1. Introduction

On September 26, 2005, the Mitigation Division of the Department of Homeland Security's (DHS's) Federal Emergency Management Agency (FEMA) deployed a Mitigation Assessment Team (MAT) to the States of Alabama, Louisiana, and Mississippi to assess damage caused by Hurricane Katrina. This report presents the MAT's observations, conclusions, and recommendations in response to those field investigations.

This chapter provides an introduction, a discussion of the event, historical information, and background on the MAT process. Floodplain management regulations and the building codes and standards that affect construction in Alabama, Louisiana, and Mississippi are discussed in Chapter 2. Chapter 3 provides a basic assessment and characterization of the observed flood and wind effects. Structural systems performance in residential and commercial buildings is detailed in Chapter 4. Chapter 5 presents an assessment of building envelope performance and Chapter 6 discusses damage to historic buildings. Chapter 7 presents damage to, and functional loss of, critical and essential facilities, and Chapter 8 discusses the short-term and long-duration flood impacts in the New Orleans area. Chapter 9 documents observed hazard mitigation successes and best practices. Chapters 10 and 11 present the conclusions and recommendations, respectively, intended to help guide the reconstruction for hurricane-resistant communities in Alabama, Louisiana, and Mississippi, and other hurricane-prone regions impacted by future hurricanes. In addition, the following appendices are presented herein:

- Appendix A contains the references for the report.
- Appendix B is a list of acknowledgments.
- Appendix C defines the acronyms and abbreviations used in the report.
- Appendix D contains a glossary of terms used in the report.
- Appendix E contains the Hurricane Katrina Recovery Advisories.
    - Reconstruction Guidance Using Hurricane Katrina Surge Inundation and Advisory Base Flood Elevations
    - Initial Restoration for Flooded Buildings
    - Design and Construction in Coastal A Zones
    - The ABC's of Returning to Flooded Buildings
    - Attachment of Brick Veneer in High-Wind Regions
    - Attachment of Rooftop Equipment in High-Wind Regions
    - Rooftop Attachment of Lightning Protection Systems in High-Wind Regions
    - Designing for Flood Levels Above the BFE
- Appendix F presents high water marks reported for the storm.
- Appendix G contains a copy of FEMA Procedure Memorandum 34 - Interim Guidance for Studies Including Levees, dated August 22, 2005.
- Appendix H contains a description of Continuity of Operations (COOP) Planning and Environmental Issues for Infrastructure.
- Appendix I presents a description of sampling and analytical methods of flood-damaged buildings.
- Appendix J describes pre- and post-disaster mitigation of historic buildings.
- Appendix K contains a list of FEMA Regional Offices.

1.1 Hurricane Katrina – The Event

Hurricane Katrina was one of the strongest and most destructive storms to impact the coast of the United States during the past 100 years. The hurricane made its first landfall on August 25, 2005, on the southeast coast of Florida as a Category 1 hurricane; the storm then crossed south Florida and moved into the Gulf, where it gained strength to a Category 5 hurricane, before weakening and making its second landfall in southeast Louisiana near Buras as a strong Category 3 hurricane. After coming ashore in Louisiana, Katrina continued to move northward, pushing storm surge into coastal areas of Alabama, Louisiana, and Mississippi, and, after crossing over Breton Sound, Katrina finally made a third landfall as a Category 3 storm near Pearlington, Mississippi, along the Louisiana/Mississippi border. Figure 1-1 shows the path of Hurricane Katrina as it moved over Louisiana and Mississippi. Katrina caused widespread devastation along the Gulf Coast, with southeast Louisiana and the coasts of Alabama and Mississippi bearing the brunt of the catastrophic damage.

THE SIGNIFICANCE OF HURRICANE KATRINA

Hurricane Katrina was the most severe hurricane to strike the Louisiana/Mississippi Gulf Coast since Hurricane Camille in 1969 and the most significant hurricane to strike the New Orleans area since Hurricane Betsy in 1965. The significance of Katrina and its effects are summarized below:

- Katrina significantly exceeded the Base Flood Elevations (BFEs) by as much as 15 feet along parts of the Louisiana and Mississippi Gulf Coast. Flooding extended well beyond the inland limits of the Special Flood Hazard Area (SFHA), and the highest storm surge in U.S. history was recorded on the Mississippi coast.
- The American Red Cross estimated that Katrina destroyed over 300,000 single-family homes throughout Louisiana and Mississippi.
- Coastal flood impacts covered a wide area, with severe flood damage extending along coastal Alabama and totally destroying over 100 houses on Dauphin Island.
- Levee failures led to severe flood damage throughout the City of New Orleans and surrounding areas of Plaquemines and St. Bernard Parishes. Hundreds of thousands of people were displaced from the damage caused by the flooding.
- Katrina's wind speeds were estimated to be at the design level in only a few areas and were less than the current code-specified speeds (per the 2000/2003 International Building Code [IBC] and the International Residential Code [IRC]) in most areas. These codes use a design wind speed map developed for the 1998 and 2002 editions of the American Society of Civil Engineers (ASCE) 7.
- Wind damage to both commercial and residential buildings was widespread through the southern portions of Louisiana and Mississippi.
- In general, buildings functioning as critical and essential facilities did not perform well, and experienced significant wind and flood damage (with damages similar in nature to their commercial counterparts). Operation of many critical and essential facilities was hampered or shut down as a result of storm-induced damage or isolation due to coastal flooding.

Figure 1-1. Hurricane Katrina's path through Louisiana and Mississippi

(BASED ON HURRICANE STORM TRACK DATA FROM THE NATIONAL HURRICANE CENTER)

Katrina's storm surge caused failure of the levee system that protects New Orleans from Lake Pontchartrain and, subsequently, an estimated 80 percent of the city was flooded. This and other major damage to the coastal regions of Alabama, Louisiana, and Mississippi made Katrina the most destructive natural disaster in the history of the United States.

The estimated death toll is over 1,700, with approximately 1,500 of those deaths occurring in Louisiana and approximately 230 in Mississippi.[1] Other deaths attributed both directly and indirectly to Katrina were reported in Florida, Alabama, Georgia, Kentucky, and Ohio. Hurricane Katrina ranks as the third deadliest hurricane in the United States, surpassed only by the Texas Hurricane at Galveston in 1900, where 6,000 lives were lost, and the Florida Hurricane in 1928 where 2,500 lives were lost at Lake Okeechobee.

1 The original toll of 1,067 issued by the Louisiana Department of Health and Hospitals included at least 14 who died prior to Katrina, and some people who were elderly or terminally ill and died outside of New Orleans after evacuation, possibly due to stress, as reported by The Times-Picayune on November 2, 2005 <http://www.nola.com/search/index.ssf?/base/library-89/113091548771970.xml?nola>.

1.1.1 Hurricane Katrina Economic Loss Summary

Estimated total economic losses from Hurricane Katrina are in excess of $125 billion and insured losses are $40.6 billion,[2] which tops Hurricane Andrew's $26.5 billion loss, Hurricane Charley's $15 billion loss, Hurricane Ivan's $14.2 billion loss, Hurricane Frances' $8.9 billion loss, and Hurricane Hugo's $7 billion loss,[3] making Katrina the most expensive natural disaster in U.S. history. As of April 2006, the number of flood insurance claims exceeded 210,000 and totaled $17 billion, covering Alabama, Florida, Louisiana, and Mississippi, with over 175,000 of those claims coming from Louisiana. Preliminary estimates indicate that Hurricane Katrina resulted in the following:

- $5.5 billion in damage to infrastructure, including roads and bridges
- 300,000 to 350,000 vehicles destroyed and approximately 2,400 ships and vessels wrecked
- 450,000 displaced people
- 800,000 Louisiana citizens requesting assistance from various Federal and State relief programs and agencies

The Small Business Administration reported that requests for $229 million in home and small business loans have been submitted. The State of Mississippi and FEMA counted the following destroyed or damaged buildings: primary homes – 157,914; multi-unit homes – 20,883; rental units – 42,187; and public housing units – 27,001.

Table 1-1 summarizes the housing damage from Hurricane Katrina as determined by the American Red Cross.

Officials estimate that, in Mobile County, 80 percent of the homes in Bayou La Batre were uninhabitable as the result of flooding; on Dauphin Island, a third of the homes on the western side of the island were destroyed and another third were significantly damaged. The worst damages in Baldwin County were along Mobile Bay south of Fairhope and along the Ft. Morgan Peninsula.

Early in 2006, the Alabama Emergency Management Agency estimated that more than 37,000 individuals sought service from Disaster Recovery Centers, and nearly 7,000 individuals were still living in interim housing facilities.

2 Insurance Information Institute

3 Estimates, not adjusted for inflation, as reported by NOAA/AOML/Hurricane Research Division, Miami, FL <http://www.nhc.noaa.gov/pastcost.shtml>.

Table 1-1. Katrina Housing Damage Summary

Location	Dwelling Type	Destroyed	Major	Minor
Alabama	Single-Family	363	966	345
	Manufactured	-	1	26
	Apartment	-	-	-
	Subtotal	**363**	**967**	**371**
Louisiana	Single-Family	241,524	38,350	40,066
	Manufactured	1,552	1,146	1,855
	Apartment	40,762	33,676	27,842
	Subtotal	**283,838**	**73,172**	**69,763**
Mississippi	Single-Family	68,466	62,981	95,468
	Manufactured	263	2,241	4,811
	Apartment*	-	-	-
	Subtotal	**68,729**	**65,237**	**100,318**
Hurricane Katrina TOTALS	Single-Family	310,353	102,297	135,879
	Manufactured	1,815	3,388	6,692
	Apartment	40,762	33,691	27,881
	Total	**352,930**	**139,376**	**170,452**

(SOURCES: AMERICAN RED CROSS, NATIONAL ASSOCIATION OF HOME BUILDERS, 10/05 <http://www.redcross.org>, <http://www.nahb.org>.)

* Data incomplete.

1.1.1.1 Hurricane Categories

Hurricanes are categorized according to their relative strength as measured by wind speed and minimum central pressure. The Saffir-Simpson Scale, presented as Table 1-2, is the standard for categorizing hurricanes and consists of five separate categories. The National Hurricane Center (NHC) reserves the term “major hurricane” for hurricanes that reach maximum 1-minute sustained surface winds of at least 111 miles per hour (mph) over open water. Therefore, Category 3, 4, and 5 hurricanes are all considered major hurricanes.

Table 1-2. Saffir-Simpson Hurricane Scale Wind Speeds and Pressures

Strength	Sustained Wind Speed (mph)*	Gust Wind Speed (mph)**	Pressure (millibars)
Category 1	74-95	89-116	>980
Category 2	96-110	117-134	965-979
Category 3	111-130	135-159	945-964
Category 4	131-155	160-189	920-944
Category 5	>155	>189	<920

* 1-minute sustained over open water
** 3-second gust over open water

1.1.1.2 Timeline and History of the Hurricane[4]

Hurricane Katrina began as Tropical Depression Twelve, which formed over the Bahamas on August 23, 2005. On August 24, the storm strengthened and became known as Tropical Storm Katrina, the 11th named storm of the 2005 hurricane season. The storm then traveled northwest from the Bahamas.

A few hours before making landfall in Florida on August 25, Tropical Storm Katrina was upgraded to Hurricane Katrina (Category 1, 74 mph winds). Katrina made landfall around 6:30 p.m. Eastern Daylight Time (EDT) with approximately 80 mph, 1-minute sustained winds on the Dade-Broward County line between Hallandale Beach and North Miami Beach, Florida. Port Everglades reported wind gusts to 92 mph. During its initial landfall in southern Florida, Katrina generated over 5 inches of rainfall across a large area of southeastern Florida. An analysis by the National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Center shows that parts of the region received heavy rainfall, over 15 inches in some locations, which caused localized flooding. Katrina tracked southwest through the Everglades National Park and exited the state near the southern tip of Florida, as shown in Figure 1-2.

