once in 100,000 years* to *once in 1,000,000 years* of operation. The red box shown in *Figure 8.1* is an approximate graphical representation of the historical performance of the hurricane protection system: a catastrophic failure, resulting in approximately 1,000 fatalities, which occurred *once in 40 years* of operation.

Figure 8.1 Risk Evaluation Chart



The USBR guidelines for achieving public protection in dam safety are shown in yellow. The risks posed by New Orleans's hurricane protection system (shown in red) were significantly higher than people are generally willing to accept.

The risk that society is willing to tolerate from a dam is not necessarily the same as that from a hurricane- or flood-protection system, primarily because the systems are different in terms of, for instance, size, resiliency, the speed with which an emergency develops, and the options available during actual emergencies. Among other differences, a dam is typically several thousand *feet* long, whereas a levee system is several hundred to several thousand *miles* long. Dams are generally more resilient than levees because they have emergency spillways to divert excess water, thus protecting the dam structure from catastrophic failure. Reservoir water levels are monitored, and water levels tend to rise slowly, as opposed to storm surges that rise rapidly. Areas downstream of the dams have emergency action plans in place to protect downstream residents. Also, evacuation of rural areas where most major dams are located is far easier than evacuation of major cities such as New Orleans.

Unlike a major dam in the United States, the risks associated with New Orleans's hurricane protection system had never been quantified prior to Hurricane Katrina. As a result, the residents of New Orleans could not have known the actual risks with which they were living. Risk quantification could have raised the awareness of planners and policy-makers so they understood that this system might have been massively under-designed relative to the standards for other critical life-safety infrastructure.

One of the most glaring results of *not* taking risk into account in the design and construction of the hurricane protection system is this: the consequence of failure—catastrophic loss of life—did not seem to be acknowledged. If nothing else, understanding these risks could have led to a much more proactive and effective evacuation program for people to be removed from harm's way.

Critical questions need to be answered about hurricane-induced levee and floodwall failure. What is the risk? How much risk is acceptable? How can this level of risk be effectively communicated? How should the hurricane protection system be designed based on risk? Work to define the frequency of hurricanes in New Orleans is on-going. It appears that Hurricane Katrina had a probability-based recurrence interval in the range of 50 to 500 years, meaning that, in the future, a storm such as Hurricane Katrina has 1 in 50 to 1 in 500 chance of occurring in any one year. Furthermore, work to define the probability that the hurricane protection system would fail from the hurricane forces is also on-going.

Hurricane Protection System Constructed Piecemeal

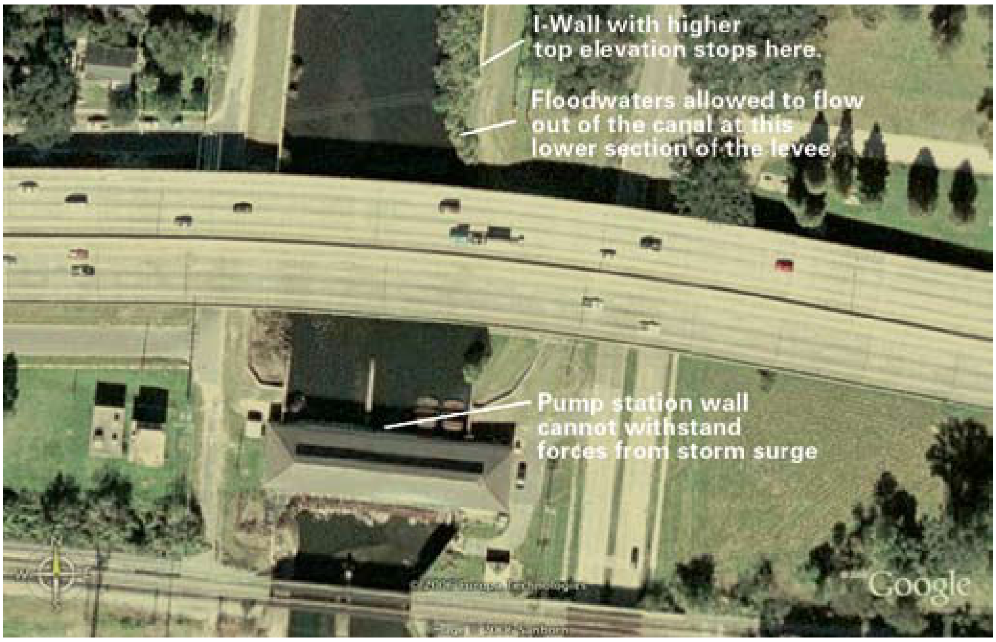
The southeast Louisiana hurricane protection system was planned, designed, and constructed over four decades without a system-wide approach or integration with land use, emergency evacuation, or recovery plans. Originally, the system grew in response to the need to protect from floods and to remove rainfall from the city. At some point, the decision was made to incorporate hurricane protection. Construction of the hurricane protection system began in earnest following Hurricane Betsy in 1965. Construction was not scheduled for completion until 2015.

The hurricane protection system, however, is a system in name only. In reality, it is a disjointed agglomeration of many individual projects that were conceived and constructed in a piecemeal fashion. Parts were then joined together in "make-do" arrangements.

