# *1. Introduction*

Hurricane Katrina was a long-lived hurricane that made landfall three times along the United States coast and reached Category 5 at its peak intensity. The storm initially developed as a tropical depression in the southeastern Bahamas on August 23, 2005. Two days later, it strengthened into a Category 1 hurricane a few hours before making its first landfall between Hallandale Beach and North Miami Beach, Florida. After crossing the tip of the Florida peninsula, Katrina followed a westward track across the Gulf of Mexico before turning to the northwest toward the Gulf Coast.

Hurricane Katrina made its second landfall as a strong Category 4 hurricane in Plaquemines Parish, Louisiana on August 29, 2005. Wind speeds of over 140 miles per hour (mph) were recorded in southeastern Louisiana and winds gusted to over 100 mph in New Orleans, just west of the eye. As Katrina made its third and final landfall four hours later along the Mississippi/Louisiana border, it was a Category 3 storm with wind speeds of approximately 125 mph. Hurricane-force winds extended up to 190 miles from the center of the storm and tropical storm-force winds extended for approximately 440 miles.

The strength and extent of Hurricane Katrina's wind field resulted in a storm surge greater than historical maximums. The combination of a storm surge of up to 30 feet, wave action, and high winds resulted in destruction of buildings and roads in the affected areas. Although recovery and reconstruction efforts will last several years, there is an urgent need for technical information to enable safer, sustainable redevelopment along the Gulf Coast.

The purpose of this project is to provide timely, up-to-date, and accurate coastal flood hazard information to local, regional, state, and Federal officials to guide reconstruction in the portions of the Gulf Coast most severely affected by Hurricane Katrina. This information is being provided in the form of high-resolution maps that show coastal flood impacts from Hurricane Katrina, as well as Advisory Base Flood Elevations (ABFEs) and wave impact zones. This report outlines the data sources and methods used to produce the Hurricane Katrina Surge Inundation and ABFE maps (herein referred to as the "Katrina Recovery Maps").

# *2. Methodology*

The Katrina Recovery Maps were developed for the three Mississippi counties bordering the Gulf of Mexico (Mississippi Sound): Hancock, Harrison, and Jackson. The maps provide the following essential elements of information:

- ✓ Preliminary surveyed coastal high water mark (HWM) flood elevations from Hurricane Katrina;
- ✓ Katrina coastal surge inundation limits; and
- ✓ ABFEs, including the estimated inland limit of wave impacts.

Although shown only on a regional overview map (described in Section 3) and not on individual Katrina Recovery Map panels, contours of the Katrina storm surge were also developed. The methods for generating each of these essential elements of information are discussed in greater detail below.

## 2.1 Hurricane Katrina Coastal High Water Mark Collection

Under separate task orders, field-based flagger and survey crews from URS and URS Team subconsultants, ESP and PBS&J, were deployed to interview residents, find evidence of coastal high water levels, take digital photographs, and survey coastal HWMs from Hurricane Katrina. Coastal HWMs included mud lines, water stains, debris, wrack lines, and eyewitness testimony.

The coastal HWM flagging crews received notice to proceed on August 30, 2005. An organization and training meeting was held in Tallahassee, Florida, on September 1, 2005. Due to ongoing recovery efforts, the concern for obtaining gasoline and other essential supplies, and the lack of lodging, all crews were place on standby for later deployment. Once conditions improved, the flaggers were deployed along the Mississippi coast on September 12, 2005.

For each HWM, the flaggers completed a form that contained detailed information about the mark. To the extent possible, field crews noted the coastal flooding characteristics captured by the coastal HWM, including storm surge, wave runup, and wave height. These designations represent the field crew's best estimate of these characteristics based on a combination of physical flood evidence and interviews with witnesses at the time of collection. These characteristics are described as follows:

- Surge - represents the rise in the normal water level, also called stillwater flooding
- Wave runup - represents the height of water rise above the stillwater level due to water rush up from a breaking wave
- Wave height - represents the coastal HWM elevation due to more direct wave action

Typically, storm surge coastal HWMs are associated with a slow-rising flood that causes more water damage than structural damage. Wave height usually results in a higher water mark elevation than storm surge alone. All attempts were made to flag storm surge elevations, but in areas where storm surge characteristics were not obvious, wave runup or wave height may have been captured. For example, witnesses might claim the flooding was associated with a storm surge when in fact the flooding was from wave runup or riverine flooding.