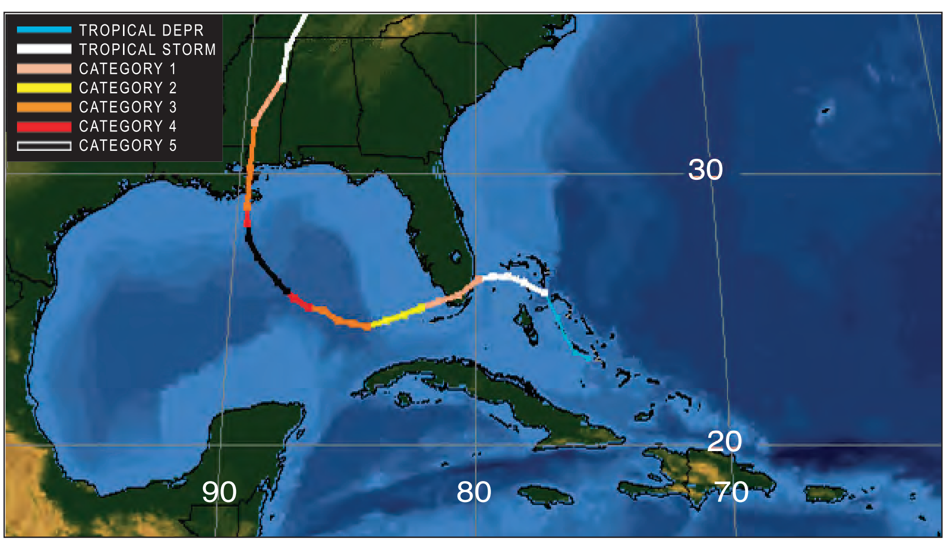


Figure 1-2. Hurricane Katrina's path

(BASED ON http://cimss.ssec.wisc.edu/tropic/archive/2005/storms/katrina/katrina.html)

[4] All wind speeds provided in this section are estimated wind speed values as provided by the National Hurricane Center.

Katrina weakened as it passed over land on August 26, and again became a tropical storm before it entered the Gulf of Mexico. However, once over the Gulf, Katrina began regaining strength and, on August 28, reached Category 5 hurricane status with sustained winds of 175 mph (gusts of 215 mph) and a central minimum pressure of 902 millibars (mb).[5] Later in the 2005 hurricane season, Hurricanes Rita and Wilma developed with minimum pressures of 897 mb and 882 mb, respectively. As a result, Katrina became the sixth most intense Atlantic Basin hurricane on record (Rita is now the third and Wilma ranks as the first). Katrina's rapid intensification was due in part to its movement over the warm Gulf waters.

At 6:10 a.m. Central Daylight Time (CDT) on August 29, Hurricane Katrina made landfall for the second time, near Buras, Louisiana, in Plaquemines Parish. According to the National Climatic Data Center (NCDC), Hurricane Katrina had 1-minute sustained winds estimated at 127 mph upon landfall, and a minimum central pressure of 920 mb, making it the third lowest landfall pressure on record for the U.S., and placing it as a strong Category 3 hurricane on the Saffir-Simpson scale. After making landfall, Katrina moved northward up the Louisiana coast, subjecting much of Plaquemines and St. Bernard Parishes, as well as Slidell in St. Tammany Parish, to the damaging effects of its storm surge and strong winds.

After passing New Orleans, Hurricane Katrina moved across the open waters of Breton Sound and the western edge of the Mississippi Sound and made landfall at 10:00 a.m. CDT for a third time near Pearlington, Mississippi, located along the Louisiana/Mississippi border. At its third landfall, Katrina was a Category 3 hurricane with 120-mph, 1-minute sustained winds. After making landfall and traveling more than 150 miles inland and reaching Jackson, Mississippi, the storm weakened, losing its hurricane strength, with sustained wind speeds dropping below 74 mph. Katrina kept moving northward, affecting weather in the central United States, until it was absorbed by a frontal boundary near southeast Quebec and northern New Brunswick, Canada, on August 31.

One of the key factors of this storm was its strength 24 hours before landfall when it was a large Category 5 hurricane with a minimum central pressure of 902 mb. Although the storm weakened from a powerful Category 5 storm to a Category 3 storm just before making landfall in Louisiana and Mississippi, the storm surge appears to have maintained a level associated with a Category 5 hurricane. The surge generated by the storm could not dissipate as rapidly as the wind speeds decreased, and the shallow depth of the offshore shelf and shape of the shoreline contributed to the high surge elevations. Storm surge pounded the coastline from southeast Louisiana to the Florida panhandle, with the Mississippi coastline experiencing the highest storm surges on record.

After landfall, the eye traveled almost 100 miles across the Louisiana Delta before reaching the Mississippi coastline. However, the highest wind areas remained largely east of the delta over open water, with little reduction in velocity before reaching the Mississippi coastline.

Katrina was a wide storm, affecting a large area and pushing record storm surge onshore in its northeastern quadrant along the Alabama and Mississippi coastlines. Typically, surge elevations

[5] Central pressure measurements are from the National Hurricane Center's *Tropical Cyclone Report* for Hurricane Katrina, dated December 20, 2005.

exceeded 23 feet North American Vertical Datum of 1988 (NAVD 88) throughout much of the Mississippi coastline, from Waveland east to Long Beach. The highest recorded surge and wave height elevation was 34.9 feet (NAVD 88).

Although the eye of Hurricane Katrina did not directly hit New Orleans, catastrophic destruction occurred throughout the southeast portion of Louisiana. As the eye of the storm moved farther inland to the northeast of New Orleans later in the morning of August 29, winds began to blow from the north. With surge levels already high in Lakes Pontchartrain and Borgne, additional pressure from the strong north winds was put on the levee system protecting New Orleans. The levees/floodwalls of the canals that normally channel water from the low-lying areas of the city (some below sea level) to pumping stations located along Lake Pontchartrain began to fail, allowing water to inundate large portions of the New Orleans area. Based on early investigations by the U.S. Army Corps of Engineers (USACE) Interagency Performance Task Force (USACE, 2006), there were three major levee breaches and a number of secondary breaches on Monday, August 29, 2005. The major breaches were located along the Industrial Canal in the St. Claude Avenue bridge area, the 17th Street Canal levee, and the London Avenue Canal on the east bank of the canal's flood wall and levee. Additional details on the levees may be found in the USACE Interagency Performance Evaluation Task Force Interim Status Report 1, *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System*, dated 10 January 2006.

A more detailed discussion of the storm surge and the wind analyses is provided in the following sections.

1.1.2 Storm Surge Analysis and Discussion

The storm surge in Alabama, Louisiana, and Mississippi caused severe flood damage to residential, commercial, and public buildings, and infrastructure. The surge brought high waves and carried floodborne debris, significantly impacting and destroying buildings.

To assist in the long-term recovery and mitigation effort, FEMA performed a coastal high water marks (HWMs) study to investigate the high water conditions throughout the impacted areas. The HWMs were surveyed by FEMA and the U.S. Geological Survey (USGS). HWMs were surveyed horizontally on the North American Datum of 1983 (NAD 83), Mississippi East State Plane Coordinates, and vertically in NAVD 88. The HWM elevations were also converted to the National Geodetic Vertical Datum of 1929 (NGVD 29) to aid review of data and maps available only in the NGVD 29 datum. The HWMs were classified as one of three basic types: surge only, surge and waves, or wave runup.

HWM Classification Types:

● Coastal - surge only

▲ Coastal - surge and waves

■ Coastal - wave runup

1.1.2.1 Mississippi – High Water Marks

The HWM data collected for this study demonstrate that the Hurricane Katrina coastal storm surge and wave-related high water conditions reached historical proportions and covered significant portions of the Mississippi study area. A total of 402 HWMs were surveyed in the three counties investigated, as shown in Figure 1-3. Surge elevations along the open coast generally exceeded 23 feet in Hancock and Harrison Counties, and over 17 feet in Jefferson County. The highest surge HWMs along the open coast were discovered in Hancock and Harrison Counties on each side of the opening to St. Louis Bay. This high surge was evident in the communities of Lake Shore, Clermont Harbor, and Bay St. Louis in Hancock County, and Pass Christian and Long Beach in Harrison County; the highest surge elevation surveyed was 28.1 feet and the highest HWM with waves was 34.9 feet. Figure 1-4 illustrates a typical map of the HWMs in Harrison County. Maps of the all counties surveyed are provided in Appendix F.

1.1.2.2 Louisiana – High Water Marks

A total of 482 HWMs were surveyed in eastern Louisiana, as shown in Figure 1-5. The locations, elevations, and descriptions of these HWMs have been tabulated into a digital database and are summarized in Appendix F. An overall discussion of the HWM elevations for the various study areas are presented in the following sections.

1.1.2.3 Coastal Areas

Overall, the Hurricane Katrina storm surge in south-central Louisiana was lower compared to many areas of eastern Louisiana and along the entire Mississippi Coast, because the storm made landfall in the eastern part of the state. The areas of the greatest impact were those where the highest winds generated in the right-front quadrant of the storm, pushing the water toward the coast until the topography of the land surface was such that it caused a piling up of the water. These areas include St. Bernard Parish on the open Gulf Coast and the parishes surrounding Lake Ponchartrain, which include St. Tammany, Tangipahoa, Livingston, St. John the Baptist, St. Charles, Jefferson, and Orleans. The Gulf of Mexico coast forms a large embayment from Plaquemines Parish, extending north then east along the Mississippi Gulf Coast. Figure 1-6 illustrates a typical map of HWMs for Plaquemines Parish. As the storm advanced toward the coast and eventual landfall, water was pushed into this area by the high winds. HWM elevations varied in St. Bernard Parish. Typical HWM elevations ranged from 10 to 12 feet; however, some were as high as 17 to 19 feet (see Appendix F).

1.1.2.4 Lake Ponchartrain

Moderate surge levels were recorded on the western shore of the lake (see Appendix F). Due to the extensive marsh and swamp land in this area, it was difficult to collect HWMs. Surge elevations in this area ranged from 2.8 feet inland west of Lake Maurepas in Livingston Parish to 6.4 feet in St. Charles Parish (see Appendix F).

As the storm approached New Orleans, strong winds blowing from the east forced water into Lake Ponchartrain from the Gulf of Mexico, causing the elevation of the lake to rise. This increased volume of water was pushed by these winds and piled up onto the northern shore of the lake, resulting in storm surge extending north as far as U.S. Highway 190 in Slidell, to Interstate 12 north of Mandeville (see Appendix F). As the eye of the storm followed its northeast track, the wind direction shifted and began blowing to the south. This resulted in the lake water being pushed southward, allowing it to pile up on the southern shoreline.