For example, the pump stations at the south ends of the 17th Street, Orleans *(Figure 8.2)*, and London Avenue Canals are old masonry structures that were built nearly a century ago to pump out rainfall. Although they were thought of as being part of the hurricane protection system, they were never strengthened or retrofitted. As a result, the pump station walls could not resist the hydrostatic (water pressure) loads caused by a storm surge.

In addition to the gaps at the pump stations, there are hundreds of penetrations for roadways, rail lines, and pipelines throughout the levee system. Many of these penetrations have gates that are supposed to be moved into place under flood conditions either automatically or by hand operation. It was found, however, that many of the closure systems were either missing or inoperable, and offered little resistance to floodwaters.

Figure 8.2 Pump Station No. 7 on the Orleans Canal



The buildings housing the pump stations were not strengthened to withstand high water pressures from a storm surge. At Pump Station No. 7, a deliberate gap was left between the I-wall (top) and the pump station (bottom) to allow the water to flow around, so as not to damage the pump station.

The gates for the levee penetrations are often supported by concrete and steel structures, built several feet higher than the adjacent earthen levees. Many levee breaches occurred immediately adjacent to penetration structures where the floodwaters preferentially overtopped the lower earthen sections, which are much more erodible than the adjacent structures. Segmented construction of levees sometimes resulted in abrupt discontinuities in top elevations as well. For example, there are several reaches of levee where the concrete I-wall ends abruptly. The steel sheet pile wall continues at a lower top elevation, eventually transitioning to an earthen levee, again several feet lower in elevation. As with the penetration structures described above, water flowed over the more fragile, erodible sections first because the tops were lower, resulting in failure in numerous locations *(Figure 8.3)*.

Figure 8.3 Failed I-Wall and Levee Sections

The levees and I-walls were constructed piecemeal with different top elevations and of different materials: earth, steel, and concrete. The floodwaters preferentially attacked the lower-elevation erodible earth first, causing major breaches.

Hurricane Protection System Under-designed

The USACE defines the standard project hurricane (SPH) as a hypothetical hurricane intended to represent the most severe combination of hurricane parameters that is reasonably characteristic of a specified region. The definition "reasonably characteristic" implies that the SPH is not an extreme hurricane event—particularly when compared with the probable maximum hurricane (PMH), which the National Weather Service defines as "a combination of meteorological parameters that will give the highest sustained wind speed that can probably occur at a specified coastal location."

The relationships between the meteorological parameters (central pressure index, forward speed, wind direction, and wind speed) are interrelated and complex. It appears that the USACE:

- Chose SPH meteorological parameters at the low end of the range of 101 to 111 mph listed by the USWB (now the National Weather Service) in 1959 as representative maximum wind speeds for a hurricane striking New Orleans

- Did not evaluate the hurricane protection system for the effects of a more severe storm such as the PMH,
- Did not update its SPH meteorological parameters when the National Weather Service issued revised numbers in 1979, and
- Did not improve previously designed and constructed components of the hurricane protection system to match updated design criteria.

Consistently using the SPH—when more severe hurricane parameters had been defined—led to hurricane protection systems that were not strong or high enough to withstand the forces of Hurricane Katrina. As an example, the Lake Pontchartrain and Vicinity Hurricane Protection Project was designed for a surface wind speed of 100 miles per hour (mph), even though the 1959 stated SPH values were 101 (moderate) and 111 (high) mph. The National Weather Service's 1979 PMH stated values for surface wind speed were 151 (moderate) and 160 (high) mph. Hurricane Katrina's maximum wind speed was measured at 161 mph as it traversed the Gulf of Mexico.