The survey crews followed the flaggers and used static Global Positioning System (GPS) methods to determine an accurate elevation for each coastal HWM. Since static GPS requires an area with no tree cover to return an accurate result, in some cases it was necessary perform a short level loop survey from the GPS point to the coastal HWM. Coastal HWM locations were surveyed horizontally in the North American Datum of 1983 (NAD 83), State Plane – Mississippi East (2301) feet, and vertically in the North American Vertical Datum of 1988 (NAVD 88) US survey feet. Coastal HWM locations have been surveyed to within accuracies of ±0.25 foot vertically and ±10 feet horizontally, with a 95% confidence level.

A more detailed discussion of the coastal HWM collection and final results will be presented in a separate report currently under development.

## 2.2 Hurricane Katrina Storm Surge Inundation Mapping

Coastline flood inundation limits were created for the Mississippi coastal counties by mapping the coastal HWM elevations onto digital, pre-storm topographic data. These inundation limits represent the estimated inland extent of flooding caused by the Hurricane Katrina storm surge.

The HWMs surveyed by URS and its subconsultants were imported into a Geographic Information System (GIS) as points and pre-processed prior to analysis and mapping. The pre-processing of the HWMs included the Anselin Local Moran's I statistical analysis to identify those points that did not match the general trend of elevations in each point's immediate area. These HWMs were not used for the inundation mapping. In addition, HWMs identified as including wave effects, described as having poor quality, or that had a low confidence were also excluded from the surge inundation mapping. Once the HWMs to be used were identified, a three-dimensional surface was created using a standard interpolation function (Second Power Inverse Distance Weighting).

In a parallel effort, a digital elevation model (DEM) was developed for this project using pre-Katrina topographic data. EarthData, a firm working under contract to the National Oceanic and Atmospheric Administration's (NOAA's) Coastal Services Center, used Light Detection and Ranging (LIDAR) technology to collect the topographic data in 2004. The LIDAR data for Harrison County were post-processed by EarthData to achieve bare-earth elevations in 2004, and the data for Hancock and Jackson Counties were post-processed in October 2005. These topographic data are referenced to NAVD 88.

To create the Hurricane Katrina surge inundation limit, the interpolated HWM raster surface was intersected with the LIDAR DEM and then smoothed using PAEK smoothing algorithms. The inundation limit was then refined to remove small-scale, isolated areas of inundated and non-inundated terrain based on knowledge of overland surge propagation and engineering judgment.

## 2.3 Hurricane Katrina Surge Elevation Contour Mapping

In addition to mapping inundation limits, the Hurricane Katrina HWM data were used to contour the elevation of the storm's surge across the coastal areas of the Hancock, Harrison, and Jackson Counties. These contours, provided in 1-foot increments, show the geographic variability of the storm's surge. To create the contours, the coastal HWMs were examined to find patterns in the coastal storm surge as it pushed against the open coast and into the inland bays. The known path and landfall location of Hurricane Katrina, together with the knowledge of how storm surge propagates inland, allowed surge contours to be drawn across the areas where the coastal HWMs indicate a change in storm surge elevation. Engineering judgment had to be applied in some locations to allow the contours to "step" up or down at 1-foot intervals.

Because of the inherent uncertainty in and the random and irregular spacing of coastal HWMs, the surge contours represent a generalized maximum storm surge elevation, and required professional judgment in their creation. Within certain surge contours, coastal HWMs may be higher or lower than the contours if they did not fit the overall pattern discerned from the coastal HWMs. Local wave effects (wave heights and wave runup), which increase the total water surface above the surge elevation, were not considered in this contouring effort. Coastal HWMs that include wave effects may be several feet higher than the surge contours in a particular area.