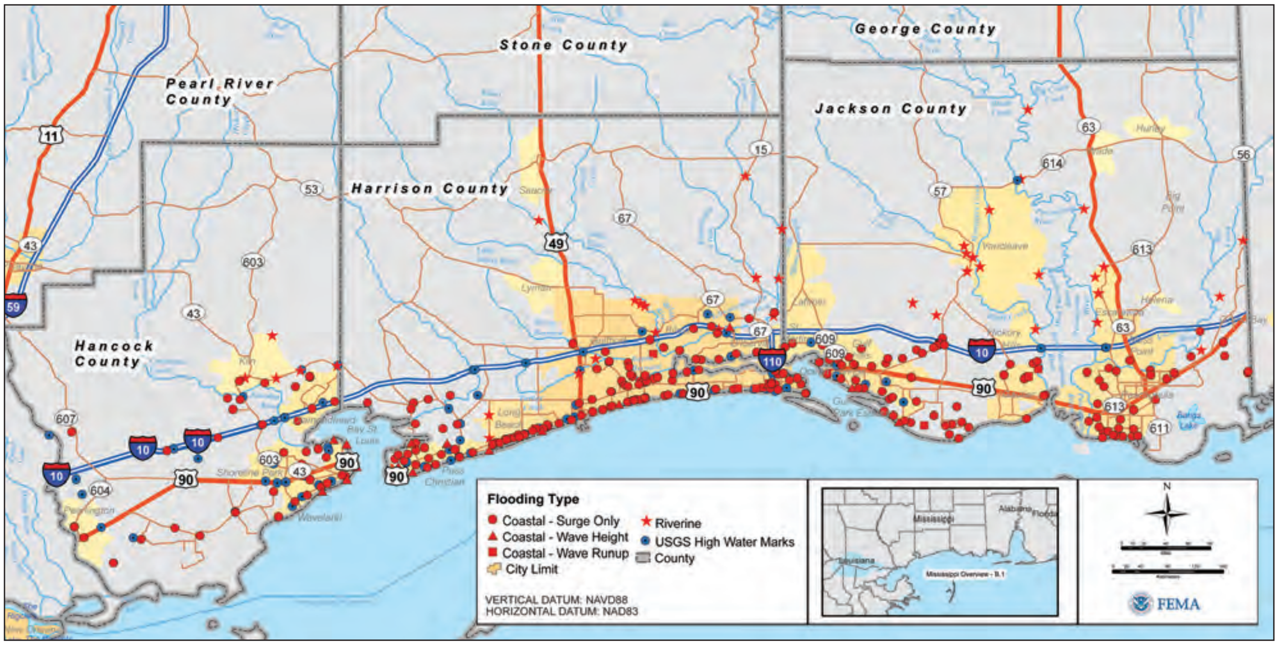


Figure 1-3. Locations of the high water marks in Mississippi

SOURCE: FEMA

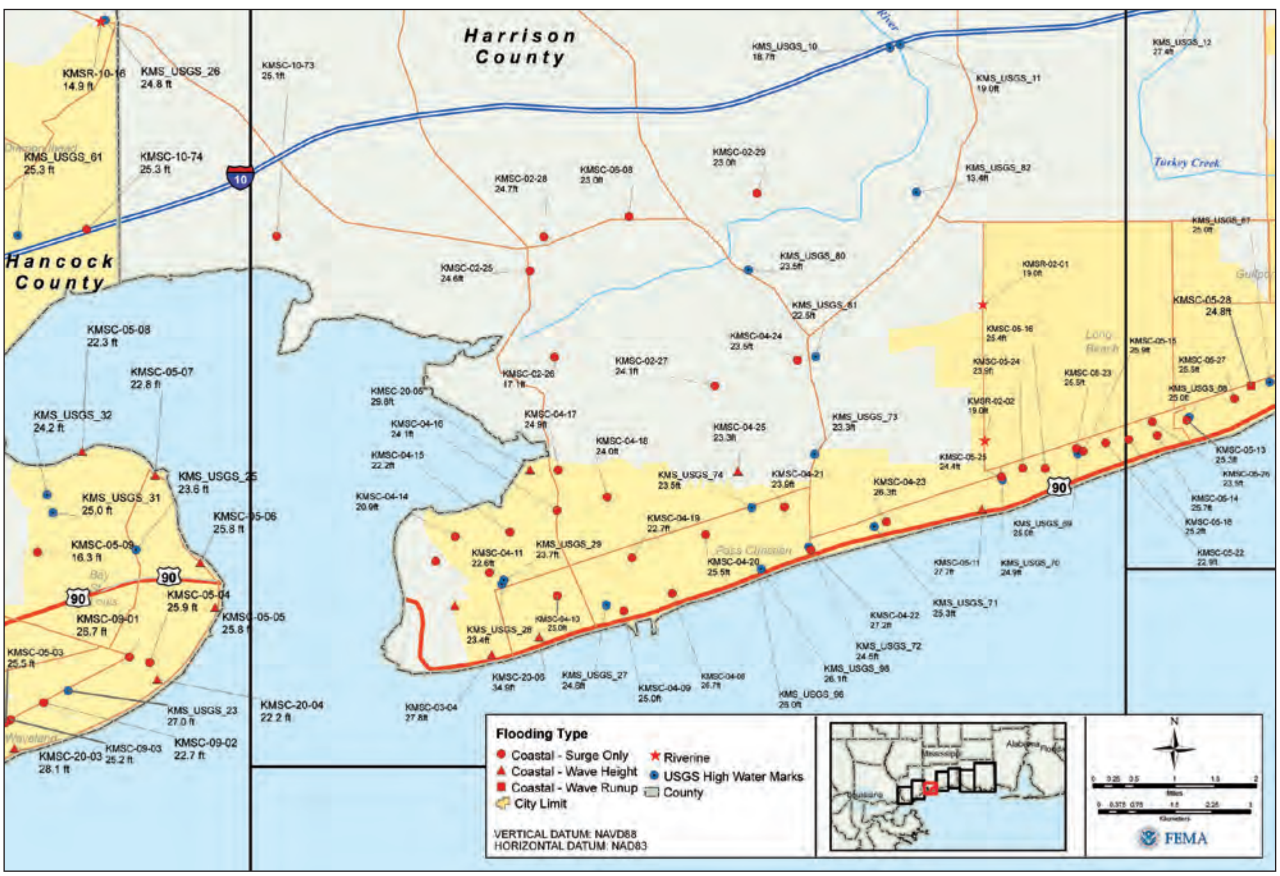


Figure 1-4. Locations of the high water marks in Harrison County, Mississippi

SOURCE: FEMA

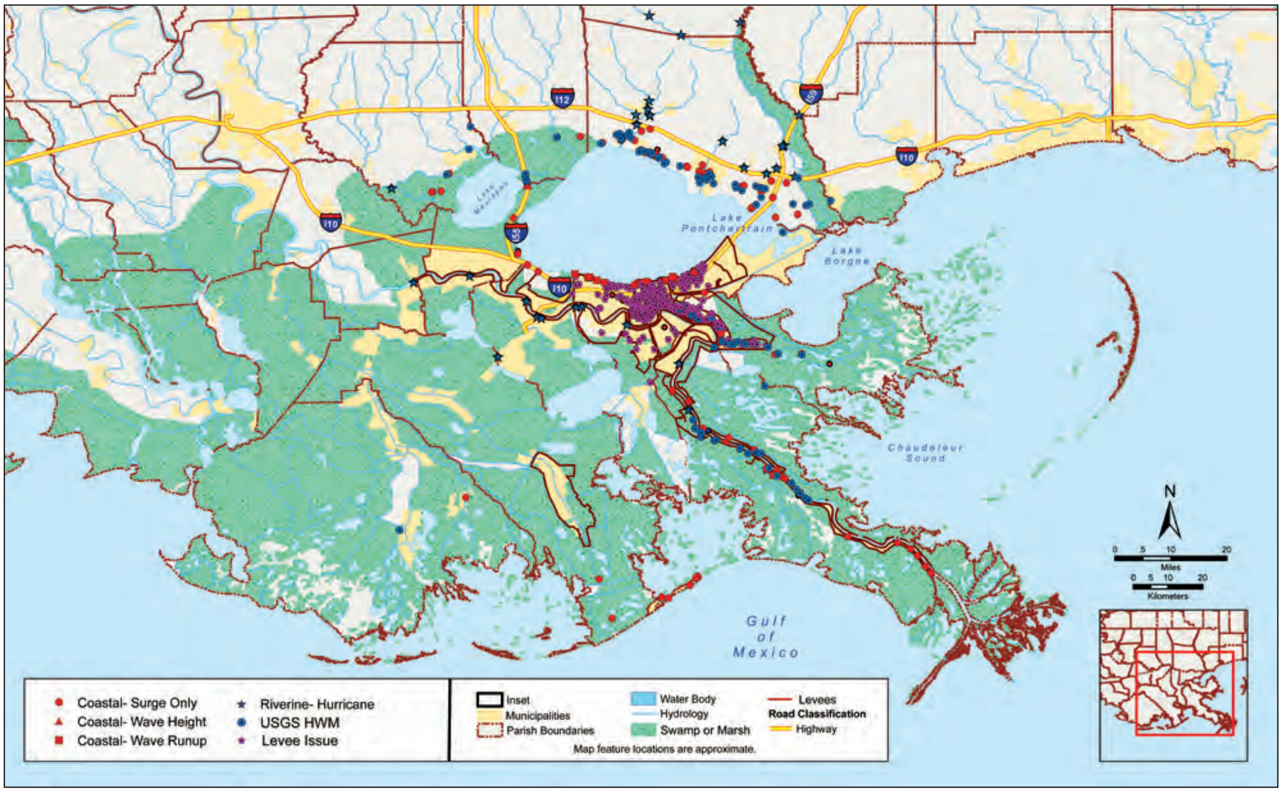


Figure 1-5. Locations of the high water marks in Louisiana

SOURCE: FEMA

On the northern shore of the lake, HWMs recorded surge levels ranging from 7 to 16 feet, with the general trend of the highest values on the east end of the north shore working westward to the lower surge values. Coastal storm surge elevations of 12.5 to 13.5 feet were recorded in the Slidell vicinity (see Appendix F). The same general pattern of higher elevations, topping at 16.6 feet, on the eastern end of Lake Ponchartrain trending to lower elevations, down to 6.8 feet, on the western end, was recorded on the southern shore of the lake (see Appendix F). These HWMs are all found on the lake side of the levee system.

1.1.2.5 Southern Area

The coastal areas least affected by Hurricane Katrina were those parishes located in the left and trailing quadrants of the storm. These include Terrebonne, Lafourche, and southern Jefferson Parishes. These parishes are sparsely populated with few roads giving access. As illustrated in Appendix F, these areas are also extensively covered by marshland and swamp. This terrain significantly lessens the impact caused by storm surge, as it applies a dampening effect to the water as it moves inland. Unfortunately, this type of terrain also lessens the availability of HWMs to be located and flagged. Appendix F shows the locations and elevations of the HWMs surveyed in these parishes. Only one HWM was found and flagged in Terrebonne Parish; seven were flagged and surveyed in Lafourche Parish. As Hurricane Katrina tracked farther inland on its northeastern path, the water in Barataria Bay was pushed southward over Grand Isle. HWM elevations were the highest in this portion of the state, measuring between 5.8 and 8.9 feet (see Appendix F).

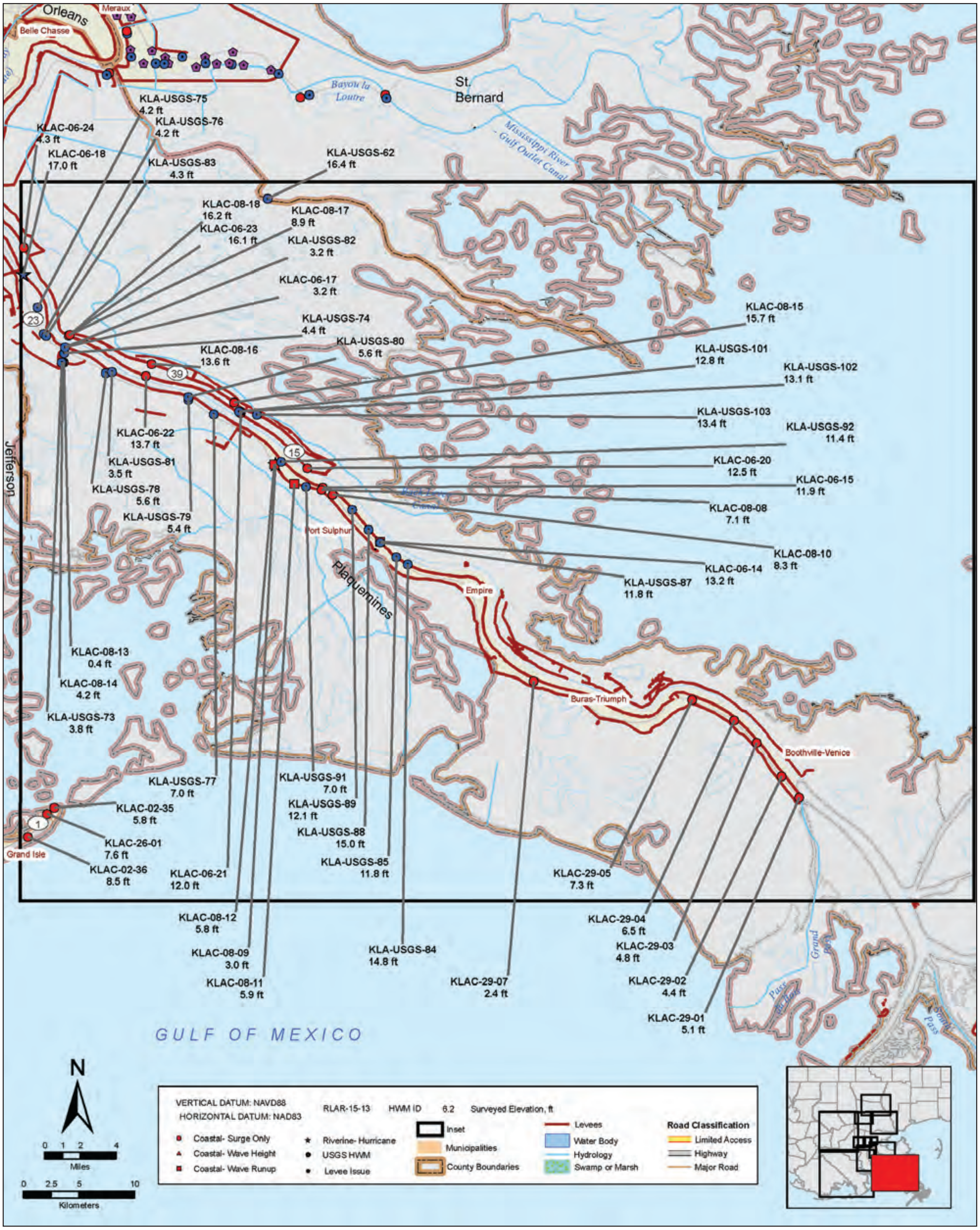


Figure 1-6. Example of map illustrating high water marks surveyed in Plaquemines Parish, Louisiana

SOURCE: FEMA

1.1.2.6 Alabama – High Water Marks

In Alabama, a total 222 HWMs were surveyed in Baldwin and Mobile Counties, as shown in Figure 1-7. The locations and elevations of the HWMs are summarized in Appendix F.