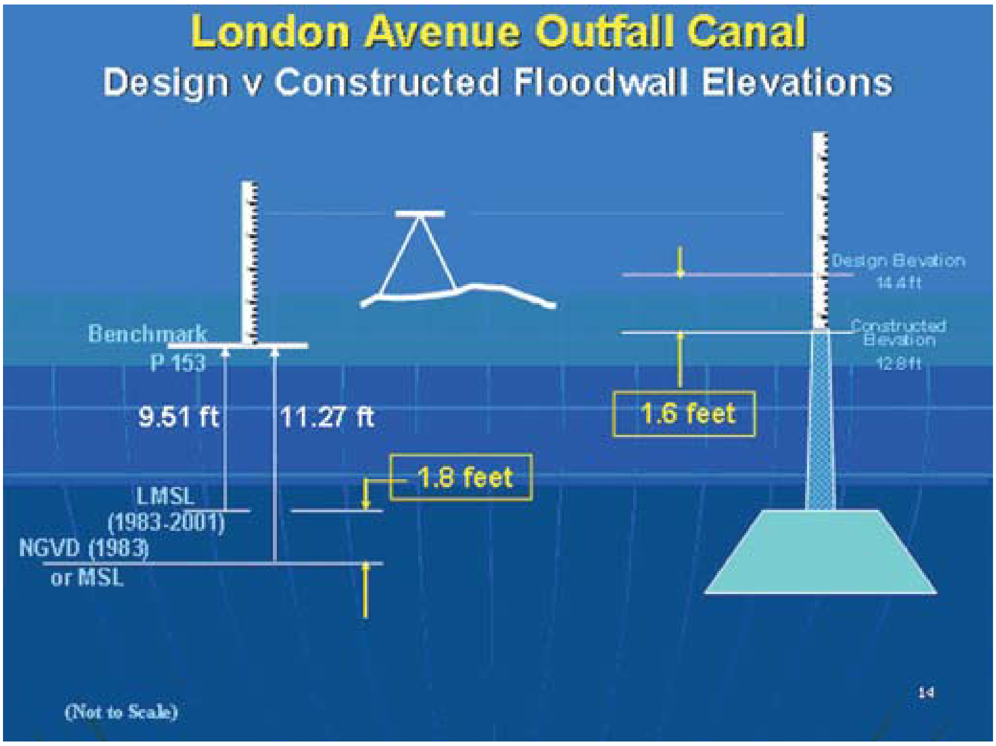
While it is clear that using a stronger wind field would have led to a higher estimated surge level, without extensive modeling there is no way to predict how much higher the levees would have been had the PMH been used instead of the SPH. Regardless of the actual numbers, had the hurricane protection system been evaluated using PMH criteria, the consequences of a more severe storm could have been incorporated. For example, levees susceptible to overtopping and erosion could have been armored. Pump stations could have been strengthened. More comprehensive evacuation programs could have been instated. The USACE's apparent non-conservative selection of the design hurricane is inconsistent with that needed to protect public safety when an extreme natural force such as Hurricane Katrina strikes.

Many Levees Not High Enough

Using the SPH and associated meteorological conditions ultimately resulted in the hurricane protection system being under-designed. However there were other factors that compounded the problem of the levees being unable to withstand the storm surge from Hurricane Katrina.

Establishing an accurate vertical datum (the basis from which all elevations are measured) is a necessary first step for the design and construction of all engineered structures. Over time, the New Orleans levees and floodwalls were designed relative to local mean sea level. However, some were constructed relative to datums that were incorrectly assumed to be equal to (or offset from) the local mean sea level data *(Figure 8.4)*.

Figure 8.4 Discrepancies between Design and Construction Elevations



Because of errors in the reference datums, segments of the hurricane protection system were constructed so that the top elevations are lower than intended by the design.

It is well understood that the entire New Orleans region is subsiding. The average rate of subsidence is about 0.2 inches per year, although rates in excess of 1 inch per year occur at some locations. Compounding the problems of using improper datums was the fact that designers and engineers did not build in an allowance for subsidence in designing the hurricane protection system. Prudent engineering would dictate that the levees and floodwalls be built higher than needed, so that over time, as the ground subsided, the levees and floodwalls would still be high enough to protect against floodwaters. This was not done.

A "freeboard" (extra height at the top of the wall to accommodate waves) allowance was included, but the freeboard was not intended to compensate for subsidence impacts. In many projects, the freeboard has been completely lost to subsidence. In older parts of the system, along the Industrial Canal (built more than 35 years ago) for instance, the impact of subsidence plus incorrect use of datum has resulted in the levees and floodwalls being up to 3 feet lower than the original design. The peak storm surges were generally only 1 to 3 feet above the tops of the levees and walls; therefore, had the tops of levees and floodwalls been at the proper elevations, fewer overtoppings and breaching failures would have occurred.

USACE officials have stated that Congressional authorization would not allow the USACE to consider water levels above "authorized levels" as estimated from the SPH. By this logic, the USACE did not specify the tops of the levees to be above authorized levels to account for possible subsidence. Similarly, the USACE did not call for armoring to protect from erosion caused by overtopping.

The result of these ill-considered decisions—coupled with the fact that the area is experiencing ongoing subsidence—is that the tops of some levees and floodwalls are as much as several feet lower than originally intended. Floodwaters from Hurricane Katrina more easily overtopped these levees. If it were not for the fact that the levees breached and I-walls toppled due to geotechnical failures (as described in Chapter 7), the overtopping caused by walls that were too low would have been the major source of flooding in New Orleans.

No One Entity Is In Charge of Hurricane Protection

In addition to discontinuities in the physical hurricane protection system caused by its piecemeal construction and incorrect elevations, there were discontinuities in organizational responsibility for the hurricane protection system as well. The management of the hurricane protection system is chaotic and dysfunctional.

As shown in *Table 8.1*, various federal, state, and local agencies are responsible for the construction, operation, and maintenance of segments of the hurricane protection system. No single agency or organization is empowered to provide the much-needed system-wide oversight or focus on the critical life-safety issues. No formal coalition of agencies is directed to provide strategic direction, definition of roles and responsibilities, and coordination of critical construction, maintenance, and operations. Indeed, it appears that no agency or group of agencies ever defined clear, mutually agreed-upon expectations of what the hurricane protection system was really intended to achieve.

