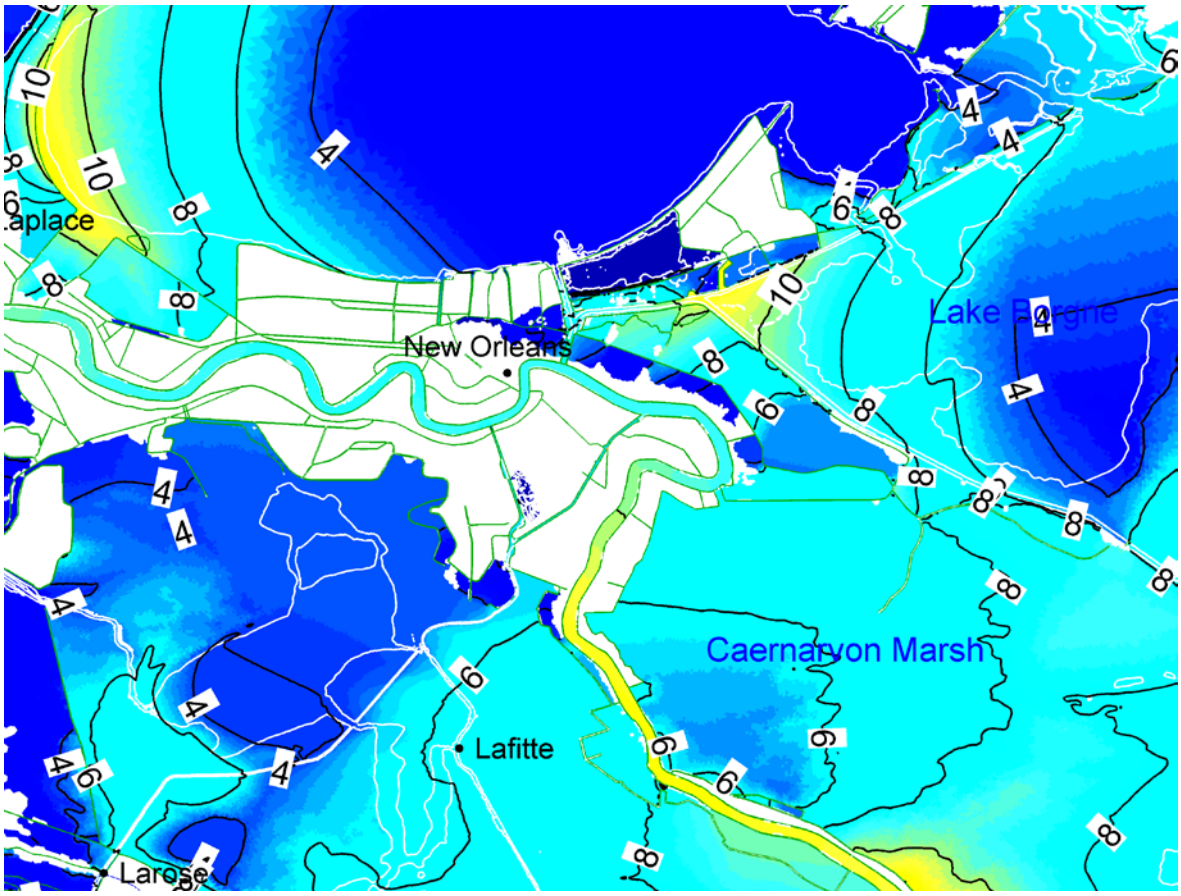
An Evaluation of Storm Surge in Areas Outside the Greater New Orleans Hurricane and Storm Damage Risk Reduction System (HSDRRS)



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1. Executive Summary

In this analysis, a series of historical and synthetic storms of high impact to the Louisiana Gulf Coast were modeled. The purpose of this modeling is to assess the impacts to surge levels due to construction of the Greater New Orleans (GNO) Hurricane and Storm Damage Risk Reduction System (HSDRRS) on communities inside and outside the system. The Greater New Orleans HSDRRS consists of the Lake Pontchartrain and Vicinity (LPV) and West Bank and Vicinity (WBV) 100-year projects as constructed post-Katrina; hereinafter referred to as the GNO HSDRRS. The analysis evaluates the projected storm surge levels in areas outside the GNO HSDRRS as the levee system existed in the years 1965 (pre-Betsy, pre-federal levees), 2005 (pre-Katrina) and 2012 (post-GNO HSDRRS construction). The analysis describes and evaluates the past, present and potential cumulative storm surge impacts of the completed GNO HSDRRS on the surrounding areas.

The modeled historical storms include Hurricanes Betsy, Camille, Katrina, Rita, Gustav, Ike and Isaac. Ten (10) synthetic storms that are a subset of the suite of 152 storms processed for the hydraulic design of GNO HSDRRS were also evaluated. These storms are simulated on three different versions of the SL15 Advanced Circulation Model (ADCIRC) grid. The SL15 grid was originally developed at the Notre Dame Computational Hydraulics Laboratory. The SL15 grid was the primary ADCIRC grid used to model a suite of 152 synthetic storms to aid in the hydraulic design of the GNO HSDRRS. The SL15 has been utilized and validated for many storm surge studies throughout Southeast Louisiana, including hindcasts of Hurricanes Katrina and Rita.

One recent evaluation which used the SL15 ADCIRC grid was conducted immediately after Hurricane Isaac in 2012. The February 2013 published report titled “Hurricane Isaac With and Without 2012 100-Year HSDRRS Evaluation” provides a complete analysis of how the GNO HSDRRS changed storm surge development and impacted communities outside the system. When compared to 2005 conditions, the 2012 GNO HSDRRS includes canal closures along Lake Pontchartrain, the Inner Harbor Navigation Canal (IHNC) Surge Barrier and Seabrook Closure, the West Closure Complex, and many upgraded levee and floodwalls. During Hurricane Isaac, these features prevented interior flooding, forcing some additional piling of water on the exterior of the system. The purpose of modeling Hurricane Isaac with and without the GNO HSDRRS was to document the characteristics and impacts of the storm, including an assessment of any GNO HSDRRS-induced impacts to the communities located outside the risk reduction system. The analysis concluded that the impacts to the surrounding communities would have been similar for the with and without GNO HSDRRS conditions.

In this analysis, we expand the post-Isaac evaluation by processing 16 more storms, including a series of high impact historical storms and a series of high impact synthetic storms. A total of 17 storms were run on three different versions of the SL15 grid. Each version of the grid represents a different year with different levee heights and alignments (1965, 2005, and 2012). The following describes the three versions of the SL15 grid used in this analysis:

SL15-2012. This version of the SL15 grid includes all of the updated features of the GNO HSDRRS, including the IHNC Surge Barrier, the West Closure Complex, the Lake Pontchartrain canal closures (at London Avenue, Orleans Ave and 17th Street), the IHNC Seabrook Closure, and upgraded levee and floodwalls throughout the system.

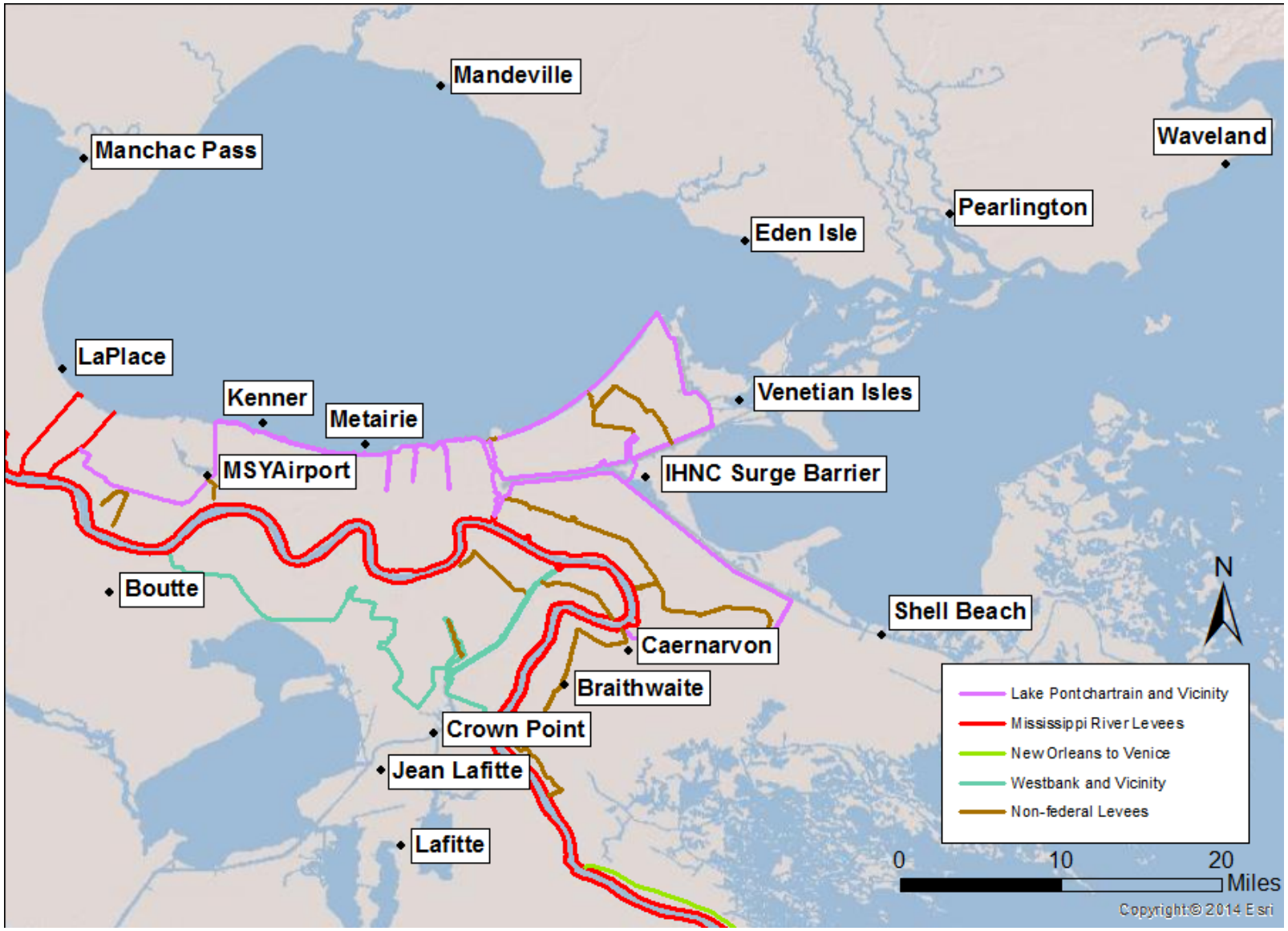
SL15-2005. This version of the grid represents conditions immediately prior to Hurricane Katrina. The grid includes various features of the 1960s-era system. This grid was used extensively to hindcast Hurricanes Katrina and Rita of the 2005 season.