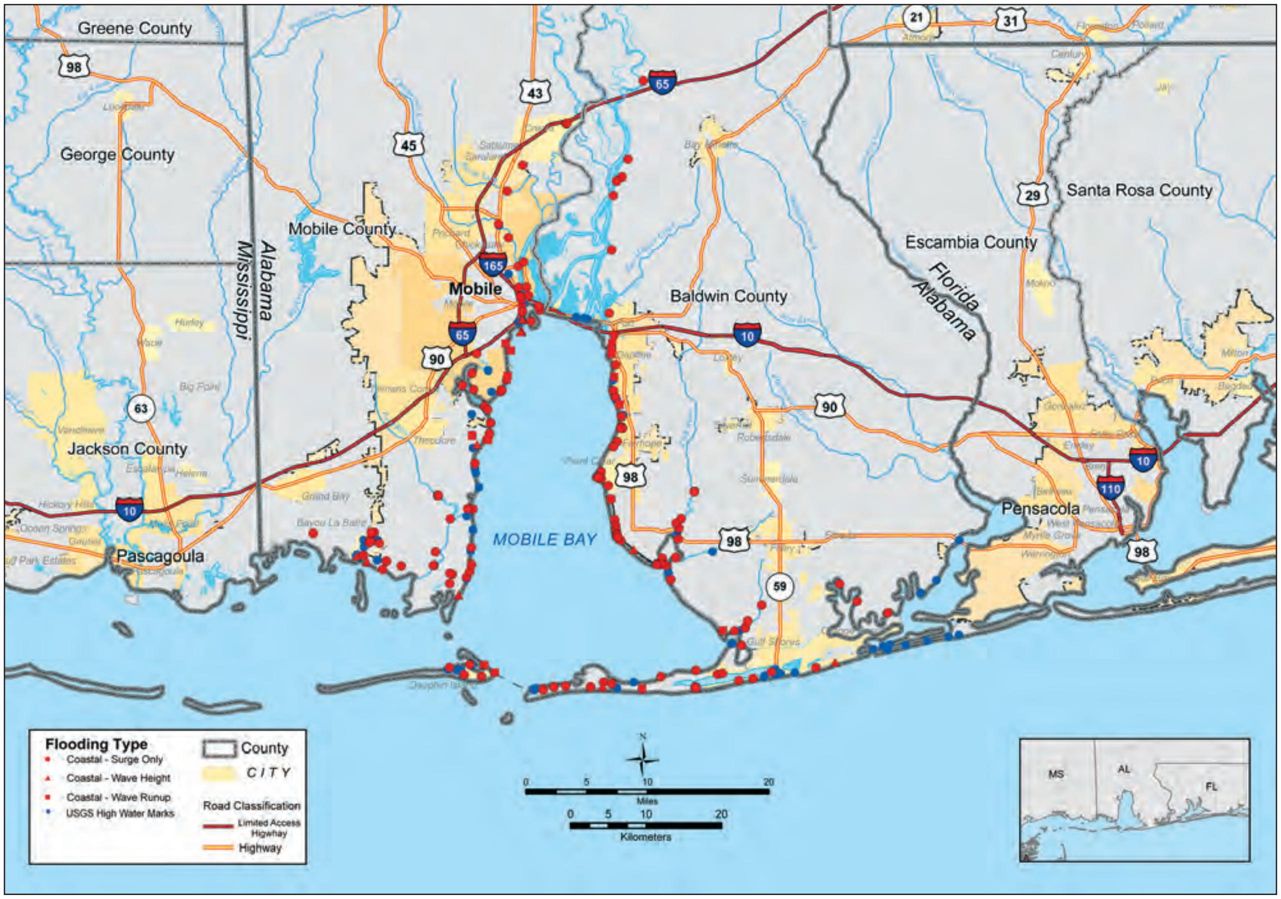


Figure 1-7. Locations of the high water marks in Alabama

SOURCE: FEMA

The Hurricane Katrina storm surge in Alabama was relatively high. The storm made landfall near the Louisiana and Mississippi state line, 65 miles west of the Alabama/Mississippi boundary. However, Katrina had a wind field that was skewed to the east and this resulted in hurricane force winds extending about 120 miles from the storm center. This caused a considerable storm surge at several places along the Alabama coast. HWMs varied throughout the two counties, typically from 10 to 12 feet on the northern end of Mobile Bay (see Figure 1-8), 8 to 10 feet along the central shorelines of Mobile Bay, and 9 to 11 feet on Dauphin Island, Alabama. Maps of HWMs in other areas of Alabama are shown in Appendix F.

1.1.2.7 Factors Affecting Storm Surge

As illustrated with the HWM data discussed in the preceding subsections, the peak storm surge in Hurricane Katrina exceeded the prior U.S. record set by Hurricane Camille, which hit in the same region of the Mississippi Coast. The fact that both records were set in the same geographic area is not just a result of two severe hurricanes striking coastal Mississippi; storm surges there are amplified by physical features, and a hurricane of a given intensity will cause higher storm surges in coastal Mississippi than almost anywhere else along the entire coast of the United States.

The two primary factors that amplify Mississippi's storm surge are the shallow offshore depths and the shape of the shoreline. As a storm surge advances toward the shoreline, it tries to return via the bottom of the water column. Along coasts with steep offshore slopes (e.g., the southeast coast of Florida, or the Pacific Coast), return flow effectively moderates the rise in water elevation. However, the shallow depths offshore of Mississippi restrict the return flow and lead to higher surge elevations over land. The shoreline shape also determines whether and how the storm surge can escape as the hurricane approaches. On a straight shoreline, the surge can partially escape at each end of the shoreline, reducing the peak elevations. The Mississippi River Delta along the Louisiana and Mississippi shoreline forms a bay-like feature that effectively confines the surge and amplifies the elevation as a hurricane moves ashore.

These surge effects are best isolated by comparing results of the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) storm surge model prepared by NOAA. Using an array of storm tracks on local bathymetric grids, a worst-case storm surge is produced for Category 1 through 5 hurricanes. A comparison of three categories of storms along the Gulf Coast is shown in Figure 1-9.

Only the developed areas along the *open coast* areas are included in Figure 1-9, to exclude storm surge amplification in the more inland bays. Predicted worst-case storm surge elevations (without waves) are shown along the Gulf Coast from Galveston, Texas, to south of Tampa Bay, Florida. The figure shows that, for a given category storm, most areas of the Gulf Coast (i.e., Texas, Western Louisiana, Alabama, the Florida panhandle, and the lower Florida Peninsula) will experience similar storm surges, with the exception of two areas – the Mississippi Coast and the "Big Bend" area of Florida, where the surge elevations are roughly 50 to 100 percent higher than those experienced along most of the Gulf Coast. The bay effect of the Mississippi Delta can be seen as the increase from Pilot Town on the outer end of the delta to a flat peak from Pass Christian to Biloxi, dropping in Eastern Mississippi.

In addition to unusually high storm surge potential for any given storm, Mississippi has one of the highest chances of a landfalling hurricane and, in some sections, the highest design wind speeds in the country. Therefore, it is not a random coincidence that Hurricanes Katrina and Camille set storm surge records in Mississippi.

Figure 1-10 shows the NOAA SLOSH model estimating the maximum storm surge along the Gulf Coast as a result of Hurricane Katrina. The storm surge in the Gulfport-Biloxi area was estimated to exceed 23 feet.

Figure 1-11 shows the primary factors driving Katrina's storm surge as the eye of the hurricane reached the Louisiana Delta (a) and the Mississippi shoreline (b). Although the initial landfall of the eye was across Plaquemines Parish, Louisiana, the radius of maximum winds remained principally east of the delta and made landfall in Mississippi. The counter-clockwise winds around the eye forced water into the shallow, western corner of Mississippi Bay, with escape prevented by the long branches of the Louisiana Delta.

Figure 1-8. High water mark locations for area covering the northern end of Mobile Bay

SOURCE: FEMA

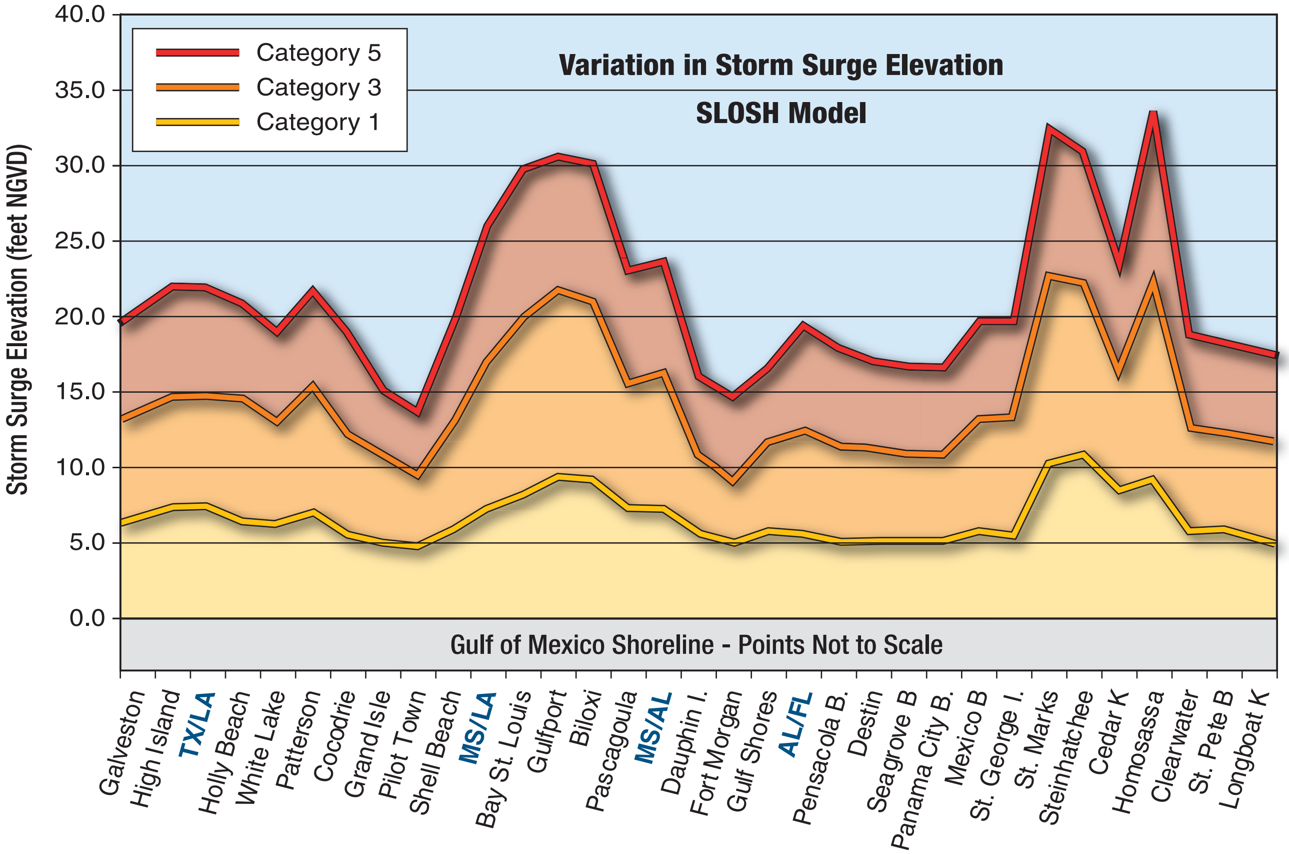


Figure 1-9. Maximum SLOSH storm surge predictions for open coast, developed shorelines