Table 8.1 Agencies and Organizations Responsible for Portions of New Orleans's Hurricane Protection System

AGENCY	ROLE AND RESPONSIBILITY
UNITED STATES CONGRESS	Authorization and funding.
USACE HEADQUARTERS	USACE guidance and oversight.
USACE ENGINEER RESEARCH AND DEVELOPMENT CENTER	Research to support new design approaches.
USACE NEW ORLEANS DISTRICT	Design and construction oversight as the "Engineer" for each of the five independent levee districts in the New Orleans metropolitan area.

AGENCY	ROLE AND RESPONSIBILITY
EAST JEFFERSON LEVEE DISTRICT	Maintenance and operation of the flood protection levee system around the east bank portion of Jefferson Parish to protect the citizens of East Jefferson from Lake Pontchartrain and Mississippi River flooding.
LAKE BORGNE BASIN LEVEE DISTRICT	Maintenance and operation of 13 miles of the Mississippi River Levee, 26 miles of back protection levee, 23 miles of the Lake Pontchartrain and Vicinity Hurricane Protection Levee, the Bayou Dupre Control Structure, 12 flood gates, the Violet Freshwater Siphon, 55 miles of drainage canals, and eight major drainage pumping stations.
ORLEANS LEVEE DISTRICT	Maintenance and operation of the hurricane and flood protection improvements for the City of New Orleans on the southern shores of Lake Pontchartrain and along the Mississippi River, including inspection and maintenance of 129 miles of levees and floodwalls, 189 floodgates, 97 flood valves, and two flood control structures.
PONTCHARTRAIN LEVEE DISTRICT	Maintenance and operation of the hurricane and flood protection improvements for St. Charles Parish, including the southern shores of Lake Pontchartrain, the Bonnet Carré Spillway, and along the Mississippi River, including inspection and maintenance of associated miles of levees and floodwalls.
WEST JEFFERSON LEVEE DISTRICT	Maintenance and operation of hurricane and flood protection improvements for the west bank of Jefferson Parish, including the levee system east and west of the Harvey Canal, along each side of the Harvey Canal, and along the Mississippi River, including inspection and maintenance of more than 50 miles of levees and floodwalls and associated floodgates.
DRAINAGE PUMP STATIONS DEPARTMENT OF JEFFERSON PARISH	Administration, direction, coordination, and implementation of major drainage and flood control programs and direct construction, operation, and maintenance of 340 miles of canal waterways, drainage ditches, cross drains, culverts, and internal levee systems; 1,465 miles of street subsurface drainage systems; and operation and maintenance of 52 drainage pump stations.

AGENCY	ROLE AND RESPONSIBILITY
SEWERAGE AND WATER BOARD OF NEW ORLEANS	Administration, direction, coordination, and implementation of major drainage and flood control programs and direct operation, construction, and maintenance of 90 miles of open canal waterways, drainage ditches, cross drains, and culverts; 90 miles of street subsurface drainage systems larger than 36 inches in diameter; and operation and maintenance of 22 drainage pump stations. The Sewerage and Water Board also operates and maintains all drainage pump stations in Orleans Parish, east and west banks, and is responsible for waterways' trash pick-up and grass cutting.

Examples of the consequences of the lack of inter-agency coordination are plentiful. For instance, the agencies responsible for floodgates at France Road in Orleans Parish (the crossing for the New Orleans Public Belt Railroad) include the Port of New Orleans, the Orleans Levee District, the New Orleans Public Belt Railroad, and the New Orleans District of the USACE. The floodgates were out of service and left open during Hurricane Katrina because of repairs, allowing water to flood through them unimpeded.

Separate organizations control design and maintenance. By necessity, the USACE made assumptions that the levees would be maintained properly over time. In fact, the levees were not always maintained properly. For instance, trees were allowed to grow on the levees, and swimming pools and hot tubs had encroached on levee rights-of-way. Although there was likely some informal or semi-formal communication between agencies, the group of agencies did not work together to ensure that the New Orleans area was protected from hurricane damage.

It is only natural that during an emergency situation such as Hurricane Katrina, without pre-planning and coordination, major gaps in emergency response will occur. Nowhere is this more evident than in Jefferson Parish, where the parish president—apparently out of concern for the safety and welfare of the pump station operators—ordered the operators to evacuate prior to the storm. There was evidently no plan or infrastructure in place to enable safe, continuous operation of pumping stations during a major hurricane. *If the five pump stations on the east bank of Jefferson Parish had remained operable, significantly less flooding would have occurred in Jefferson Parish, east bank.*

The USACE acts as "Engineer" on behalf of the levee districts. However, the USACE's position is that it cannot do anything that a local sponsor (in this case, a levee district) does not approve. Several key USACE attempts to implement system-wide solutions were often met by fierce local opposition, and were not approved. For instance, following Hurricane Betsy, the USACE proposed providing hurricane protection along the Lake Pontchartrain lakefront instead of along the canals. This proposal was strongly opposed by the Sewerage and Water Board of New Orleans and by the Orleans Levee District, and ultimately dropped by the USACE.