The results from the surge elevation contouring have been provided to two other Federal agencies, the U.S. Geological Survey (USGS) and NOAA, for review and comment. Predictive numerical models of surge flooding, such as Hurricane Katrina forecasts from NOAA's Sea, Lake and Overland Surge from Hurricane (SLOSH) computer model, were used qualitatively to help refine the surge contours in areas of complex topographic and bathymetric changes. These reviews were not complete at the time this report and the maps were prepared. In addition, NOAA will be developing hindcasts of Hurricane Katrina's surge in the coming months. Consequently, the results presented should be viewed as preliminary and subject to update as additional data become available.

## 2.4 Advisory Base Flood Elevations

Until more detailed coastal flood risk data are developed, FEMA developed ABFEs for each coastal Mississippi county to provide communities with advised building elevations for use in the reconstruction process. ABFEs are based on a new flood frequency analysis that takes into account Hurricane Katrina as well as additional tide and storm data from other events that have occurred during the 25 years since the existing Flood Insurance Rate Maps (FIRMs) were developed. Specifically, tide gage data and estimated HWMs across the three-county project area were used in the analysis to determine updated 1%-annual-chance stillwater elevations (SWELs).

In a typical FEMA coastal flood hazard study, numerical surge models are used to produce detailed SWEL values mile by mile across a study area spanning several hundred miles of shoreline. Many tide

gages failed or malfunctioned during Hurricane Katrina, limiting the number of locations for which new advisory SWELs could be calculated in the new flood frequency analysis to roughly one per coastal county. Wave setup, a momentum flux phenomenon that causes an increase in stillwater elevation on the exposed open coast, was also calculated in the frequency analysis. This allowed FEMA to provide one updated SWEL for open coast areas that included wave setup, and another SWEL for back bay areas that excluded wave setup. Thus, the advisory SWELs for each county are as follows:

| **Hancock:** | | **Harrison:** | | **Jackson:** | |
|---|---|---|---|---|---|
| Open Coast: | 20 feet | Open Coast: | 18 feet | Open Coast: | 14 feet |
| Back Bay: | 18 feet | Back Bay: | 16 feet | Back Bay: | 12 feet |

Coastal Base Flood Elevations (BFEs) shown on FIRMs reflect 1%-annual-chance SWELs plus local wave effects, such as wave heights and wave runup. Detailed coastal modeling using FEMA's Wave Height Analysis for Flood Insurance Studies (WHAFIS) and RUNUP (or comparable models) is required to develop BFEs. Given the expedited schedule for this recovery mapping, a simplified method had to be used to estimate wave effects that could be added to the advisory SWEL. The equation below, which is based on the depth-limited wave height calculation used in WHAFIS, was applied to calculate ABFEs for Mississippi:

ABFE = Advisory SWEL + Wave Height

Where Wave Height = ½ stillwater flooding depth (relative to the ground surface)

More information on how the advisory SWELs were developed and how to determine advisory flood elevations at a site is provided in FEMA Flood Recovery Guidance documents prepared for each county. These documents can be found at the following FEMA Web site: www.fema.gov/hazards/floods/recoverydata/katrina_ms_resources.shtm.

To map the ABFEs, flood depths were calculated by comparing the advisory SWELs against the LIDAR topographic data, with wave effects estimated using the flood depth, as prescribed by the ABFE equation listed above. The resulting ABFEs were then mapped in 1-foot intervals across the project area and smoothed with the same PAEK algorithms used in the inundation mapping. FEMA also determined that within the area covered by these ABFEs, there is a zone where waves are 1.5 feet or greater – large enough to cause significant damage to structures. One of the ABFE contours, shown in red on the Katrina Recovery Maps, represents this estimated inland limit of wave action. This line roughly corresponds to where the wave height is 1.5 feet.

In general, the ABFE equation was used directly to calculate the ABFEs in all areas where coastal surge exceeded the 1%-annual-chance flooding shown on the current effective FIRMs. The timeframe of the project did not allow for a detailed technical assessment of wave impacts throughout the three-county area. Therefore, wave heights were included in nearly all mapped areas. While this is a conservative estimate of flood risk, it is recognized that there are likely to be areas where the open water fetch, water depth, and other factors may inhibit development of waves to the maximum height reflected by the ABFEs.