SOURCE: SLOSH DISPLAY CD-ROM/JANUARY 5, 2006/NOAA

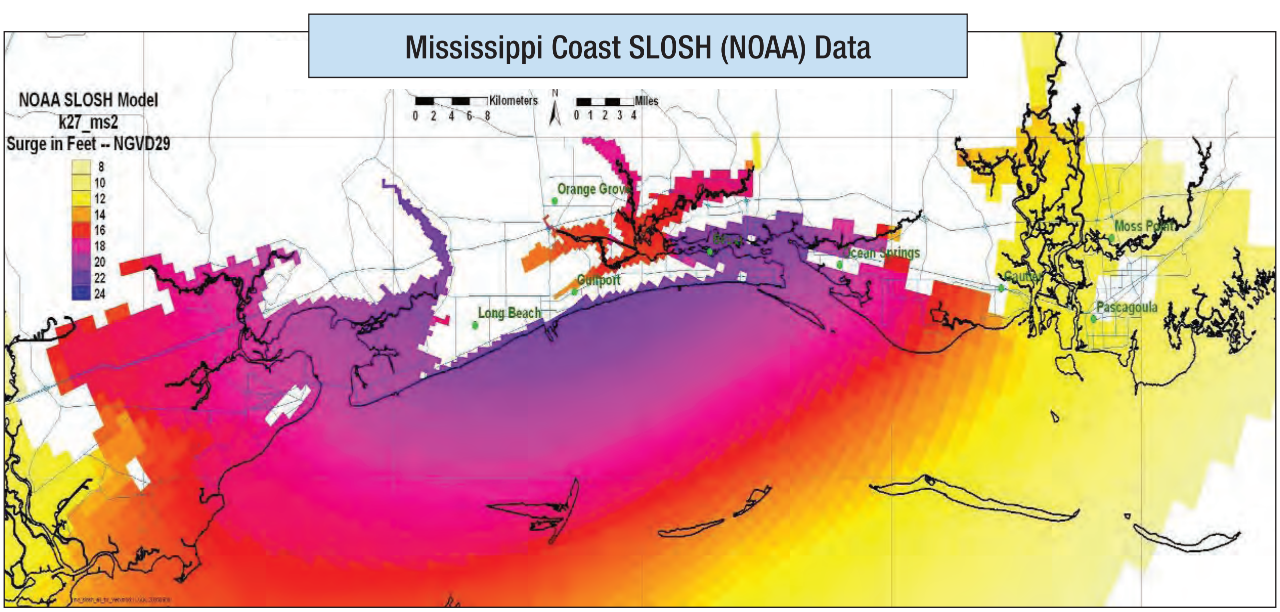
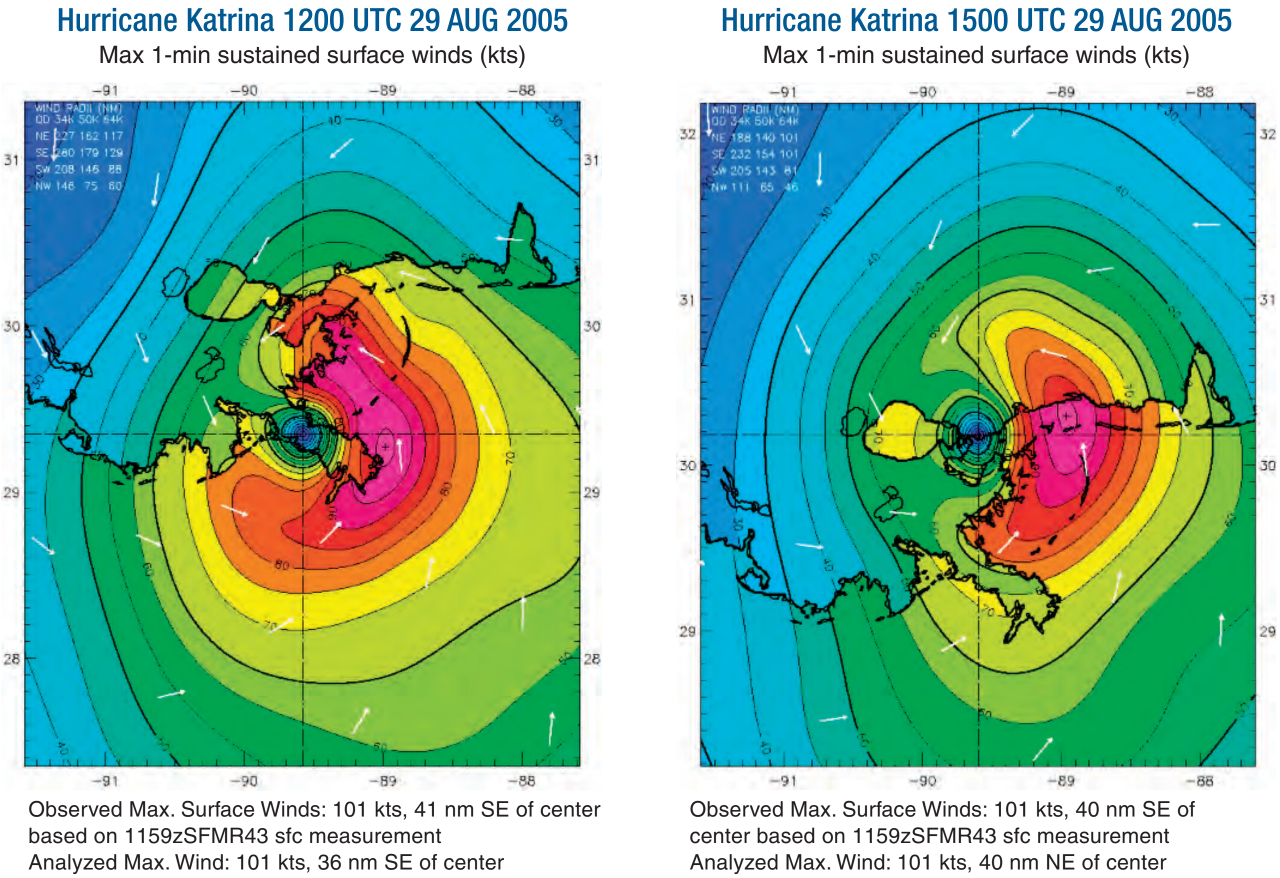


Figure 1-10. The SLOSH model of high water elevations for Hurricane Katrina

SOURCE: NOAA



a) Louisiana Delta

b) Mississippi Shoreline

Figure 1-11.
H*Wind[6] snapshots of Katrina 1-minute winds as the eye reached the Louisiana Delta (a) and Mississippi shoreline (b). Counter-clockwise winds pushed peak storm surge into the west end of the Mississippi Bay.

SOURCE: NOAA, ATLANTIC OCEANOGRAPHIC AND METEOROLOGICAL LABORATORY [AOML], HURRICANE RESEARCH DIVISION [HRD]

Several other factors contributed to Katrina's record storm surge. The storm was very large, with hurricane wind speeds covering approximately 200 miles in diameter as it came ashore. As described previously, Katrina’s wind speeds and central pressure were that of a very strong Category 5 hurricane within a hundred miles of the coast. The surface flow and deepwater wave heights were therefore initiated under these higher wind speeds. If the offshore conditions of the storm’s strength had been similar to those at landfall, storm surge elevations would have been lower.

In short, it is not surprising that Katrina caused high storm surges along the western Mississippi coastline. The shallow offshore slope and the confining corner created by the Louisiana Delta make it predictable that a hurricane of any intensity on a similar track would result in a higher storm surge than along most other shorelines in the United States. Refer to Section 1.1.3 for more information on H*Wind.

[6] One of the better known products for representing hurricane winds is H*Wind from NOAA's Hurricane Research Division. H*Wind is an experimental research product developed by the HRD.

1.1.2.8 Coastal Flood Frequency Analysis

Under a separate Hazard Mitigation Technical Assistance Program (HMTAP) Task Order, URS was tasked to prepare Flood Advisory Maps for the three counties in Mississippi that were affected by Hurricane Katrina. Part of this task involved performing a flood frequency analysis of tidal gauge data to quickly provide information to assist in the planning and rebuilding efforts, while more detailed analyses are being conducted. The results of this study are provided in *Draft Report, Hurricane Katrina Flood Frequency Analysis,* dated September 2005. The analysis was based on 30 years' worth of tidal gauge data collected from NOAA and USGS.

The long-term gauge analysis was based on Hurricane Katrina gauge data from select NOAA and USACE stations. While the best data available were used at the time of the flood frequency analysis, the reference data had limitations. Some stations were damaged, destroyed, or malfunctioned during Hurricane Katrina and did not record the peak stage. Another limitation was that gauges with long records of data were sparsely distributed, but they did provide useful records of a long period of historic storm surge peak heights. Preliminary HWM surveys in the vicinity of the existing gauge were used in the analysis.

The historical data were analyzed using seven different methods to estimate the 2-, 10-, 50-, 100-, and 500-year elevations. Methods of the analysis include the Weibull and Cunnane plotting positions, the Pearson Type III and log-Pearson Type III distribution, the Generalized Extreme Value (GEV) distribution, and the Gumbel distribution using both untransformed and log-transformed elevation data. Details on the analysis, including the gauge data and the frequency distributions, may be found in the report.

The following is a summary of the results from the *Hurricane Katrina Flood Frequency Analysis* report:

- At Biloxi, the 100-year elevation is 15.7 feet and the 500-year elevation is 28.7 feet. Therefore, the Hurricane Katrina elevation of 24 feet is estimated to be about a 250-year event at Biloxi, Mississippi.
- At Pascagoula, the 100-year elevation is 11.9 feet and Katrina was 13 feet. Katrina is estimated to be about a 125-year event at Pascagoula, Mississippi.
- At Waveland, the 100-year elevation is 17.6 feet and Katrina was 23 feet. The 200-year event is 22.8 feet; therefore, Katrina is estimated to be about a 200-year event at Waveland. Note that the Katrina elevation of 23 feet was estimated from four HWMs obtained by USGS at a location north of Waveland near the intersection of I-10 and SR 43. It is possible that Katrina was higher than 23 feet at Waveland. The elevations of HWMs flagged at Waveland had not yet been determined when the Flood Frequency Analysis report was written.
- On the west end, bay side of Dauphin Island, the 100-year event is 7.5 feet and Katrina was 5.81 feet. The 50-year event is 6 feet; Katrina was about a 50-year event on the west end, bay side of Dauphin Island, Alabama.
- At Pensacola, the 100-year event is 7.3 feet and Katrina was 6.07 feet. The 50-year event is in the range of 5.8 feet, so Katrina is estimated to be about a 50-year event at Pensacola, Florida.

The results of the flood frequency analysis were used to develop Advisory Base Flood Elevations (ABFEs) and prepare the Katrina Recovery Maps.

1.1.2.9 Flood Recovery Maps

FEMA requested that URS evaluate coastal flood hazard conditions for Hurricane Katrina in Mississippi using data from the Flood Frequency Analysis and the High Water Mark Study, and prepare surge inundation and ABFE maps. The Hurricane Katrina Surge Inundation and ABFE maps (herein referred to as the "Katrina Recovery Maps") were provided in the form of high resolution maps that show coastal flood impacts for Mississippi and Louisiana.

These maps can be viewed at <http://www.fema.gov/hazard/flood/recoverydata/katrina/>. A sample of a Katrina Recovery Map is shown in Figure 1-12.

1.1.3 Wind Hazard Analysis and Discussion

According to the National Weather Service (NWS) December 20, 2005, report, Hurricane Katrina made landfall in Buras, Louisiana, with an estimated 1-minute sustained wind speed of 110 knots (127 mph) or approximately 150 mph 3-second gust. After landfall in Louisiana, Katrina traveled almost 100 miles across the Louisiana Delta before reaching the Mississippi coast where it made a third landfall (one in Florida and two in the Gulf) near Poplarville, Mississippi. The NWS estimated 1-minute sustained surface winds of 105 knots (120 mph) or approximately 145 mph 3-second gust.

The estimates were higher than any recorded by land-based instruments. The highest land-based wind speed recorded was 117 mph gust from a Texas Tech University tower located at the Stennis International Airport, approximately 8 miles west-northwest of Bay St. Louis, Mississippi. However, like many previous storms the MAT has investigated, ground-based anemometers either failed before they recorded maximum winds or were located great distances from the storm's path. As a result, no wind speed instruments likely recorded the maximum winds produced by Katrina.

Table 1-3 provides a summary of some of the data available from the measuring devices, including recorded wind speed, location, and the source of the data. Wind speeds have been converted from knots to mph.