The problems that led to poor decision-making—the root cause of the catastrophe in New Orleans—thus lie within and amongst the cultures of key organizations. Protecting against life-threatening risk was put on the back burner of public priority. Perhaps no one truly realized how catastrophic levee failures would be. Perhaps no one was willing to pay the price necessary to build a reasonably safe levee system. Perhaps the levee boards became distracted by development projects, airports, parks, casinos, or other matters that were given priority above the primary task of caring for the levees. Perhaps the political will needed to implement a rationally based hurricane protection system was simply too great to be achieved. However, to achieve a different outcome in the future, these cultures must change, focusing more on protecting peoples' lives and less on "business as usual."

External Peer Review Lacking

During the design of major engineering projects, senior experts in the appropriate fields of engineering are often called in to conduct external peer review. These peer reviewers typically provide input on the overall direction of the project, the validity of assumptions, the correctness of analytical methods, and the design approach. Design peer reviews are conducted to provide a completely independent assessment of a public works project.

External peer reviews were conducted on very few, if any, of New Orleans's hurricane protection system projects. In fact, the USACE's internal directives fall short of ASCE's recommended policies to protect the public health, safety, and welfare against the catastrophic failure of water resources projects.

The USACE's peer reviews are discretionary, are not triggered by sound engineering principles, do not have a mechanism to gauge their fidelity, and contain vague processes for selecting reviewers. As a result, questionable engineering decisions were made for the New Orleans hurricane protection system. Margins of safety were too low in designing the levees. Improper datums were used in construction. The standard project hurricane was not updated.

The engineering decision-making process became "self-referential," meaning that designers were forced to look to their own organizations to help guide decisions, not to the greater engineering community. Individuals within a self-referential organization can lose step with technological advances and alternative solutions. The organizational culture (for instance, "it's how we've always done it") influenced behavior over the many years that the hurricane protection system was under design and construction. Proper and effective external peer review could have prevented these errors of judgment from occurring.

Funding Process Flawed

As a federal agency, the USACE and its projects are funded by the federal government, with a share of the costs borne by the local sponsor. Every year, the USACE requests funding. Through the federal budget-setting process, the Executive Branch (via the Office of Management and Budget) and the United States Congress authorize a project and allocate funding, but not necessarily at the same dollar amounts as requested or required.

Because of the Congressional budgeting process, the stream of funding for the New Orleans hurricane protection system was irregular, at best. If a project was not sufficiently funded, the USACE was often required to delay implementation or to scale back the project.

This "push-pull" mechanism for the funding of critical life-safety structures such as the New Orleans hurricane protection system is essentially flawed. The process creates a "disconnect" between those responsible for design and construction decisions and those responsible for managing the purse-strings. The pressure for tradeoffs and low-cost solutions likely compromised quality, safety, and reliability.

The project-by-project approach—in which projects are built over time based on the availability of funding—resulted in the hurricane protection system being constructed piecemeal, with an overall lack of attention to "system" issues. In effect, it appears that the project-by-project approach was associated with Congressional limitations. The USACE was forced into a "reductionist's" way of thinking: reduce the problem into one that can be solved within the given authority and budget. Focusing only on the primary problem to be solved inevitably makes the issues of risk, redundancy, and resilience a lower priority.

Decisions were made, for example, not to armor the land-side of the floodwalls and levees in the high-risk areas; this armoring, if installed, could conceivably have limited the flood damage from an infrequent storm event such as Hurricane Katrina. It has been stated by some that the USACE may have considered this option to be outside of their Congressional authority, because to armor the levees would apparently concede that the USACE was designing for storm surges above the "authorized level."

The design and construction of critical life-safety systems is beyond the expertise of the Executive Branch or United States Congress. However, the Congress exercised tight control over spending and even over design criteria. The USACE accepted these controls without fully addressing the associated issues, risks, and tradeoffs. For whatever reason, the USACE and its local sponsors did not argue vigorously enough for adequate funding to provide a high level of assurance for the public safety of New Orleanians.

CHAPTER 9

What Must We Do Next?

Serious deficiencies in the southeast Louisiana hurricane protection system must be corrected if the New Orleans area is to avoid a similar catastrophe when the next major hurricane strikes. There are flaws in the way the hurricane protection system was conceived, budgeted, funded, designed, constructed, operated, and managed.

There is no quick fix for problems of this complexity. Overcoming the deficiencies in the New Orleans hurricane protection system—and instituting real change in its engineering, management, and governance—will require leadership, courage, conviction, and funding.

The lessons learned from Hurricane Katrina also have profound implications for other American communities and a sobering message for people nationwide: ***we must place the protection of public safety, health, and welfare at the forefront of our nation's priorities.*** To do anything less could lead to a far greater tragedy than the one we have witnessed in New Orleans.

What follows are ten critical actions the ASCE Hurricane Katrina External Review Panel believes necessary. Each action falls under one of four required shifts in thought and approach: understand risk and embrace safety; re-evaluate and fix the hurricane protection system; revamp the management of the hurricane protection system; and demand engineering quality. We consider each action essential, and we strongly recommend that each be implemented.