SL15-1965. In this version of the SL15 grid, levee heights are reduced for the New Orleans East, St. Bernard, and portions of the New Orleans metropolitan area to project construction grades present in 1965 (pre-Betsy conditions). In these areas, this grid represents a condition without federal levees in place. Prior to federal participation, local levees existed at many of these locations. In other areas, including a large portion of the WBV project area, no levees existed prior to federal involvement. The 1965 grid is set up to evaluate the impact to communities outside the GNO HSDRRS due to federal levee construction after Hurricane Betsy.

When comparing the storm surge model output from the SL15-1965 grid to SL15-2012 grid, the results show a larger impact to peak water levels at areas immediately adjacent to the GNO HSDRRS. For example, at the present location of the IHNC Surge Barrier, the peak water level produced on the SL15-2012 grid is 4.56 ft higher than the water level produced on the SL15-1965 grid for one synthetic storm S023. At Venetian Isles, New Orleans, LA, which is located immediately outside of the New Orleans East area, the peak water level produced on the SL15-2012 grid is 2.17 ft higher than the water level produced on the SL15-1965 grid for storm 023. At Eden Isle, Slidell, LA, which is located about 7 miles from the eastern most portion of GNO HSDRRS, the peak water level is 0.23 ft higher than the peak water level produced on the SL15-1965 grid for storm S023. The impacts to peak water levels due to the levee system that existed in 1965 pre-Betsy and the GNO HSDRRS vary by storm and location. The impacts are greatest in the immediate vicinity of the GNO HSDRRS; impacts diminish as the distance from the GNO HSDRRS increases.

In the group of storms modeled for this analysis, the storm which produces the greatest impact at Eden Isle is synthetic storm S094. At this location, for this storm, a 0.48 ft rise in water level (an increase of 4.6%) can be attributed to construction of the 1965 pre-Betsy levees around New Orleans East and St. Bernard and construction of the GNO HSDRRS. Storm S094 is an extreme storm which produces approximately 500-year surge values at portions of GNO HSDRRS. In the 1965 and 2005 conditions, the St. Bernard, New Orleans East, and Orleans Metro areas are inundated for storm S094. In the 2012 condition, no overtopping is modeled. The displaced water causes an increase in surge on the GNO HSDRRS exterior.

With additional post processing of peak surge results, we compare peak water levels produced on the SL15-1965 and SL15-2012 grids and conduct a regression analysis to estimate changes to surge-frequency for the 50-year, 100-year, 200-year and 500-year return periods at various locations of interest, pictured in the map below. When assessing the impacts to surrounding communities, it is useful to compare surge statistics, rather than focusing on effects on a storm–by-storm basis. The regression analysis shows the 100-year surge produced on the SL15-1965 grid at the present location of the IHNC Surge Barrier is estimated to be 14.7 ft NAVD88 2004.65. At this location, the 100-year surge produced on the SL15-2012 grid is 17.5 ft. NAVD88. At the IHNC Surge Barrier, a 2.8 ft increase to 100-year surge levels can be attributed to the combined effects of 1965 pre-Betsy levee system and the GNO HSDRRS. The regression analysis shows a 1.2 ft increase to the100-year water level at Venetian Isles, New Orleans, LA, and a 0.2 ft increase to the 100-year water level at Eden Isle, Slidell, LA. At Mandeville, LA, 100-year water levels decrease -0.1 ft because the levees constructed around New Orleans east reduce flow into Lake Pontchartrain. The impacts to surge frequency vary by location, with the largest impacts in immediate vicinity of the GNO HSDRRS. The following table provides detailed output at Metairie, Kenner, Caernarvon, IHNC Surge Barrier, Shell Beach, Venetian Isles, Eden Isle, Pearlington, Manchac Pass, Mandeville, LaPlace, New Orleans International (MSY) Airport, Braithwaite, Jean Lafitte, Lafitte, Crown Point, Waveland, and Boutte (the following figure and table are also provided in the main body of the report).



Map of selected model output locations in SE Louisiana

			Sl15-2012 Stage-frequency (ft. NAVD88 2004.65)				Sl15-1965 Est. Stage-frequency (ft. NAVD88 2004.65)				Difference (ft) and Percent Difference for various return periods							
Location	Long	Lat	50 YR	100 YR	200 YR	500 YR	50 YR	100 YR	200 YR	500 YR	50 Yr Dif	50 Yr %Dif	100 Yr Dif	100 Yr %Dif	200 Yr Dif	200 Yr %Dif	500 Yr Dif	500 Yr %Dif
Metairie	-90.144	30.028	7.8	9.1	10.2	11.5	7.9	9.3	10.5	12.0	-0.1	-1%	-0.2	-2%	-0.3	-3%	-0.5	-4%
Kenner	-90.236	30.047	7.9	9.1	10.2	11.3	7.9	9.0	10.1	11.1	0.0	0%	0.1	1%	0.1	1%	0.2	2%
Caernarvon	-89.906	29.842	14.6	17.7	19.8	21.9	14.0	16.9	18.8	20.8	0.6	4%	0.8	5%	1.0	5%	1.1	5%
IHNC Surge Barrier	-89.891	29.999	14.6	17.5	19.5	21.5	12.6	14.7	16.2	17.5	2.0	16%	2.8	19%	3.3	20%	4.0	23%
Shell Beach	-89.678	29.856	10.7	12.5	14.1	16.0	10.0	11.6	13.0	14.6	0.7	7%	0.9	8%	1.1	8%	1.4	10%
Venetian Isles	-89.807	30.069	11.7	13.7	15.3	16.9	10.7	12.5	13.9	15.3	1.0	9%	1.2	10%	1.4	10%	1.6	10%
Eden Isle	-89.801	30.212	8.6	10.5	12.2	13.9	8.5	10.3	12.0	13.7	0.1	1%	0.2	2%	0.2	2%	0.2	1%
Pearlington, MS	-89.616	30.236	11.6	13.9	16.0	18.4	11.2	13.4	15.4	17.6	0.4	4%	0.5	4%	0.6	4%	0.8	5%
Manchac Pass	-90.397	30.286	7.1	8.3	9.3	10.3	7.1	8.4	9.5	10.5	0.0	0%	-0.1	-1%	-0.2	-2%	-0.2	-2%
Mandeville	-90.075	30.351	8.2	9.6	10.7	11.8	8.2	9.7	10.9	12.2	0.0	0%	-0.1	-1%	-0.2	-2%	-0.4	-3%
LaPlace	-90.416	30.096	7.3	9.6	11.3	13.0	7.3	9.6	11.3	12.9	0.0	0%	0.0	0%	0.0	0%	0.1	1%
MSYAirport	-90.285	30.001	9.3	11.0	12.3	13.8	9.1	10.6	11.7	13.0	0.2	2%	0.4	4%	0.6	5%	0.8	6%
Braithwaite	-89.963	29.811	14.4	17.7	20.0	22.1	13.8	17.0	19.2	21.2	0.6	4%	0.7	4%	0.8	4%	0.9	4%
Jean Lafitte	-90.129	29.734	5.3	7.0	8.4	9.9	5.2	6.8	8.1	9.5	0.1	2%	0.2	3%	0.3	4%	0.4	4%
Lafitte	-90.112	29.667	6.0	7.8	9.3	11.0	6.0	7.7	9.1	10.7	0.0	0%	0.1	1%	0.2	2%	0.3	3%
Crown Point	-90.081	29.769	5.7	7.5	9.1	10.9	5.3	6.9	8.3	9.9	0.4	8%	0.6	9%	0.8	10%	1.0	10%
Waveland	-89.368	30.280	13.1	15.6	17.8	20.2	12.9	15.4	17.6	20.0	0.2	2%	0.2	1%	0.2	1%	0.2	1%
Boutte	-90.374	29.895	3.2	3.6	4.0	4.3	3.2	3.6	4.0	4.2	0.0	0%	0.0	0%	0.0	0%	0.1	2%

Summary of changes to stage-frequency at various output locations

2. Storm Surge Modeling Methodology

2.1 Introduction

This section describes the methodology used to model the 7 historical storms (Betsy, Camille, Katrina, Rita, Gustav, Ike and Isaac) and 10 synthetic storms. First we describe how the 10 synthetic storms were picked from the full suite of 152. Storms were selected to cover a parameter space representative of the historical record. We then describe and compare the individual storm characteristics for all 17 storms.