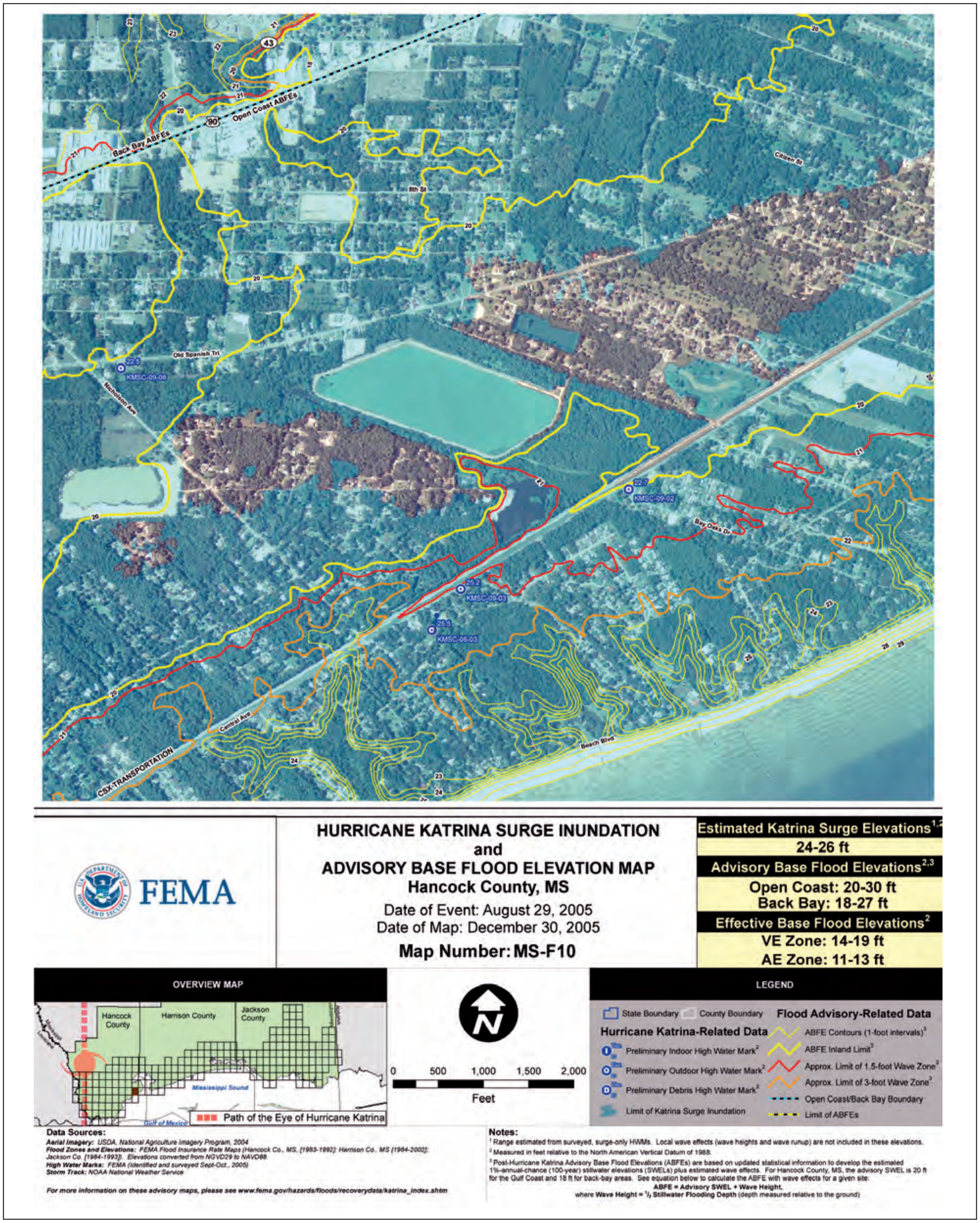


Figure 1-12.
Sample recovery map, which illustrates surge inundation and ABFEs for Hancock County, Mississippi

SOURCE: FEMA

Table 1-3. Wind Speeds Recorded for Hurricane Katrina

Location	Wind Speed
Alabama	
Dauphin Island at Coastal Marine Automated Network (C-MAN) Station DPIA1 (Source: NWS)	101 mph gust
Louisiana	
Slidell (Source: Texas Tech University mobile wind tower)	100 mph gust
Belle Chasse (Source: FCMP mobile wind tower T1)	102 mph gust
Galliano (Source: FCMP mobile wind tower T2)	96 mph gust
Vacherie (Source: Texas Tech University)	73 mph gust (data collection ceased near the storm's peak)
Grand Isle (Source: NOAA Buoy GDIL1)	114 mph gust, before gauge failed
Port Sulfur (Source: LSU AgCenter)	101 mph gust, peak before station failed
Buras (Source: University of Louisiana near Buras reporting)	114 mph gust (2 meter tower on top of a levee)
Mississippi	
Stennis International Airport (Source: Texas Tech University)	117 mph gust
Biloxi (Source: ASOS)	111 mph gust (max gust before failing)
Pine Belt Airport (12 miles NE of Hattiesburg)	Max gust 80 mph. After this, power was lost and recording stopped.
Forrest County Emergency Operations Center (EOC)	Max gust 100 mph. After this, the anemometer was blown down.
Laurel-Jones County Airport	Max gust of 110 mph. After this, the anemometer was blown down.
Jackson International Airport	Max gust of 64 mph (10 seconds), unofficial gust of 74 mph (5 seconds). After this, power was lost and recording stopped.
Pascagoula (Source: FCMP mobile wind tower T3)	95 mph gust

SOURCE: NOAA, NCDC

The wind speed data listed in this table have not been normalized to a single exposure category and instrument height.

To help fill in the gaps that exist in ground-based wind data, wind speeds are estimated using a variety of methods.

H*Wind employs estimates of surface level winds obtained from a variety of sources and yields near real-time analyses of the surface winds produced by tropical cyclones. Based on past experience of comparing modeled estimates with actual recorded wind speeds, H*Wind provides reasonably accurate estimates of maximum wind speeds over large areas impacted by a storm. Contours of 1-minute sustained wind speeds from Katrina were developed utilizing HRD's H*Wind model (see Figure 1-11). The contours are at selected "snapshots" taken as Katrina's eye passed over Plaquemines Parish and over Breton Sound.

FEMA's wind model used in HAZUS-MH (Hazards U.S. - Multi-Hazard) is also used to estimate wind speeds. HAZUS was developed as a loss estimation model, but produces reasonable estimates of maximum speed and the lateral distribution of wind. Wind swath contour plots based on HAZUS-MH methodology were modeled by Applied Research Associates (ARA) (see Figure 1-13). ARA's model uses a series of surface level observations of wind speeds and pressures obtained from portable towers, buoys, and Automated Surface Observing Systems (ASOS) stations to obtain estimates of the time variation in the storm's radius to maximum winds and the Holland B parameter (a function of the shape of the storm). Measured wind speeds are adjusted to "standard conditions" (that is 10 meter instrument height in open terrain) using either estimates of the surrounding roughness from aerial photography or from estimates of the turbulence intensity where full digital time series are available. The variation of the Holland parameter B is used with NHC position and central pressure estimates and pre-computed solutions of a numerical hurricane model to develop estimates of wind speeds as a function of time and location. Unlike the H*Wind snapshots shown in Figure 1-11, Figure 1-13 shows the highest estimated wind speeds experienced as Katrina moved through the area.

In the case of Hurricane Katrina, there were very little wind speed and pressure data inland and, as a result, estimates of wind speeds farther inland have greater uncertainty than those near the coast. Comparisons to anemometer data suggest the model has an uncertainty (estimated using the standard deviation of the observed minus modeled wind speeds) of about 6 percent, indicating that, in most cases, the modeled wind should be accurate to about 10 percent or better.

With Katrina, wind speeds generated by the HAZUS model and those estimated utilizing the H*Wind results compare favorably to each other. Also, both methods suggest that, except for a few areas along the Mississippi coast, Katrina's winds failed to reach the design wind speeds specified by ASCE 7 (the wind standard referenced by the latest building codes).

DEFINITION OF WIND EXPOSURE ZONES

Exposure B. Urban, suburban, wooded areas.

Exposure C. Open terrain, flat open country, grasslands, all water surfaces in hurricane-prone regions.

The modeled wind speeds also generally correlate with damages observed by the MAT, particularly when the model results are adjusted for exposure (HAZUS and H*Wind depict wind speeds in Exposure C (open terrain) areas; most of the MAT observations were in the more protected Exposure B areas). Exceptions to this general correlation occurred in some areas east of Gulfport and north of Picayune. In those areas, HAZUS predicted higher wind speeds than what the observed ground-based damages would appear to support. For example, HAZUS predicted wind speeds in Biloxi only 5 mph less than Bay St. Louis, but the observed wind damages in Biloxi were significantly less than those in Bay St. Louis. Also, HAZUS predicted 115 mph Exposure C wind speeds in Poplarville, but the damages observed in that area were more typical of lower wind speeds. The apparent lack of correlation between ground-based damage observations and the computer models in these areas may result from terrain effects, from construction variations, or from the uncertainty of the computer models.

Much of the wind-based damage from Hurricane Katrina occurred in areas where the wind speeds were well below the design levels specified in the latest codes. In discussing wind damage, it is important to differentiate between structural damage and building envelope damage. Many buildings experienced little or no structural damage, but may be total losses due to water entry that resulted from building envelope failure. It is also important to differentiate between the design wind speeds and their resulting design pressures specified by the latest codes and the design wind speeds/pressures specified by the older codes that were in effect when many of the buildings the MAT investigated were constructed. In many areas, the design wind pressures specified in current codes are higher than those specified in older codes.

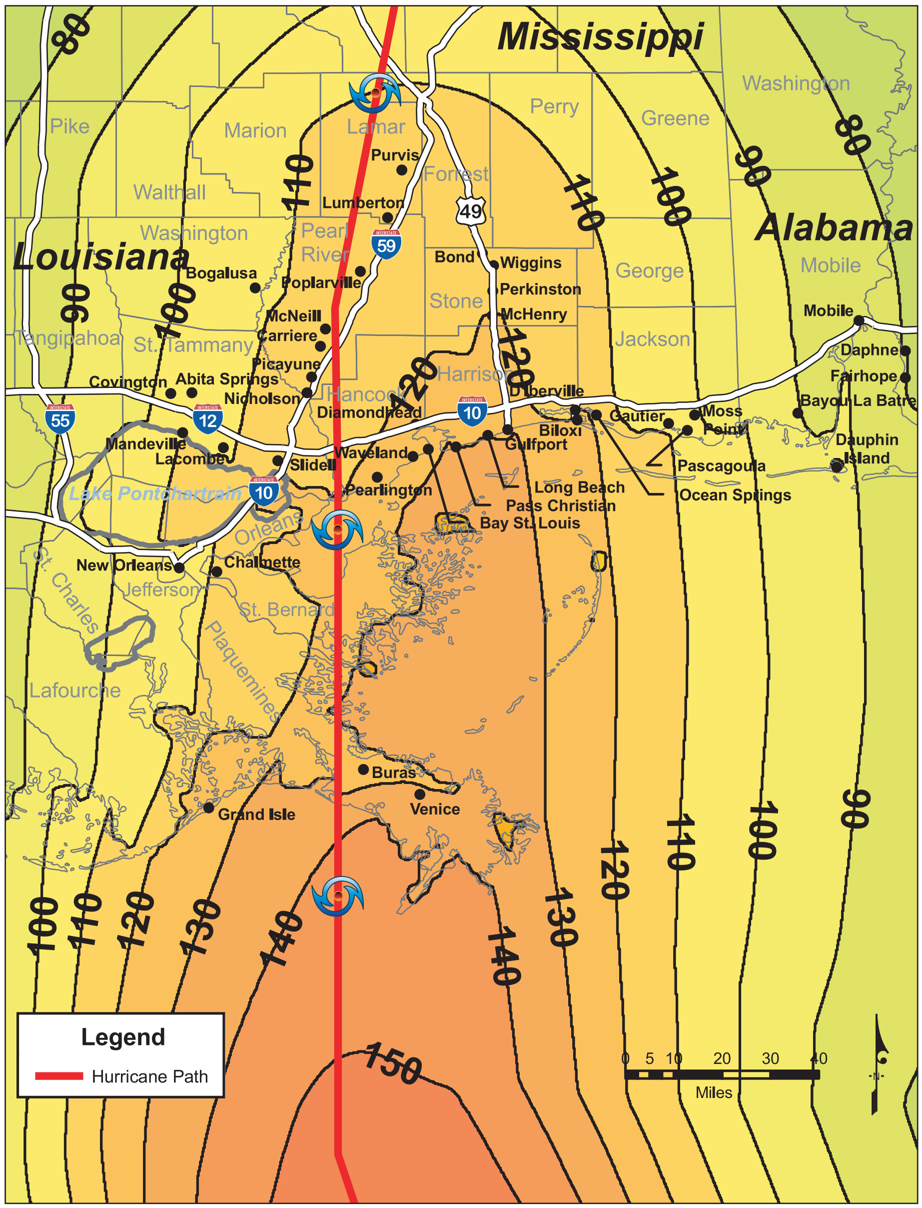


Figure 1-13.
Wind swath contour plot of 3-second gust wind speeds in mph at a height of 10 meters above ground (open exposure) based on HAZUS-MH wind field methodology

SOURCE: ARA

Table 1-4 lists the HAZUS-modeled Exposure C wind speeds in selected cities and converted wind speeds for Exposure B areas. The conversion from Exposure C to Exposure B was made using an equivalent wind pressure calculation using equations contained in ASCE 7-05.