Understand Risk and Embrace Safety

When Hurricane Katrina came ashore, the hurricane protection system failed, with tragic consequences. The catastrophe that befell New Orleans was born, in part, out of failure to recognize the fragility of the levee system in the face of storms of Hurricane Katrina's magnitude. Few appreciated how devastating the consequences of failure could be. There was far too little priority or urgency given to the hurricane protection system by political leaders at all levels of government, by designers and operators, and by the people who lived in its shadow—evidenced by the fact that the system took decades to build and remains incomplete yet today.

The people of New Orleans—and all those who live in hurricane- and flood-prone communities around the country—must understand and acknowledge the risks under which they live. From this knowledge comes insight into what risks are acceptable for their communities and for the nation.

CALL-TO-ACTION NUMBER 1:

Keep safety at the forefront of public priorities.

No single authority has ever been charged with responsibility for defining in clear, specific, and unambiguous terms what was to be expected from the hurricane protection system in the New Orleans region in terms of protection from flooding and loss of life. As the hurricane protection system for New Orleans was being designed and debated amongst the USACE and state and local stakeholders, compromises were made based on cost, land use, environmental issues, and other conflicting priorities. Protection of the public's safety was not always the outcome of these compromises.

It is human nature—both at a personal and institutional level—to lose focus of long-term needs in the light of short-term demands. The infrequency of major hurricanes tends to lull society into neglect and inaction, but long-term safety must take precedence. Without a significant elevation of safety as a priority, the hurricane and flood protection systems in New Orleans, and across the nation, have the potential to return to a low priority. *All responsible agencies in New Orleans and throughout the nation should re-evaluate their policies and practices to ensure that protection of public safety, health, and welfare is the top priority for the infrequent but potentially devastating impacts from hurricanes and flooding.*

Consistent inspection, maintenance, and repair of the hurricane protection system are essential. We cannot afford to permit our hurricane and flood protection systems to deteriorate. *The United States Congress should establish and fund a program for nationwide levee safety and rehabilitation, much as we do for major dams.* The levee safety program will help ensure that levee structures and components—in New Orleans and throughout the country—receive the level of attention needed for critical life-safety systems.

CALL-TO-ACTION NUMBER 2:

Quantify the risks.

Assessment of risk is a key engineering function. Engineers must assess and communicate clearly to decision-makers and the public how risk-cost-benefit tradeoffs will impact performance and safety. They must take an active role in formulating public policy and in decision-making at all levels of government.

The IPET has undertaken the critically important effort of quantifying the risks associated with the New Orleans hurricane protection system. Using sophisticated risk models, the IPET is analyzing the potential consequences from a range of storm scenarios. Among the variables considered are hurricane intensity, hurricane location and direction of approach, height and strength of levees, ability of pump stations to remove water, whether levee penetrations are closed, and land elevation and its propensity for flooding.

The ASCE Hurricane Katrina External Review Panel encourages the IPET's work toward quantifying risk for each geographic region of the New Orleans area. Completing this work must remain a very high priority. Only then can fully informed decisions be made regarding the future of the region.

The level of risk also changes with time, depending on changes in the natural and man-made environment. Therefore, the risk analyses need to be updated as new information becomes available.

The USACE should complete the work necessary to quantify and effectively communicate the risk as soon as possible, and, because risk assessment and communication is not static, should periodically update the assessment of risk. This risk assessment approach should be extended to all areas of the nation that are vulnerable to major losses from hurricanes and flooding.

CALL-TO-ACTION NUMBER 3:

Communicate the risks to the public and decide how much risk is acceptable.

The future of New Orleans and the State of Louisiana depends on peoples' confidence in the hurricane protection system. Local, state, and federal leaders—in concert with the engineering community—need to embrace a common risk-based decision support tool for planning and decision-making. These leaders need to initiate and maintain an honest and open dialogue with all major stakeholders about the risks of living in a hurricane-prone region.

The people of New Orleans—and those who live in flood- and hurricane-prone communities around the country—must have a voice in decisions about the conditions under which they live. Decisions that have the potential for profound impact are best based on knowledge, insight, and timely, structured debate.

Local, state, and federal agencies should create and maintain quality programs of public risk communication in New Orleans and other areas threatened by hurricanes and flooding. The public risk communication program should be based on state-of-the-art best practices for process and content, and address a full range of pertinent topics. The public needs to know, for instance, the probability that a major hurricane will hit a particular region and the level of protection provided by their region's hurricane protection system. People also need to know the full range of citizen-based emergency preparedness and response options and evacuation plans.

The ultimate goal of the risk communication program should be to produce an informed and engaged public. A number of examples could be used as a model for the New Orleans risk communication initiative, including the work of the State of California's Office of Emergency Services as part of the Parkfield Earthquake Prediction Experiment in the 1980s, and the work done by the United States Geological Survey in the San Francisco Bay area after the Loma Prieta earthquake in 1989.

Major hurricanes of the scale of Katrina are infrequent. Without an effective risk communication program, people will gradually forget about the risks. In doing so, they will unknowingly contribute to the severity of the consequences from the next hurricane that strikes.

Re-evaluate and Fix the Hurricane Protection System

The first line of defense in the hurricane protection system for New Orleans includes levees and floodwalls to hold back the high water from a storm surge, yet it failed catastrophically at more than 50 different locations during Hurricane Katrina. There was no second line of defense except for the pump stations, which were ineffective.