The next section describes the methodology used to create the SL15-1965 grid using data from 1960s-era General Design Memorandums (GDM) for the LPV construction that was authorized after Hurricane Betsy in 1965. These documents contain pre-construction ground elevations and elevations of the levees that were in place before the corps began construction of the federal levees after Betsy in New Orleans East and St. Bernard.

The next section describes sources of wind and pressure fields for the different historical storms. Prior to presenting results, the final section in the methodology chapter describes some assumptions and limitations of the overall analysis.

2.2 Synthetic Storms

The left portion of Table 1 displays stage-frequency data developed for the design of GNO HSDRRS at Lake Pontchartrain, Lake Borgne and the West Bank for 50-year, 100-year and 500-year return periods. This data is based on the suite of 152 ADCIRC runs completed for the IHNC Surge Barrier project, referred to as the “IHNC 152”. At each location, storms were selected to match as closely as possible the 50-year, 100-year and 500-year surge values. The right portion of Table 1 displays the selected synthetic storms and the associated storm surge value. For example, at Lake Borgne, storm 014 produces a 50-year surge, storm 077 produces a 100-year surge, and storm 094 produces a 500-year surge. One extra storm was modeled (storm 008). Storm 008 was selected at random from the suite of 152. Storm 008 produces less than 50-year water levels at Lake Pontchartrain, Lake Borgne, and the West Bank.

Table 1 Synthetic Storm Selection

Stage-Frequency					Selected Synthetic Storms					
Location	Qpt	50yr (ft. NAVD88)	100yr (ft. NAVD88)	500yr (ft. NAVD88)	**~50yr**	surge elevation (ft. NAVD88)	**~100yr**	surge elevation (ft. NAVD88)	**~500yr**	surge elevation (ft. NAVD88)
Lake Pontchartrain	Q-149	7.6	8.8	11.4	S023	7.4	S146	8.7	S085	11.1
Lake Borgne	Q-305	14.6	17.5	21.5	S014	14.0	S077	16.4	S094	20.6
West Bank	Q-466	5.7	7.5	11.0	S012	5.5	S126	7.3	S069	10.4

2.3 Historical Storms

Table 2 summarizes the dates of the historical storms evaluated in this analysis. These storms were selected based on their relatively high impact to Southeast Louisiana and the Gulf Coast. Figure 1 displays the tracks of the historical storms, including Ike (blue), Rita (magenta), Gustav (green), Betsy (light blue), Isaac (black), Katrina (red), and Camille (orange). The 10 synthetic storms are plotted as light grey lines.

Table 2 Historical Storm Selection

Storm Name	Date
Betsy	9/8/1965 to 9/11/1965
Camille	8/16/1969 to 8/19/1969
Katrina	8/25/2005 to 8/31/2005
Rita	9/18/2005 to 9/24/2005
Gustav	8/26/2008 to 9/4/2008
Ike	9/5/2008 to 9/14/2008
Isaac	8/24/2012 to 9/1/2012

Figure 2 displays the windspeed versus distance from landfall. In this case, landfall is defined as the location where the track intersects the coastline which is drawn as a white line in Figure 1. The windspeeds of the past historical storms vary from category 1 to category 5 on the Saffir-Simpson scale. The synthetic storms vary from a category 1 to category 5. Intensification and decay rates of the synthetic storms are consistent with that of the historical storms. Figure 3 displays the storm central pressures versus distance from landfall location. The central pressures of some of the more intense synthetic storms are 900mb, which is lower than any of the selected historical storms. The central pressure and windspeeds of the synthetic storms are consistent with the historical storms.

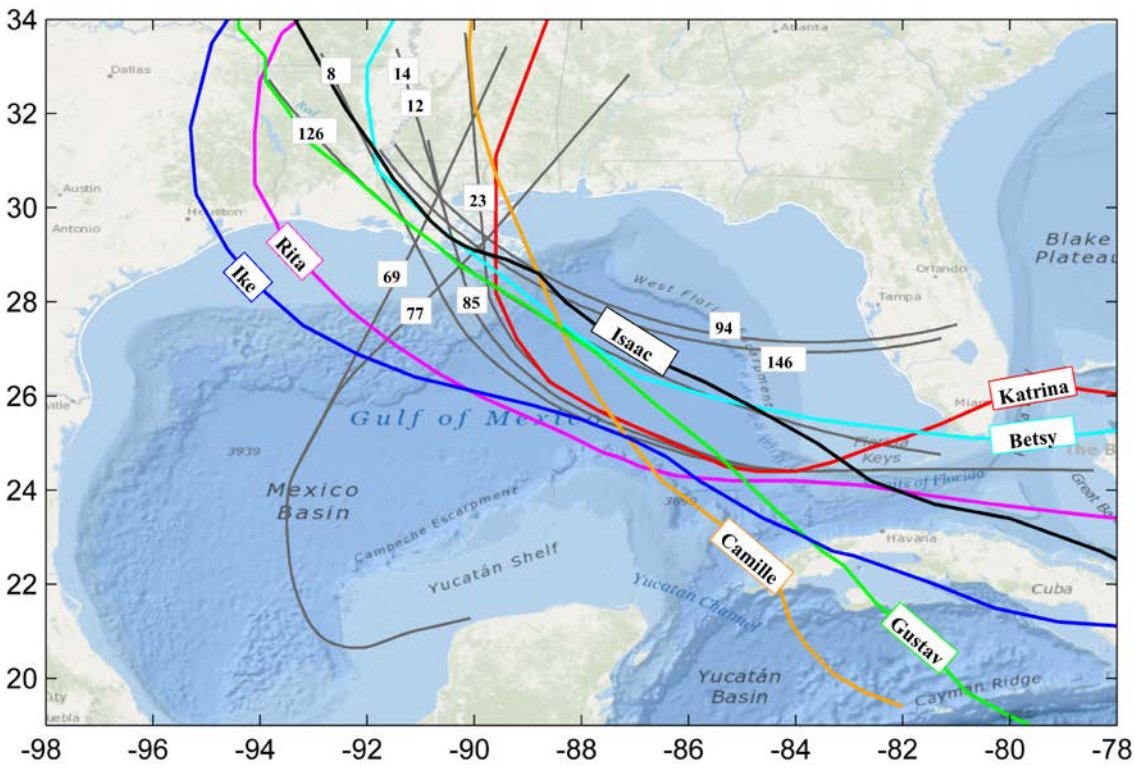


Figure 1 Storm tracks of past and synthetic storms.