Table 1-4. HAZUS Estimated Wind Speeds

Location	3 –Second Gust Wind Speeds* Exposure C	3 –Second Gust Wind Speeds** Exposure B
Bay St. Louis, MS	125	105
Belle Chasse, LA	110	95
Biloxi, MS	120	100
D'Iberville, MS	120	100
Dauphin Island, AL	95	80
Diamondhead, MS	120	100
Gautier, MS	110	95
Gulfport, MS	130	110
Long Beach, MS	130	110
Mobile, AL	85	70
Moss Point, MS	100	85
New Orleans, LA	105	90
Ocean Springs, MS	120	100
Pascagoula, MS	105	90
Pass Christian, MS	130	110
Poplarville, MS	115	100
Slidell, LA	115	100
Waveland, MS	125	105

* Wind speeds based on ARA wind speeds as shown in Figure 1-13.

** Calculated wind speeds, Exposure B – calculated from wind pressure conversions for components and cladding for buildings with a mean roof height of 33 feet (see ASCE 7-05 Table 6-3).

Tornadoes from Hurricane Katrina

According to the NCDC, there were 13 confirmed tornadoes in Mississippi, ranging from F1 to F2, and 11 confirmed tornadoes in Alabama, ranging from F0 to F1, as a result of Hurricane Katrina occurring on August 28 and 29, 2005. At the time the report was being developed, data for Louisiana were not available. Locations of the confirmed tornadoes are shown in Figure 1-14. Most of the tornadoes were rated F0 or F1 on the Fujita Scale, as shown in Table 1-5.

Table 1-5. The Fujita Scale

F-Scale Number	Intensity Phrase	Wind Speed	Type of Damage Done
F0	Gale tornado	40-72 mph	Some damage to chimneys; breaks branches off trees; pushes over shallow-rooted trees; damages sign boards.
F1	Moderate tornado	73-112 mph	The lower limit is the beginning of hurricane wind speed; peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off the roads; attached garages may be destroyed.
F2	Significant tornado	113-157 mph	Considerable damage. Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light object missiles generated.
F3	Severe tornado	158-206 mph	Roof and some walls torn off well constructed houses; trains overturned; most trees in forest uprooted.
F4	Devastating tornado	207-260 mph	Well-constructed houses leveled; structures with weak foundations blown off some distance; cars thrown and large missiles generated.
F5	Incredible tornado	261-318 mph	Strong frame houses lifted off foundations and carried considerable distances to disintegrate; automobile sized missiles fly through the air in excess of 100 meters; trees debarked; steel reinforced concrete structures badly damaged.
F6	Inconceivable tornado	319-379 mph	These winds are very unlikely. The small area of damage they might produce would probably not be recognizable along with the mess produced by F4 and F5 winds that would surround the F6 winds. Missiles, such as cars and refrigerators, would do serious secondary damage that could not be directly identified as F6 damage. If this level is ever achieved, evidence for it might only be found in some manner of ground swirl pattern, for it may never be identifiable through engineering studies.

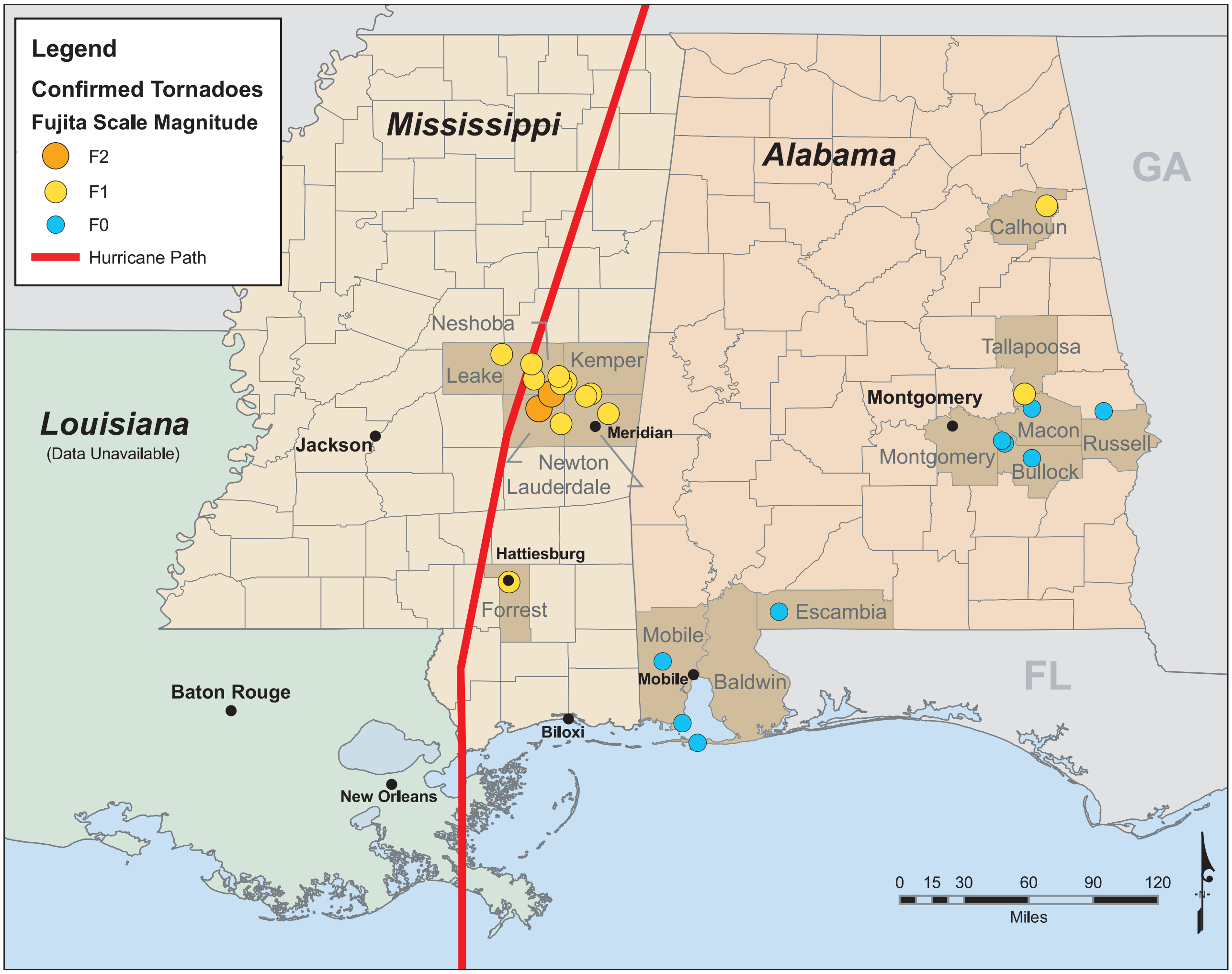


Figure 1-14. Confirmed tornadoes in Mississippi and Alabama attributed to Hurricane Katrina

(BASED ON NATIONAL CLIMATIC DATA CENTER RECORDS)

1.2 Historic Hurricanes

At its peak in the Gulf, Hurricane Katrina reached a minimum central pressure of 902 mb, although at landfall it weakened to 920 mb. Other severe hurricanes (and the minimum central pressure at landfall) were Hurricane Camille (909 mb) and the Labor Day hurricane that struck the Florida Keys in 1935 (892 mb). Hurricane Andrew in 1992 recorded a pressure of 922 mb at landfall and destroyed over 25,000 houses and damaged over 100,000 houses. Hurricanes Rita and Wilma, which occurred in 2005, recorded some of the lowest pressures in history. Table 1-6 provides a summary of the most intense hurricanes to make landfall on the U.S. mainland.

Table 1-6. Summary of Most Intense Hurricanes to Make Landfall in the United States Based on Minimum Pressure

Hurricane	Minimum Pressure (millibars)	Pressure at Landfall (millibars)	Category at Landfall	Location	Year
Wilma	882	950	3	near Everglades City, FL	2005
Unnamed Storm	892	892	5	Florida Keys	1935
Rita	897	937	3	Texas/Louisiana border	2005
Allen	899	948	3	south Texas	1980
Katrina	902	920	3	Plaquemines Parish, near Buras, LA	2005
Camille	905	909	5	Mississippi	1969
Andrew	922	922	5	southeast FL - Homestead, FL	1992

SOURCE: NOAA, NCDC, *CLIMATE OF 2005 ATLANTIC HURRICANE SEASON*

When discussing past hurricanes, many residents of southeast Louisiana and the Gulf Coast of Mississippi had always referred to the power, high surge elevations, wind speeds, and resultant damage of Hurricanes Betsy and Camille for comparison. Now the benchmark for future hurricanes has become Hurricane Katrina. In Alabama, Dauphin Island residents referred to the destruction caused by Hurricane Frederic. Table 1-7 shows the comparisons for Hurricanes Betsy, Camille, Frederic, and Katrina. Figure 1-15 shows the paths of Hurricanes Betsy, Camille, Frederic, and Katrina.

Table 1-7. Comparisons of Hurricanes Betsy, Camille, Frederic, and Katrina

Hurricane	Year	Category at Landfall	Surge Elevation (feet)	Wind Speed-gust (mph) at Landfall	Central Pressure (mb) at Landfall	Casualties	Economic Loss (billions) (adjusted 2005)	Number of Homes Damaged/ Destroyed
Betsy	1965	3	16	160	948	76	$10-12	164,000
Camille	1969	5	25	190	909	256	$6.99	19,577
Frederic	1979	3	12	145	946	5	$7.3	N/A
Katrina	2005	3	28	150	920	>1,700	$125	>300,000

SOURCE: NOAA, NCDC

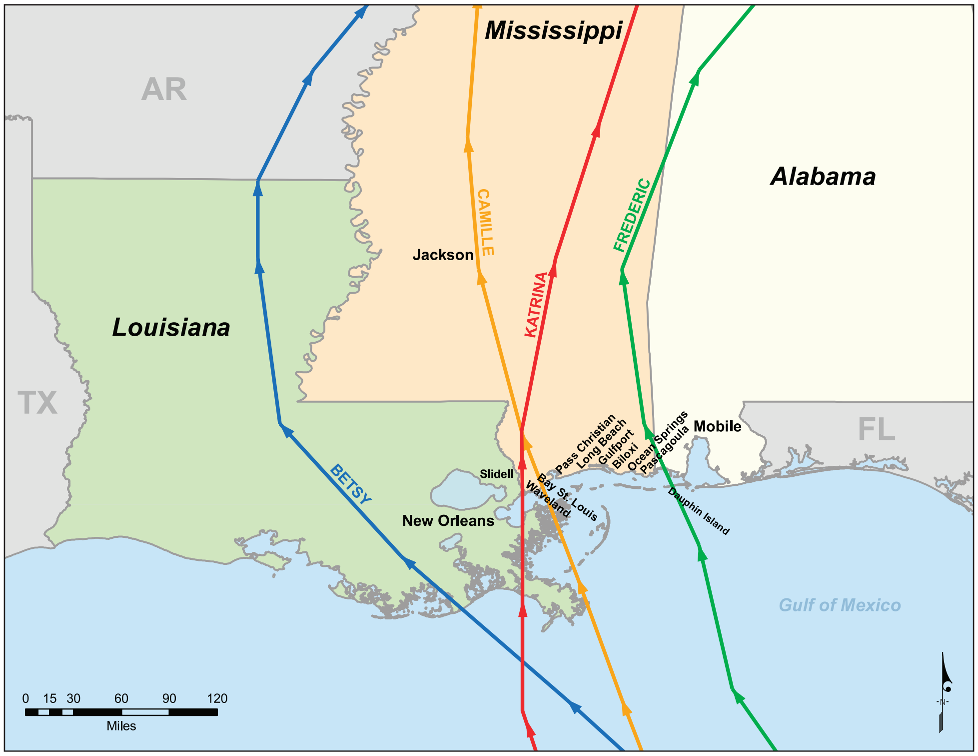


Figure 1-15. Historic hurricane storm tracks: Betsy (1965), Camille (1969), Frederic (1979), and Katrina (2005)

(BASED ON HURRICANE STORM TRACK DATA FROM THE NATIONAL HURRICANE CENTER)

1.2.1 Hurricane Betsy

A major hurricane of the 1965 hurricane season, Hurricane Betsy tracked through the Bahamas and Florida before reaching Louisiana, causing major damage along its path. Betsy made landfall on September 9, 1965, as a Category 3 Hurricane at Grand Isle, Louisiana, bringing 160-mph gusts and a 16-foot storm surge that flooded the entire island. Winds gusted to 125 mph in New Orleans and a 10-foot storm surge caused major flooding. Winds in most of southeast Louisiana reached 100 mph and, in areas as far inland as Monroe, winds exceeded 60 mph. Offshore oil rigs, public utilities, and commercial boats all suffered severe damage, resulting in approximately $1.4 billion in damage (in 1965 dollars, the equivalent of approximately $10-12 billion in 2005). Seventy-six people lost their lives as a direct result of Hurricane Betsy, the first storm to cause $1 billion in damage. Figure 1-16 shows all hurricane storm tracks in the Gulf Coast "catcher's mitt" from 1851 to the present, according to the NHC.