Not only did the hurricane protection system have many weak links—in the form of penetrations, low points, and gaps—but it lacked "redundancy." If one component failed, there was no back-up component or strategy to take its place to reduce the damage. Internal levees were not used as much as they could have been to isolate various sub-sections of the city and prevent floodwaters from spreading. The pump stations, which might have removed water from the city more quickly, were not designed to function in a major hurricane or mitigate flooding if the levees were overtopped or breached. The "system" was *not* a system.

CALL-TO-ACTION NUMBER 4:

Rethink the whole system, including land use in New Orleans.

The nation learns lessons after every major disaster: lessons in decision-making, structural integrity, disaster response, and communications. The nation is now at a unique juncture where past mistakes in the hurricane protection system for New Orleans can be learned from and rectified.

The IPET has made excellent progress on the task of identifying deficiencies in the hurricane protection system. There is still much to be done to build on IPET's work, and we strongly urge that this work be funded and pursued to its completion. Information from the IPET analyses, coupled with a clear definition of the public's expectations (as framed in Call-to-Action Number 3), will form the basis for rethinking the entire hurricane protection system.

At the outset, the design hurricane and storm surge levels need to be re-assessed and updated using a risk-based approach. The design hurricane conditions cannot be static design criteria. Risk and levels of acceptable risk evolve with time—as does the knowledge on which storm criteria are based.

The future system will incorporate existing infrastructure (such as levees and pump stations) but must include other appropriate tools and strategies as well. Prudent land-use decisions (for example, limiting development in the most flood-prone areas, or establishing minimum first-floor elevations) can put fewer people and less property at risk. More rigorous building requirements can reduce the impact of flooding on structures. A more effective hurricane warning, response, and evacuation protocol can be instituted and practiced in regular training exercises. Pre-planning can expedite recovery and reconstruction after a major hurricane.

The ASCE Hurricane Katrina External Review Panel calls on New Orleans and all hurricane- and flood-prone communities around the nation to use the lessons learned from Hurricane Katrina to develop roadmaps for safety and protection. ***Local, state, and federal leaders should review the overall strategy and systems approach, integrating hurricane protection tactics, land-use considerations, and emergency response strategies into a coherent and well-thought-out system.***

CALL-TO-ACTION NUMBER 5:

Correct the deficiencies.

Hurricane Katrina obliterated many critical hurricane protection structures and wreaked great damage on others. The disaster also brought to light many weaknesses and deficiencies in the existing system that, if not fixed, will remain vulnerable to future hurricanes. The work to be done includes making up for past design deficiencies as well as strengthening existing components of the system to make them more resilient to damage.

Hurricane Katrina offers a cautionary tale and subsequent mandate to other hurricane-prone communities as well. Now is the time to fix deficient or damaged parts of existing flood and hurricane protection systems throughout the country to provide the intended levels of protection. *Local, state, and federal leaders should continue the work necessary to correct the deficiencies in the hurricane protection systems, and bring this work to completion with urgency.* In the New Orleans region, "must-do" items include:

- **Establish mechanisms to incorporate changing information.** The dynamics of the hurricane protection system — such as levee heights and meteorological and oceanographic conditions — need to be monitored routinely, especially when processes like subsidence are known to occur. Advances in surveying technology need to be fully utilized to establish and regularly update geodetic vertical datum and water surface elevations. Levee design, construction, and maintenance must be tied to elevations that provide the true level of flood and hurricane protection intended for New Orleans.

- **Make the levees functional even if overtopped.** During Hurricane Katrina, water rushing over the levees severely damaged and compromised their integrity. Overtopping of levees due to hurricanes is inevitable. To prevent damage, the levees need to be armored by resurfacing them with protective non-erodible materials.

- **Strengthen or upgrade the floodwalls and levees.** Floodwalls and levees must be fully investigated and analyzed to ensure that they have adequate margins of safety against failure, consistent with critical life-safety structures. Such was not the case pre-Katrina, and may not always be the case now.

- **Upgrade the pumping stations.** Not only was the pumping system not fully integrated into the hurricane protection system, but many of the pump stations were not strong enough to withstand the forces of a hurricane. The pump stations need to be made survivable from flooding caused by hurricanes and un-anticipated levee breaches. If this is not done, New Orleans will remain unnecessarily vulnerable.

Revamp the Management of the Hurricane Protection System

The management of New Orleans's hurricane protection system was dysfunctional because there were too many organizations involved in managing individual pieces of the system. No one entity or person was in charge. Many agencies had partially overlapping roles, yet there was no effective coordination between agencies.

The members of the ASCE Hurricane Katrina External Review Panel believe that correcting the management deficiencies of the hurricane protection system is just as important as correcting the physical deficiencies. With effective management comes a more unified approach to hurricane protection—which is greatly needed in New Orleans.

CALL-TO-ACTION NUMBER 6:

Put someone in charge.

No complex program or system can be successful without good leadership, management, and someone in charge. The New Orleans hurricane protection system evolved over decades under the initiative and management of numerous agencies, none of which had definitive authority to adjudicate conflicting priorities. Until someone is put in charge of overall management and made accountable, organizational dysfunction will continue.