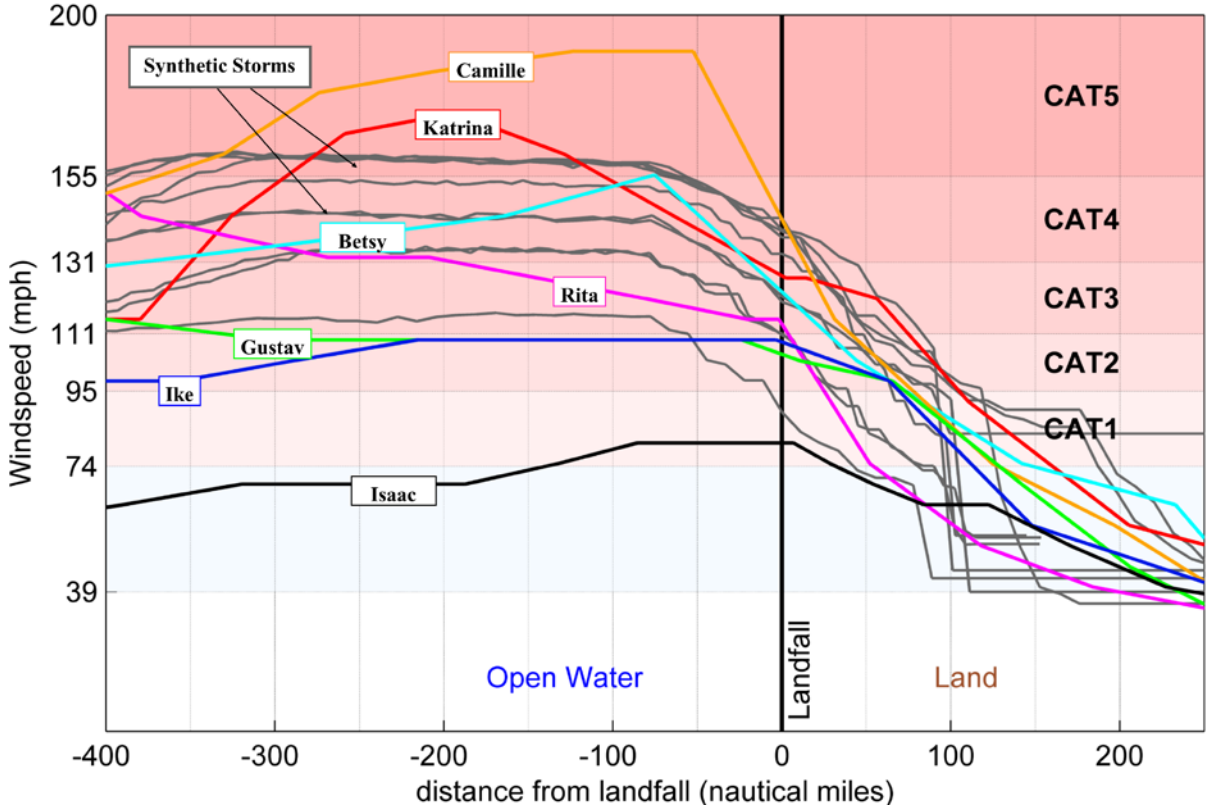


Figure 2 Storm Windspeed vs. Distance from Landfall

Figure 4 displays the storm forward speed versus distance from landfall for the historical and synthetic storms. The 10 selected synthetic storms have two forward speed values at approximately 7 or 12.5 mph. There is more variation within the historical records, however the synthetic storm forward speeds are representative of the historical record. Slower storm forward speeds can produce higher surge values, particularly in deltaic and inland regions. Isaac has the slowest storm forward speed in the selected historical storms. The slow forward speed is one characteristic of Hurricane Isaac which facilitated some of the highest ever observed inland flooding, despite being a category 1 storm on the Saffir-Simpson scale.

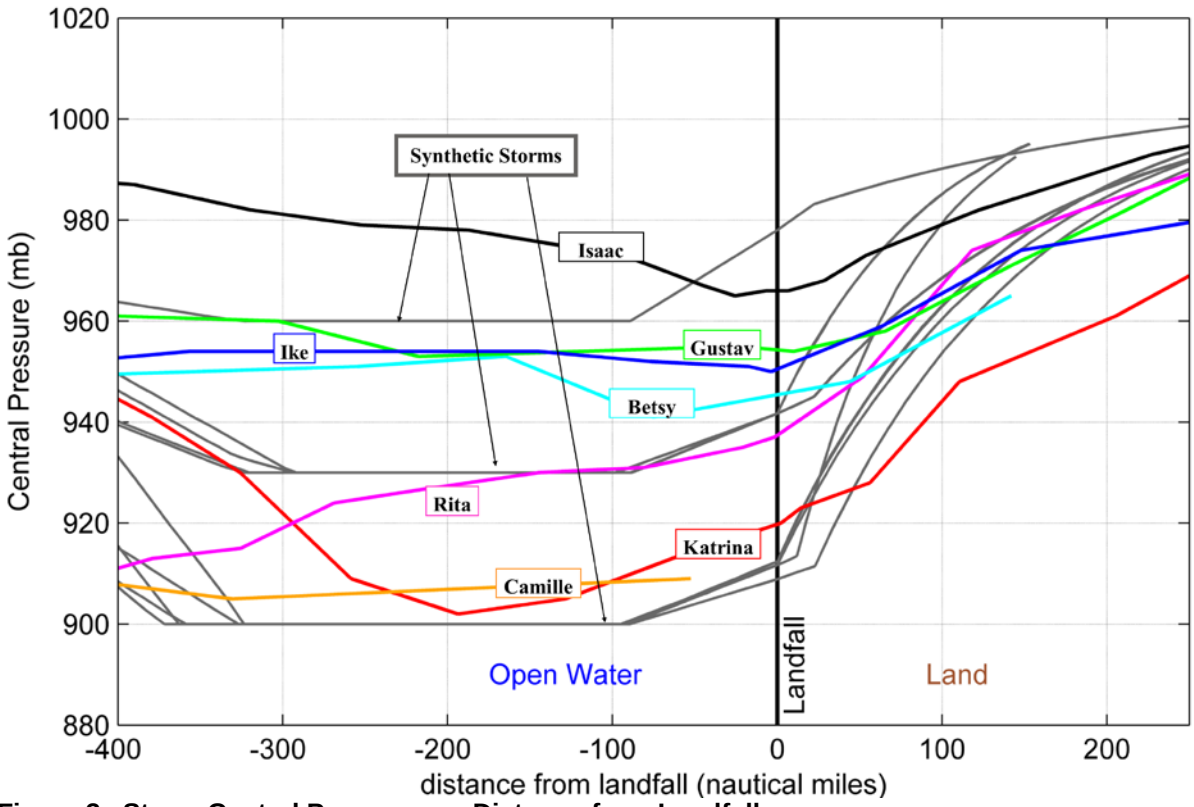


Figure 3 Storm Central Pressure vs. Distance from Landfall

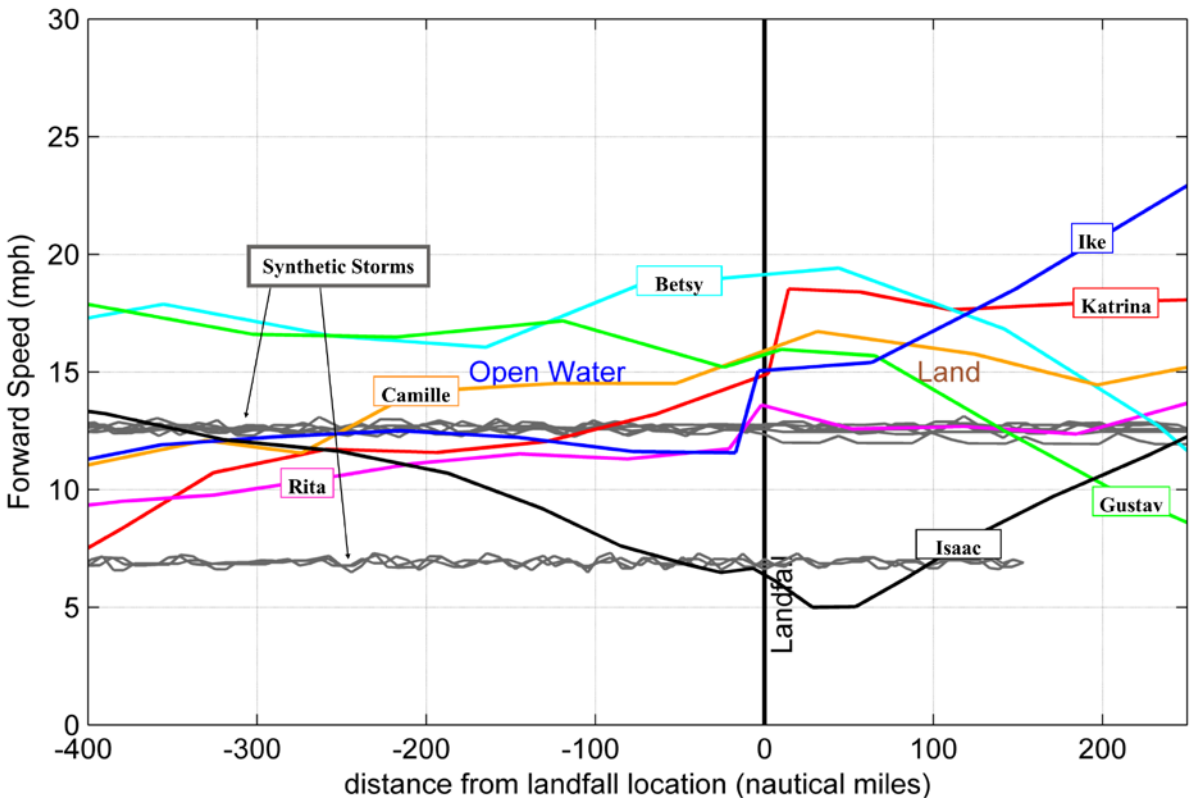


Figure 4 Storm Forward Speed vs. Distance from Landfall

In conclusion, the characteristics of the selected storms are consistent with the historical record. The selected group of storms covers a plausible parameters space of storm characteristics. It is important to note that the selected storms are only a sample, and do not completely encompass the full range of possibilities.

2.4 Grid Modifications

In the 2013 Isaac analysis, two versions of the grid were developed. The first one contained levee and floodwall elevations as they existed at the timing of Hurricane Katrina, or roughly 2005. In this analysis we will call this grid SL15-2005. This grid was developed for hindcasting Hurricanes Katrina and Rita.

The second version of the SL15 grid developed contains all of the GNO HSDRRS features including the IHNC Surge Barrier, the IHNC Seabrook Closure, and the West Closure Complex. Levee and floodwall elevations are set to 2013 as-built surveys. In this analysis, we will call this grid the SL15-2012.

For this analysis, the SL15 grid was modified to remove portions of the levee alignment, effectively lowering elevations around St. Bernard, New Orleans East, and portions of the New Orleans metropolitan area. This grid represents the levees that existed prior to federal levee construction (pre-Betsy). The purpose of this modification is to determine changes in surge patterns and development at Lake Borgne and Lake Pontchartrain,

comparing 1965 pre-Betsy levees to the GNO HSDRRS levees. The analysis will show whether or not levees that existed in 1965 pre-Betsy and the GNO HSDRRS changed to way water flows into Lake Pontchartrain. This version of the grid is called the SL15-1965. To develop this grid, pre-project existing grade surveys were extracted from the 1960s-era General Design Memorandums (GDM) and applied to the SL15 grid.