While the project time frame did not permit detailed assessments of all areas for potential wave generation, a limited review revealed five relatively large areas, primarily in areas of overland flooding in protected, back bays and associated tributaries in Harrison and Jackson Counties, where it was readily apparent that the water depth and open water fetch was unlikely to permit significant wave generation. Therefore, wave heights were removed from the ABFEs in these areas, leaving only stillwater flood levels to be shown.

Another implication of applying a single set of SWELs for each county was the need to address incongruous information in areas of transition between different SWEL values and their associated ABFEs. This occurs at county boundaries and where open coast SWELs give way to back bay SWELs. In the latter case, engineering judgment concerning wave setup, including how and where its effects can be diminished or eliminated, was used to determine open coast to back bay transition points. Generally, the transition was placed wherever there was a barrier of sufficient elevation to cause shoaling and breaking waves. This barrier can be natural, such as high ground parallel to the Mississippi Sound shoreline on each side of a bay (e.g., St. Louis Bay, Biloxi Bay). The barrier can also be man-made, such as Highway 90 or the CSX Railroad track bed. Hurricane Katrina HWMs in the vicinity of Highway 90 in Jackson County, for example, showed that stillwater elevations were only 1 to 2 feet above the road, which is shallow enough to cause waves to break. HWMs farther north show a decrease in stillwater level comparable to the 2-foot decrease between the advisory open coast and back bay SWELs, suggesting that wave setup effects were lost at the highway. Without more detailed modeling and analysis, the natural and man-made barriers were chosen and mapped as the transition points (breaklines) in the ABFE mapping. This breakline is labeled “Open Coast” and “Back Bay” on the Katrina Recovery Maps. The ABFEs will decrease by 3 feet between the open coast and back bay to reflect the estimated decrease in stillwater elevations and wave effects.

## *3. Presentation of Results*

The results of the technical analysis are presented in a series of Katrina Recovery Maps, on a regional overview map, and in the form of GIS files. Each of these products is summarized below:

- Hurricane Katrina Surge Inundation and ABFE Maps (228 panels) – When plotted at their native size (ANSI D, 34 inches by 22 inches), the data on these maps are shown at a scale of 1 inch = 500 feet. Each map depicts the coastal HWMs used in the inundation mapping, the surge inundation limit, and ABFEs on a base map of aerial photographs collected by the U.S. Department of Agriculture (USDA) National Agriculture Imagery Program in 2004.
- Overview Map (1 panel) – This map, which covers the entire three-county study area, shows the location of HWMs used in the inundation limit mapping, the inundation limits, storm surge elevation contours, and the numbered paneling scheme for the Katrina Recovery Maps (see Figure 1).
- GIS Data – GIS-compatible data for the following themes are provided for download on FEMA’s Katrina Recovery Map site (www.fema.gov/hazards/floods/recoverydata/katrina_ms_gis.shtm): HWMs, including both the points used in the inundation mapping and points with wave effects or quality concerns; surge inundation limits; surge elevation contours; and ABFE contours, including open coast to back bay breaklines.