Local, state, and federal leaders should agree to assign to a single individual the responsibility for managing critical hurricane and flood protection systems such as the one in the New Orleans area. The ASCE Hurricane Katrina External Review Panel recommends that the "person-in-charge" or "authority" or commissioner be a high-level, licensed engineer (or, alternatively, a panel comprising licensed engineers). We suggest that this authority should have the wherewithal and latitude of a direct gubernatorial appointment.

This authority must be empowered and authorized by the mutual consent of all responsible agencies to become deeply engaged with all these agencies. The authority's over-arching responsibility will be to keep hurricane-related safety at the forefront of public priorities. The authority will provide leadership, strategic vision, definition of roles and responsibilities, formalized avenues of communication, prioritization of funding, and coordination of critical construction, maintenance, and operations.

Changes to the New Orleans area levee board structure approved by voters in 2006 will help streamline communications and establish a stronger technical basis for managing the levees. The ASCE Hurricane Katrina External Review Panel endorses this effort, which comprises a good first step until the appointment of the authority goes into effect.

CALL-TO-ACTION NUMBER 7:

Improve inter-agency coordination.

There has been an historic lack of coordination between agencies at all levels: local, state, and federal. The only practical way to overcome this organizational confusion is to implement strong, sustainable mechanisms for communication, cooperation, and coordination. We envision that the commissioner (as identified in Call-to-Action Number 6) will be able to provide overall direction and make sure that all parties are working together.

All agencies involved in the hurricane protection system should implement far better and more effective mechanisms for coordination and cooperation. The agencies responsible for funding must coordinate with and advocate for those responsible for implementation. Those responsible for the hurricane protection system must establish iron-clad protocols with those who are responsible for emergency response. Those responsible for maintenance of the hurricane protection system must collaborate with system designers and constructors to upgrade their inspection, repair, and operations to ensure that the system is hurricane-ready and flood-ready. Those responsible for operating the floodgates must take direction from those responsible for emergency preparedness, and close the levee penetrations when a hurricane threatens.

Demand Engineering Quality

The ASCE Hurricane Katrina External Review Panel believes that the failures in New Orleans's hurricane protection system constitute one of the worst catastrophes ever to befall this country. The flaws uncovered as a result of Hurricane Katrina must serve as a sobering reminder to engineers everywhere that their work has life-or-death implications. Whatever the constraints—whether related to cost, schedule, political resistance, or inertia—engineers must continue to uphold the highest standards of their profession, knowing that peoples' lives are at stake.

CALL-TO-ACTION NUMBER 8:

Upgrade engineering design procedures.

The USACE and its consultants—as well as ASCE and its members—must upgrade engineering design procedures, placing greater emphasis on safety, taking into account lessons learned from Hurricane Katrina, and incorporating the latest research findings and best engineering practices. *The engineering community should review and update engineering design procedures for hurricane and flood protection systems to ensure that these updated procedures take all reasonable steps to protect the public safety, health, and welfare.*

The USACE—and engineering research organizations around the country—should increase research into the design and construction of better hurricane protection systems. The latest technological advances should be used to improve the models, designs, retrofits, and maintenance of hurricane protection systems in New Orleans and other parts of the country.

CALL-TO-ACTION NUMBER 9

Bring in independent experts.

ASCE has a long-standing policy that recommends independent external peer review for all public works projects where performance is critical to public safety, health, and welfare; where reliability of performance under emergency conditions is critical; that use innovative materials or techniques; that lack redundancy in design; or that have unique construction sequencing or a short/overlapping design-construction schedule.

The ASCE Hurricane Katrina External Review Panel believes that many of the major deficiencies in New Orleans's hurricane protection system could have been avoided if the engineering plans and designs had undergone high-level, independent engineering review by external experts.

Agencies responsible for design of hurricane and flood protection systems and other critical life-safety structures should engage independent experts in high-level review of every project.

CALL-TO-ACTION NUMBER 10:

Place safety first.

Although the conditions leading up to the New Orleans catastrophe are unique, the fundamental constraints placed on engineers for any project are not. Every project has funding and/or schedule limitations. Every project must integrate into the natural and man-made environment. Every major project has political ramifications.

In the face of pressure to save money or to make up time, engineers must remain strong and hold true to the requirements of the profession's canon of ethics, never compromising the safety of the public. Organizations must be structured to enable, not to inhibit, this focus on safety. Engineers must continually evaluate the appropriateness of design criteria. They must always consider how the performance of individual components affects the overall performance of a system.

The first Fundamental Canon of ASCE's Code of Ethics states that "Engineers shall hold paramount the safety, health, and welfare of the public…." This canon *must* be the guiding principle for rebuilding the hurricane protection system in New Orleans. And it must be applied with equal rigor to every aspect of an engineer's work—in New Orleans, in America, and throughout the world. ***ASCE, working in partnership with the USACE and other engineering organizations, should reinforce the need to place the safety, health, and welfare of the public first, and should communicate that public safety must always be the highest priority.***

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