Figure 5 displays a map from one GDM for New Orleans East. The map is taken from the report titled “Lake Pontchartrain High Level Plan: Design Memorandum No. 16 General Design: New Orleans East Levee South Point to GIWW, September 1987”. The map shows the location of different plan and profile plots. For example purposes, one profile plot at the location immediately south of I-10 is selected and displayed in Figure 6. Although difficult to read, the profile plot shows the authorized design grade and the existing levee crown elevations plotted for the levee segment. The existing grade profiles show the local levees around New Orleans East prior to corps federal levee construction.

The elevations of pre-Betsy pre-federal levees were extracted from the GDMs using a specialized procedure and MATLAB code. Each of the GDM plan and profile plots were converted to digital format (.png) and cropped and straightened. The plan and profile plots were manually cropped at the beginning and end of the x and y axes. Next, a red line was manually drawn along the existing grade profile. A MATLAB code was written to extract the elevations along the drawn red. Figure 7 displays an example of a cropped profile plot, with the red line drawn at the existing grade. The program works by reading in the image, finding the location of the red pixels, and relating the location of the red pixels to the stationing and elevation. The method provides reasonable estimates of topographic elevations based on available data. The elevations were converted to NAVD88 using an assumed and uniform -0.6 ft conversion factor. It is very difficult to properly convert NGVD to NAVD88 in southern Louisiana, especially surveyed elevations from over 20 years ago. Although there are many assumptions in the levee elevation extraction and assignment procedure, the resulting grid is a reasonable estimate of what existed prior to the corps federal levee construction.

Figure 8 displays a plan and profile plot for a portion of the IHNC. This profile plot shows an existing levee elevation of approximately 15.0 ft NGVD. The plot reads “Existing Levee Crown El. 15 ft Constructed by Orleans Levee District”. These profile plots show that levees did exist around New Orleans East prior to the corps effort to construct federal levees post-Betsy. It is important to note that the SL15-1965 grid is only modified at New Orleans East, St. Bernard and the portion of the New Orleans metropolitan area from Seabrook to the Mississippi River. The WBV project area levee elevations are the same in the SL16-1965 grids and the SL15-2005 grids.

Figure 9 displays the existing ground taken from the GDM for the Chalmette Area Plan. The profile shows that no levees existed prior to federal levee construction post-Betsy in this location. The SL15-1965 grid, elevations are lowered substantially in order to match the pre-Betsy existing ground profile. Dredging of the MRGO created a spoil bank in this area, and those elevations are plotted on the profile plot.

Figure 10 displays the final SL15-1965 sub-grid feature elevations. The plot shows relatively low elevations around New Orleans East, St. Bernard, and the eastern portions the New Orleans metropolitan area. Prior to construction of the federal levees post-Betsy, the relatively low levee and floodwall elevations allowed surge to overflow between separate areas during modest storm surge events. Figure 11 displays the SL15-2005 sub-grid feature elevations. With construction of the federal levees post-Betsy, levee elevations were significantly raised around New Orleans East, St. Bernard, and the eastern portions the New Orleans metropolitan areas; essentially forming separate areas and reducing the surge overflow between these separate areas which was previously experienced in modest storm surge events

Figure 12 displays the SL15-2012 sub-grid feature elevations. This version of the grid includes the new features of the GNO HSDRRS, including the IHNC Surge Barrier, the IHNC Seabrook Closure and the West Closure Complex. These features, along with raised levees and floodwalls, prevent water from flowing into the interior canals of the city during significant surge events. In the St. Bernard area, a roughly 30' floodwall now exists where a spoil bank with low elevations of approximately 4-6 ft existed prior to construction of federal levees post-Betsy. This is a major modification to the landscape. The goal of this analysis is to determine the cumulative effect of these major modifications on storm surge patterns in Lake Borgne and Lake Pontchartrain for a group of possible events.

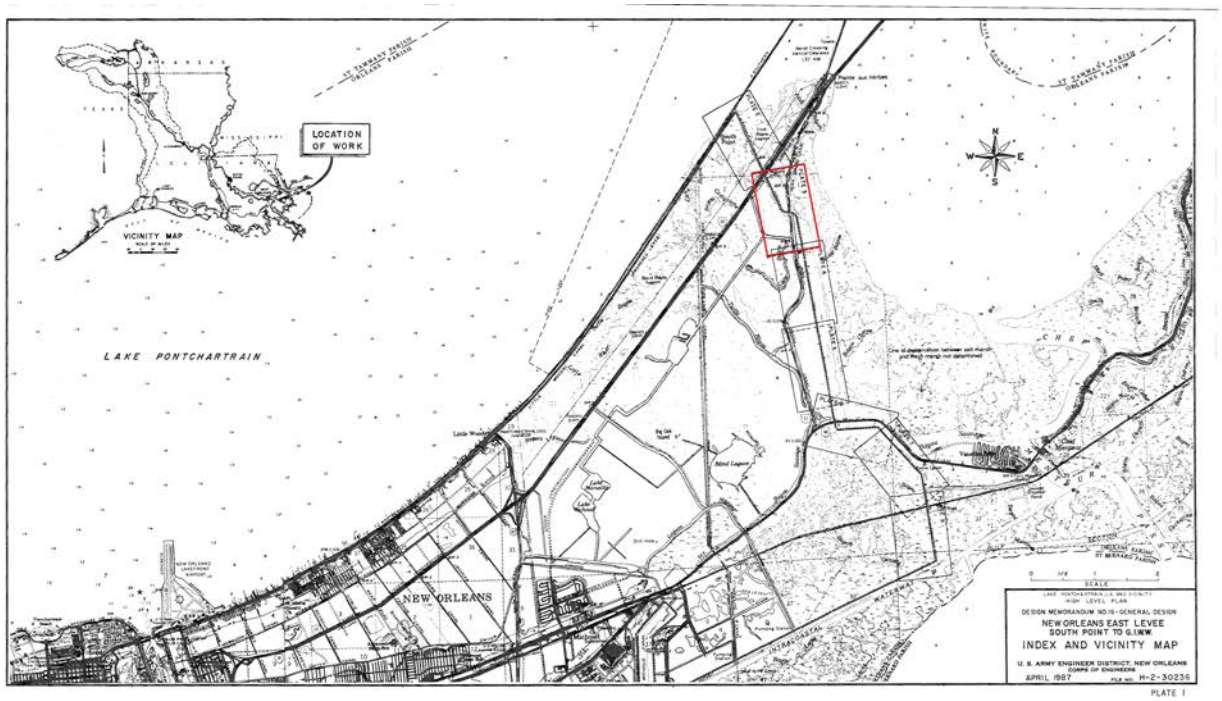


Figure 5 General Design Memorandum Map of New Orleans East – South Point to GIWW.