Like Katrina, Betsy caused surge effects in Lake Pontchartrain. The storm surge from the lake caused a section of the levee to fail, resulting in flooding within New Orleans in the Ninth Ward and in the Chalmette area of St. Bernard Parish. In most low-lying areas of the city, floodwaters reached to the roofs of houses, resulting in drowning deaths of some of those whom had sought refuge from the floodwaters in their attics. Water levels receded after approximately 10 days. It is estimated that approximately 164,000 homes were flooded in Louisiana as a result of Hurricane Betsy.

After Betsy, the USACE created the Hurricane Protection Program and constructed a new levee system both higher and stronger than the former system. This system protected New Orleans from Hurricane Camille's storm surge in 1969.

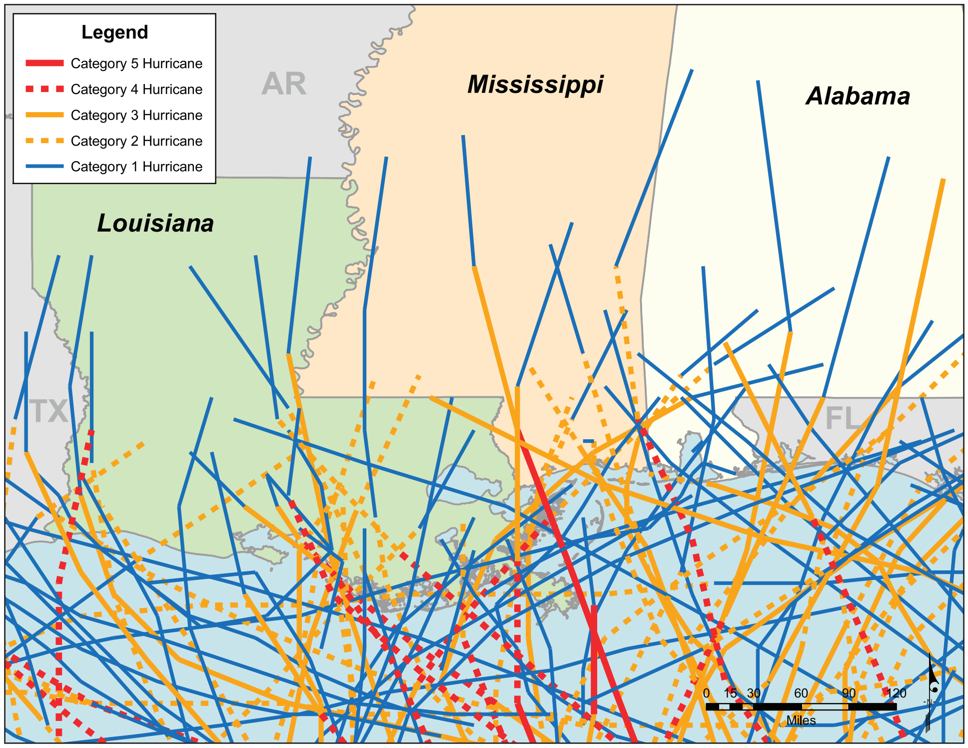


Figure 1-16. Historic hurricane storm tracks and categories (1851 – present)

(BASED ON HURRICANE STORM TRACK DATA FROM THE NATIONAL HURRICANE CENTER)

1.2.2 Hurricane Camille

Hurricane Camille (1969), the previous "hurricane of record" for the Mississippi Gulf Coast, recorded a 25-foot storm surge. At its peak strength over the Gulf (902 mb and 175 mph sustained winds), Katrina's intensity was comparable to Camille's, but at landfall Katrina's measured winds (127 mph sustained) were lower and its central pressure (920 mb) was higher than Camille's estimated landfall measurements of 190-210 mph gust speeds and 909 mb central pressure.[7] However, Katrina was a larger storm affecting a wider area than Camille, and was pushing higher storm surges onshore along the Gulf Coast.

Camille made landfall as a Category 5 hurricane in western coastal Mississippi in the Waveland/ Bay St. Louis area on August 17, 1969, approximately 15-20 miles east of where Katrina made its third landfall near Pearlington, Mississippi. Like Katrina, Hurricane Camille brought severe destruction to the Mississippi Gulf Coast, causing $1.42 billion in total damage (in 1969 dollars – the equivalent of $6.99 billion when adjusted to 2005 dollars), and was directly responsible for 143 deaths in Alabama, Louisiana, and Mississippi. Many of those who died were residents along the coast who did not evacuate. After losing hurricane strength, Camille traveled north, causing major flooding in Virginia and leading to the deaths of an additional 113 people. Throughout its path, Camille caused injury to 8,931 people, destroyed 5,662 homes, and severely damaged 13,915 homes.

[7] Camille's landfall measurements are estimates because a reconnaissance aircraft was unable to estimate surface wind just prior to the storm's landfall and because terrestrial weather observation equipment did not survive the storm.

For the past 36 years, Camille has stood out as the benchmark storm for those living along the Mississippi Gulf Coast, both in their minds and in records set. However, with Hurricane Katrina's arrival in 2005, residents of the area have a new standard for devastation and destruction. Although not as powerful as Hurricane Camille according to wind speed and pressure measurements at landfall, Hurricane Katrina was a much larger diameter storm. The most overwhelming source of damage was Katrina's record-breaking storm surge along the Mississippi coast, which topped Camille's surge elevations by several feet in most areas. Although Hurricane Katrina is considered the new standard for comparing hurricanes along the Louisiana and Mississippi Gulf Coast, future storms could equal or exceed the impact caused by Katrina.

1.2.3 Hurricane Frederic

In 1979, Hurricane Frederic caused considerable damage along Dauphin Island and Gulf Shores, Alabama. Making landfall near Gulf Shores-Mobile, Alabama, peak storm surge levels reached 12 feet in Gulf Shores, destroying much of the community, and 11 feet at Dauphin Island, destroying the causeway connecting the island to the mainland. Over 50 homes were destroyed along the 22-mile reach from Fort Morgan to Gulf Shores, and 73 percent of the beachfront buildings were destroyed. In comparison, the high surge of Hurricane Katrina was similar to that of Hurricane Frederic, in some areas along Dauphin Island. Hurricane Katrina's high surge provided a good opportunity to assess the adequacy of National Flood Insurance Program (NFIP) floodplain management requirements as well as current construction practices in resisting storm surge damage.

1.3 FEMA Mitigation Assessment Teams (MATs)

Most people know FEMA for its response to disasters and its assistance to people impacted by disasters. Another important contribution of the agency is the building performance studies it conducts after disasters in order to better understand how natural and manmade events affect the built environment. These studies are conducted with the intent of reducing the number of lives lost to these events and minimizing the economic impact on the communities where these events occur. In addition, lessons learned are applied to the rebuilding effort after disasters to enhance the disaster-resistance of new building stock.

Since the mid-1980s, FEMA has sent MATs to Presidentially-declared disaster areas to evaluate building performance. The MAT studies the adequacy of current building codes, other construction requirements, and building practices and materials. Based on estimates from preliminary information of the potential type and severity of damage in the affected area(s) and the magnitude of the expected hazards, FEMA determines the potential need to deploy one or more MATs to observe and assess damage to buildings and structures, as caused by wind, rains, and flooding associated with the storm. These teams are deployed only when FEMA believes the findings and recommendations derived from field observations will provide design and construction guidance that will not only improve the disaster resistance of the built environment in the impacted state or region, but will also be of national significance to all disaster-prone regions.

1.3.1 Purpose of the MAT

In response to a request for technical support from FEMA Joint Field Offices in Montgomery, Alabama; Baton Rouge, Louisiana; and Jackson, Mississippi, FEMA's Mitigation Division deployed a MAT to Alabama, Louisiana, and Mississippi on September 26, 2005, to evaluate both building performance during Hurricane Katrina and the adequacy of current building codes, other construction requirements, and building practices and materials.

The flood levels for Hurricane Katrina far exceeded the current design flood event (i.e., 100-year base flood event), as illustrated on the FEMA Flood Insurance Rate Maps (FIRMs), along the entire Gulf Coast of Mississippi, and caused levee failures in Louisiana. The wind speeds from Katrina were less than the design speeds for most areas based on the model codes (International Building Code [IBC]/International Residential Code [IRC]) and on the engineering standard (ASCE 7) referenced in the building codes.

In New Orleans, FEMA was particularly interested in the long-term impacts of flooding on the structural and non-structural elements of buildings, as well as the floodplain management issues surrounding the levee breaches.

Except at a few locations along the Mississippi coast, Hurricane Katrina was below a design level wind event. The storm provided an opportunity to examine building elements that failed even when they shouldn't have and the team had hoped to determine how buildings built to new building codes performed in those areas that did experience near-design wind conditions. However, due to a limited stock of buildings built to the newer I-codes and the fact that many areas did not experience a design wind event, it was difficult to evaluate the effectiveness of the newer codes. The team was able to collect information about building damage that helps correlate wind speeds to building performance.

1.3.2 Team Composition

The MAT included FEMA Headquarters and Regional Office engineers and experts from the design and construction industry. Team members from FEMA's database of national experts included structural engineers, architects, wind engineers, civil engineers, coastal scientists, building code experts, and flood preservation specialists. In addition, representatives from the USACE, the National Institute of Standards and Technology (NIST), Oak Ridge National Laboratory (ORNL), the Association of Floodplain Managers (ASFPM), the International Code Council (ICC), and wind engineers and scientists from Texas Tech University, Louisiana State University (LSU), and University of Mississippi also participated.

In response to the unique situation presented by the flooding in New Orleans, FEMA deployed a portion of the MAT resources (hereafter referred to as the New Orleans Flood Team) to observe and assess damage to residential buildings and critical and essential facilities from the levee breach flooding associated with the storm. Therefore, the New Orleans Flood Team also included experts from the flood restoration industry.

1.3.3 Methodology

Aerial reconnaissance was performed by MAT members to assess overall building damage in the areas affected by Katrina on September 11 and 12, 2006. As shown in Figure 1-17, the aerial observations were conducted from Dauphin Island, Alabama, along the Mississippi Gulf Coast, over New Orleans, and inland over Slidell and Mandeville, Louisiana, and Hattiesburg, Mississippi.

Preliminary field investigations to assess building conditions in limited areas were conducted between September 17 and 21. Based on the data collected by the aerial reconnaissance and the preliminary field investigations, the area of focus for the full MAT was more fully defined. The full MAT was deployed on September 26 for 2 weeks, conducting extensive ground observations from Dauphin Island, Alabama, along the Mississippi Gulf Coast, through the City of New Orleans to Venice and Grand Isle, Louisiana, as shown in Figure 1-18.

The MAT focused their efforts in Alabama, Mississippi, and St. Tammany Parish, Louisiana, from September 26 through October 3, 2005. In Alabama, the team worked on the western coastline, including Dauphin Island, collecting building damage data. In Mississippi, the team worked in the state's three coastal counties performing ground inspections from Pascagoula in Jackson County to Waveland and Pearlington in Hancock County. Field investigations to assess building conditions in Louisiana began on October 4 and concluded on October 8, 2005. The team conducted ground inspections throughout the New Orleans area, including the City of New Orleans and Orleans Parish, as well as the nearby communities of Chalmette in St. Bernard Parish and Metairie in Jefferson Parish. Additionally, the team visited affected areas in Plaquemines and Lafourche Parishes.

Damages were observed to single- and multi-family buildings, manufactured housing, commercial properties, and historic buildings. In addition, critical and essential facilities, such as Emergency Operations Centers (EOCs), fire and police stations, hospitals, nursing homes, schools, and storm shelters were also evaluated in order to document building performance as well as loss of function from Hurricane Katrina. Documentation of observations is presented in this report. Photographs and figures are included to illustrate building performance in the wind field and surge areas produced by Katrina. The conclusions and recommendations of the MAT's findings will assist in minimizing damages from future hurricanes.

Figure 1-17.
Flight paths of aerial reconnaissance conducted by the MAT

(BASED ON http://www.nationalatlas.gov AND MAT GPS POINT LOCATIONS)

Figure 1-18. Locations visited by the MAT

(BASED ON http://www.nationalatlas.gov AND MAT OBSERVATIONS)