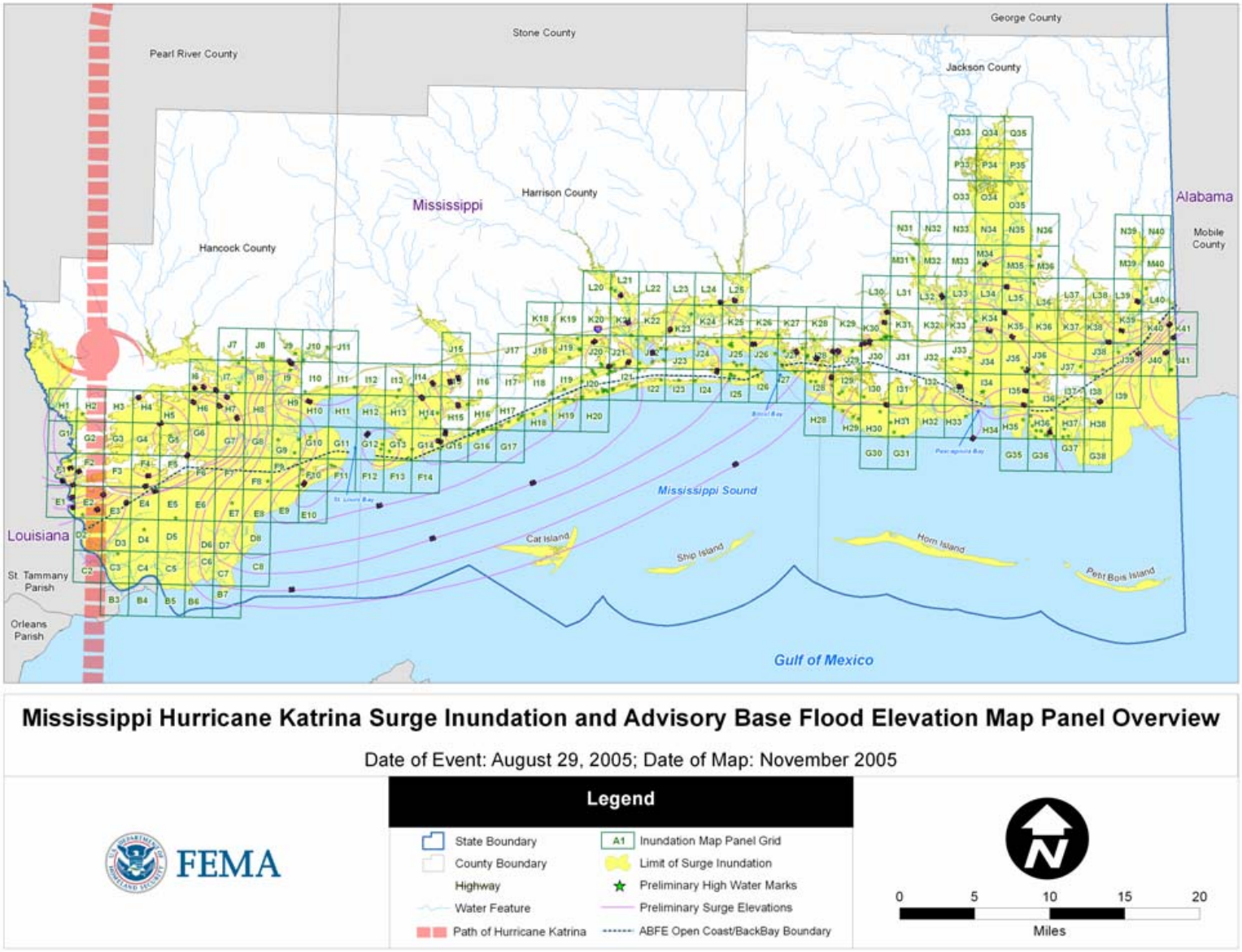


Figure 1 – Regional overview map of Katrina Recovery Map paneling scheme and surge elevation contours. Map also available at: www.fema.gov/hazards/floods/recoverydata/pdf/katrina_ms_overview.pdf.

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The USGS Water Resources Division at the Jackson, Mississippi office and National Headquarters in Reston, Virginia office provided valuable review comments on the Hurricane Katrina HWM data, as well as comments on proposed Hurricane Katrina surge inundation mapping methodology and draft datasets. The USGS also flagged a number of coastal HWMs in the three-county region. Although these points could not be included quantitatively in the inundation mapping, the data were used qualitatively to assess and refine the inundation limits and surge elevation contours.

NOAA provided technical assistance concerning recent efforts by the National Ocean Service's National Geodetic Survey to re-level many of the benchmarks in the Gulf Coast region, which helped ensure that the high-water mark data collected by FEMA and other agencies were properly referenced to the most current elevation datum. In addition, tide gage data for the flood frequency analysis was provided by the NOAA National Ocean Service's Center for Operational Oceanographic Products and Services (CO-OPS).

The National Weather Services' National Hurricane Center (NHC) provided maximum storm surge forecast products for every storm making landfall during the 2005 hurricane season, including Hurricane Katrina. The NOAA National Ocean Service's Coastal Services Center (CSC) has been coordinating the effort to synthesize flood-related data along the Gulf Coast in the wake of Hurricane Katrina. CSC has acted in a coordination role with FEMA Region IV and the USGS to make sure HWM data were reviewed by the above NOAA offices for consistency. CSC has also evaluated the HWM data and the recovery mapping methods, providing many helpful comments.