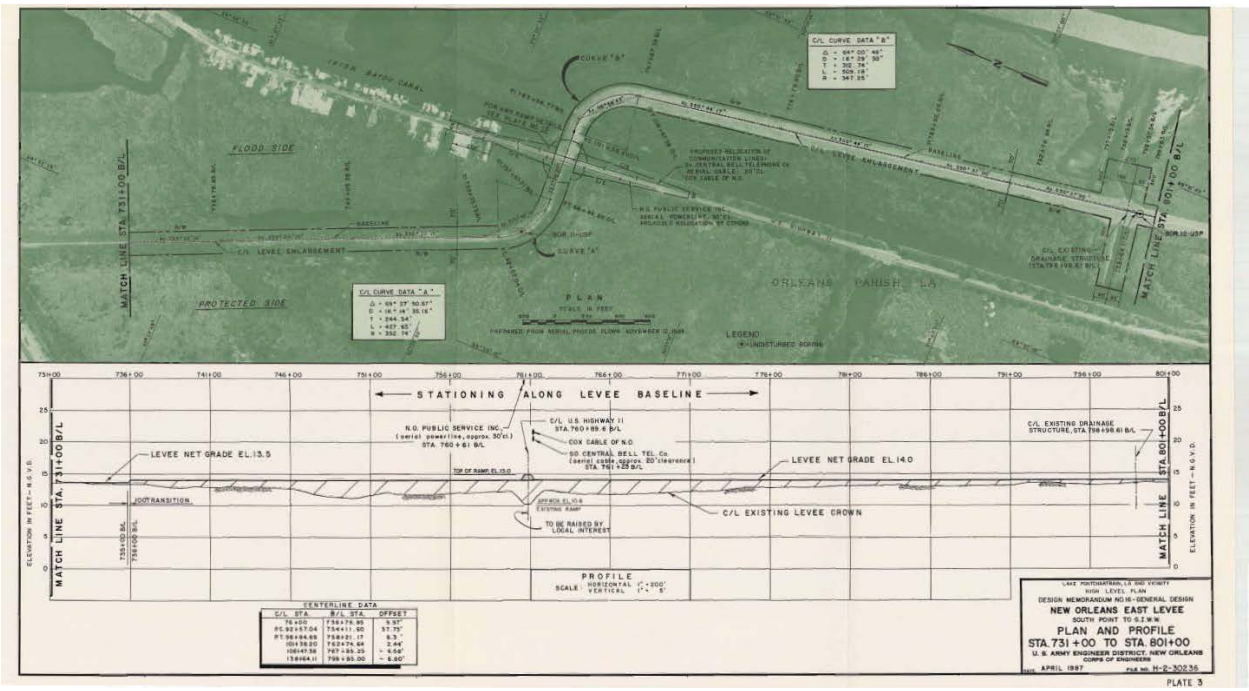


Figure 6 Plan and Profile Plot Showing Existing Grade Levee Elevations in GDM

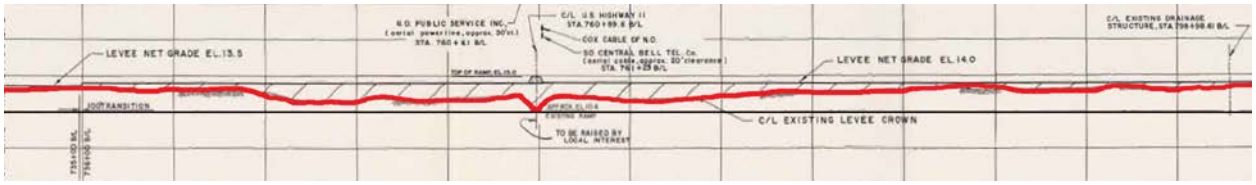


Figure 7 Example of Trimmed Plan and Profile Plot

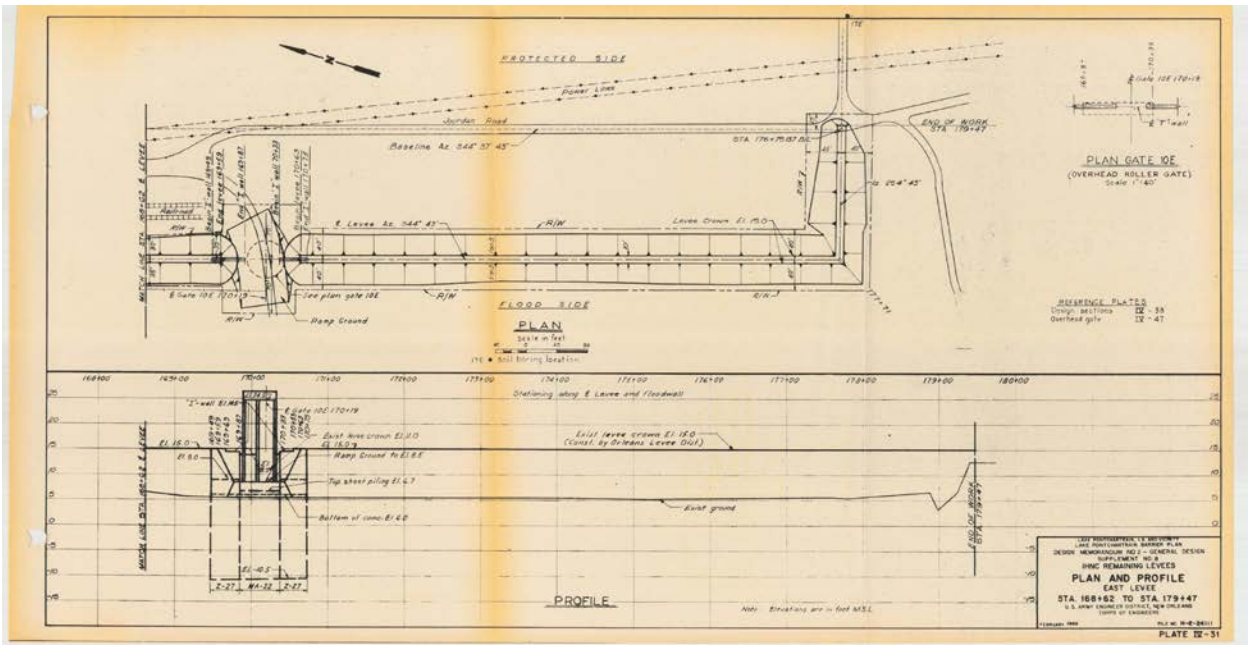


Figure 8 Plan and Profile Plot Showing Existing Grade Levee Elevations in GDM - IHNC

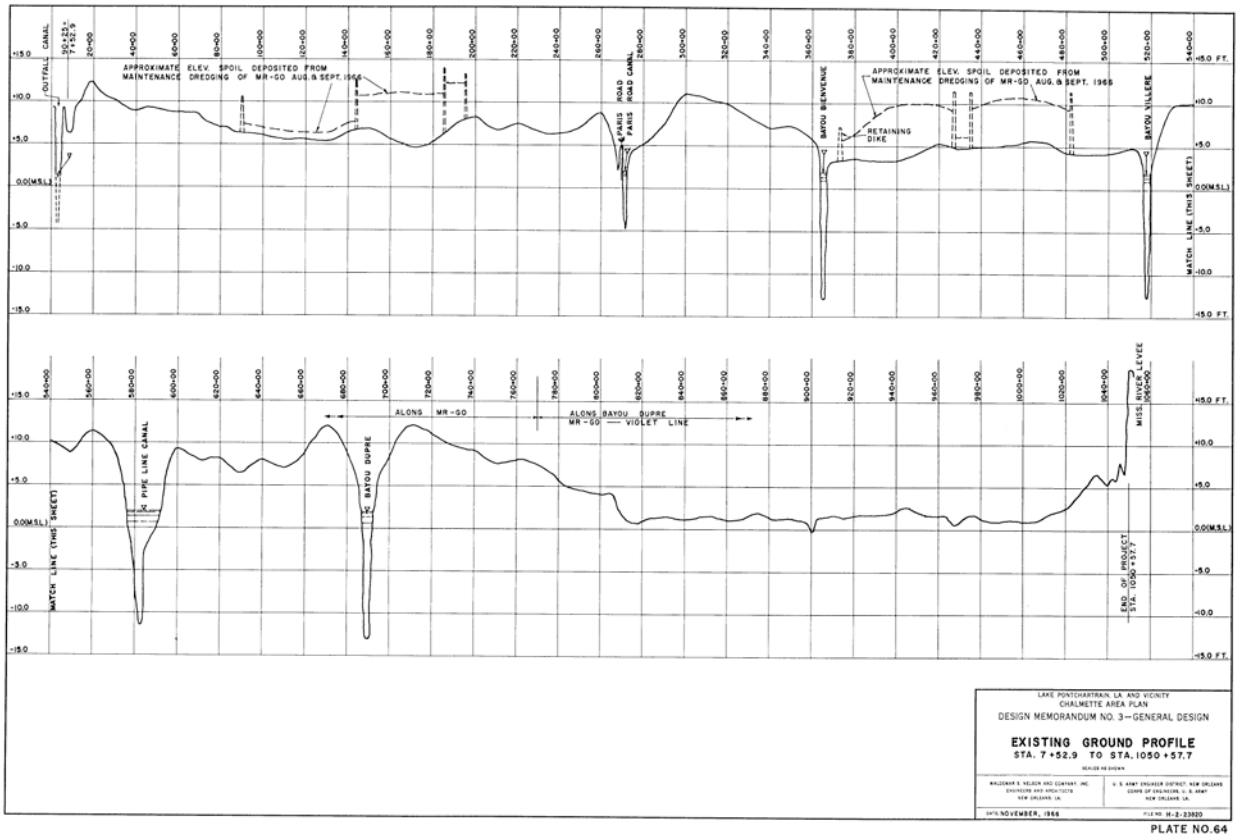


Figure 9 1966 Existing Ground Profile of St Bernard Area – Prior to HPS Construction

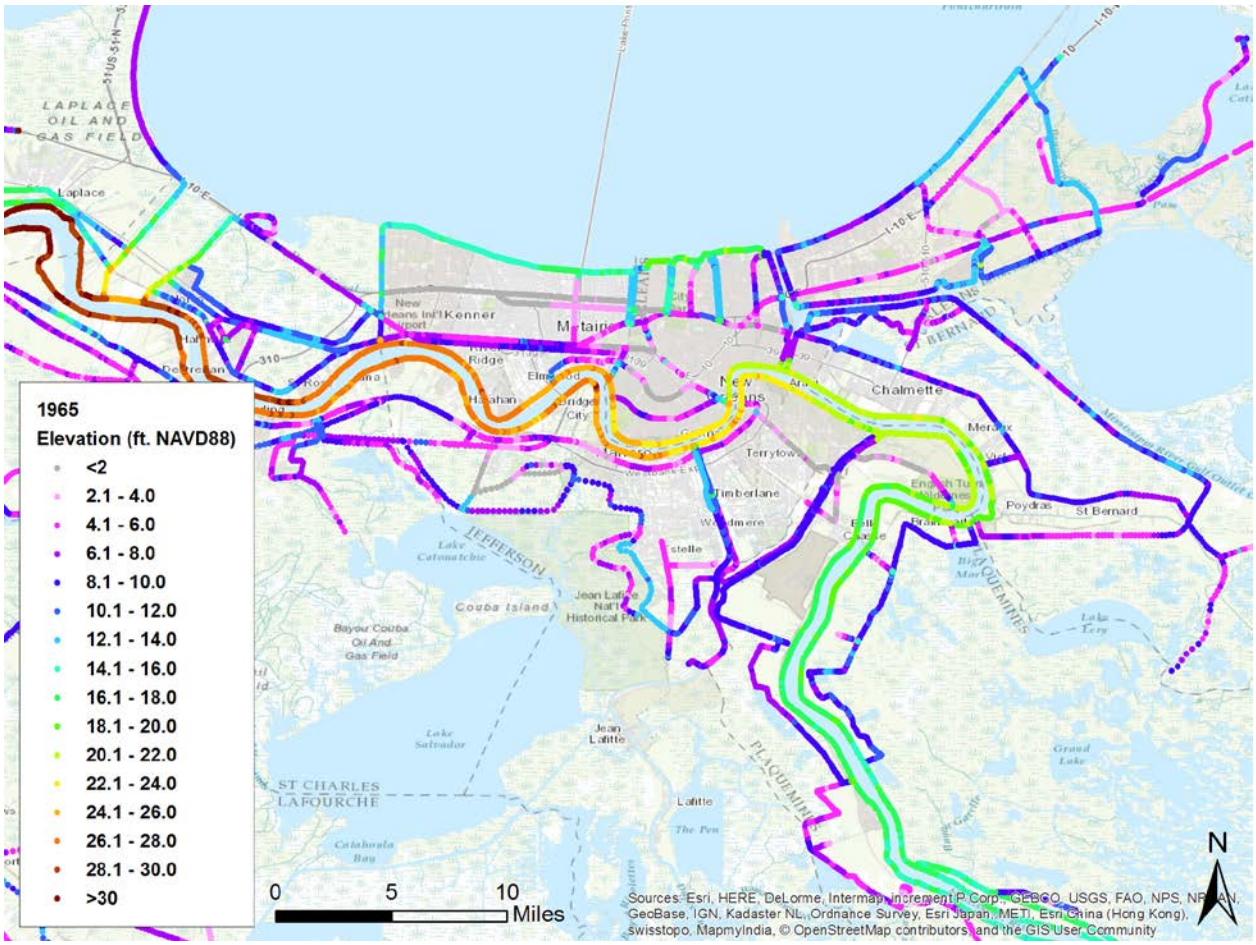


Figure 10 SL15-1965 Sub-grid Feature Elevations

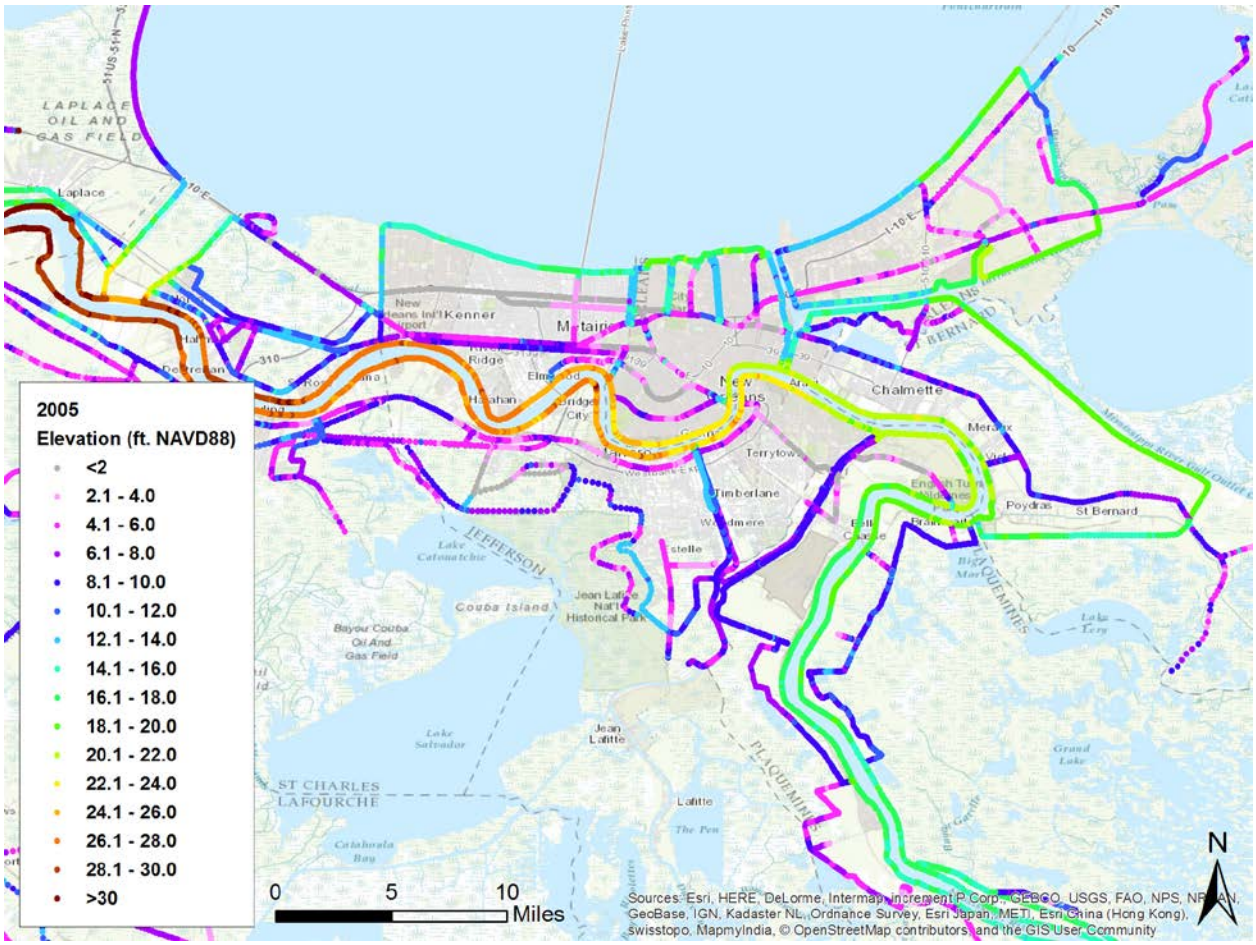


Figure 11 SL15-2005 Sub-grid Feature Elevations

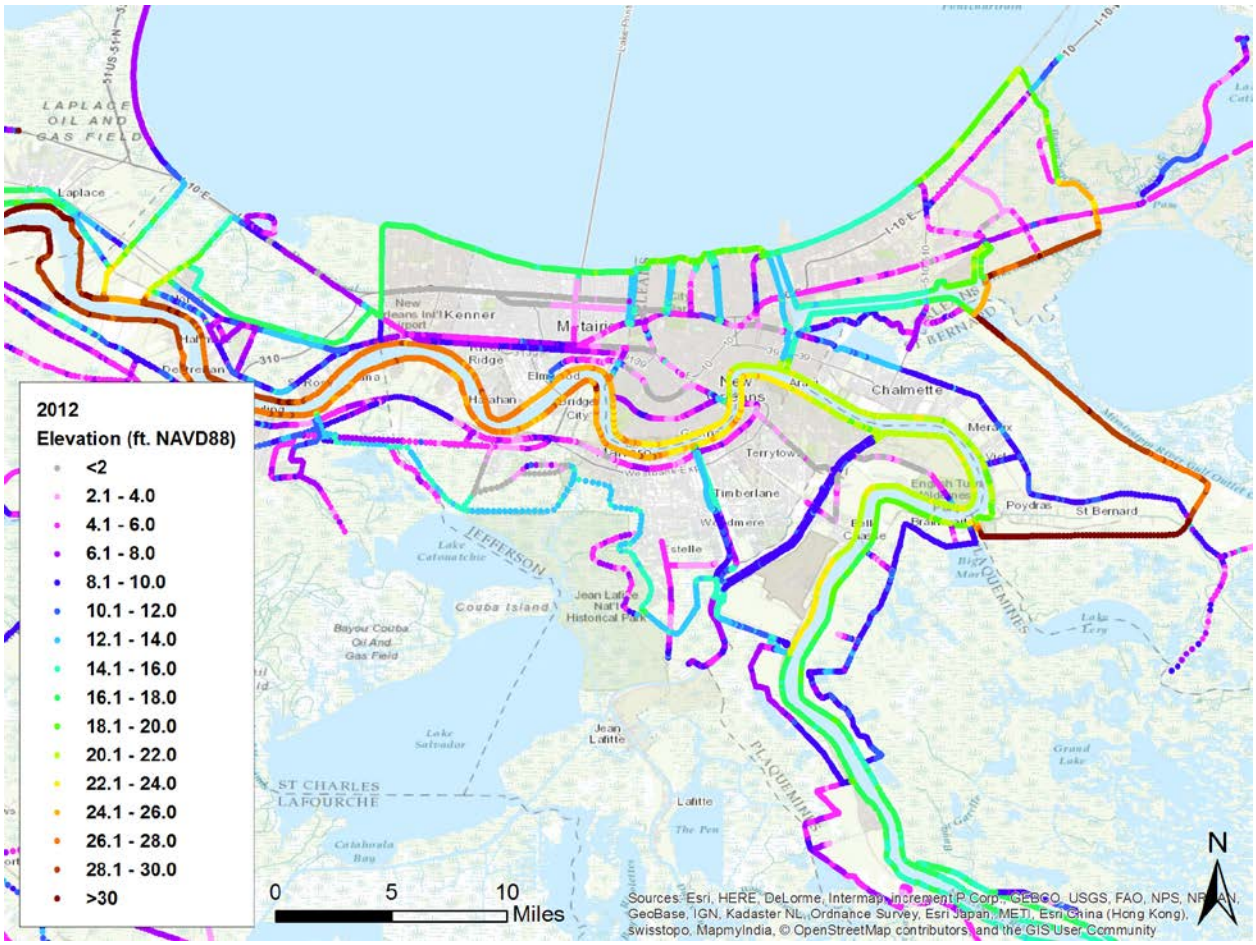


Figure 12 SL15-2012 Sub-grid Feature Elevations

2.5 Wind Input

One of the major inputs needed to model storms using ADCIRC is wind data. The wind drives the storm surge. For Hurricane Betsy, the wind input was taken from NOAA's H*Wind Project (http://www.aoml.noaa.gov/hrd/data_sub/wind.html). The H*Wind project uses measurements from a variety of observation platforms to develop a realistic distribution of wind speeds for major hurricane events. Figure 13 displays some of the snapshots of Hurricane Betsy's winds as the storm progressed across the Gulf of Mexico. H*Wind data provides a realistic approximation of what occurred because it is primarily based on recorded observations.

H*Wind data is only available for the timing of landfall for Hurricane Camille, as shown in Figure 14. Therefore H*Wind cannot be used to model the entire storm. However, NOAA records important track data for all hurricanes in the HURRDAT database. (http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html).
This track data, which include lat/long coordinates, central pressure and wind speed data, can be used to produce wind input for the ADCIRC model. Using the ADCIRC utility program called ASWIP, the NOAA Camille track file was converted to a special format, which provides the pertinent hurricane parameters to ADCIRC's internal

parametric vortex model, producing a wind field for the storm. For Camille, we have selected the NWS=19 internal vortex model within ADCIRC.

For Hurricanes Katrina, Rita, Gustav, Ike and Isaac, “best winds” in the OWI format have been applied in the modeling. “Best winds” were developed as part of previous analyses for accurate hindcasting of Hurricanes Katrina, Rita, Gustav, Ike and Isaac. The “best winds” are also data-assimilated, meaning that they incorporate observations from many wind and pressure gages throughout the region.

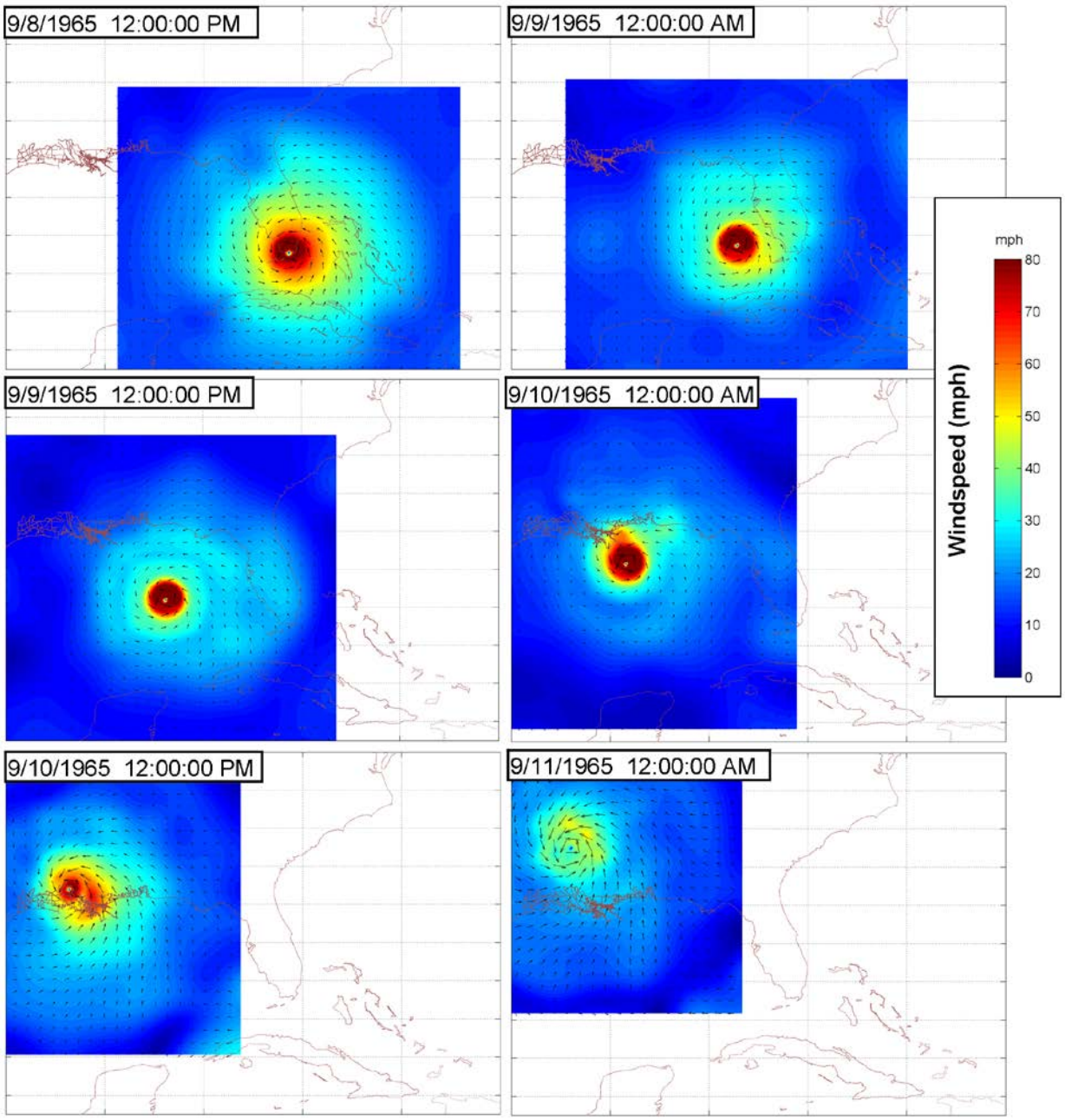


Figure 13 Hurricane Betsy Wind Field – NOAA H*Wind

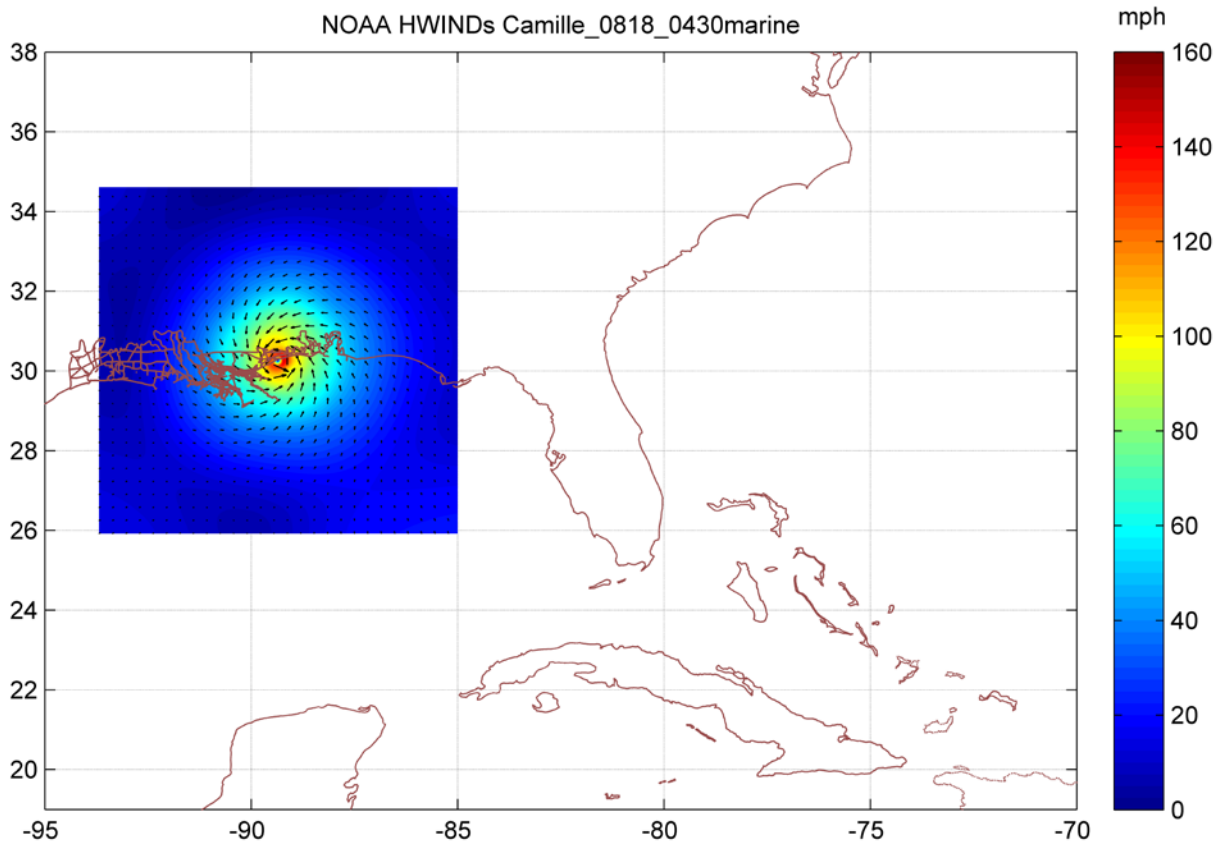


Figure 14 Hurricane Camille Wind Field at Landfall – NOAA H*Wind

2.6 Limitations and Assumptions

One of the limitations of the analysis is the limited sample size of the selected synthetic and historical storms. The sample of storms does not cover the full range of possibilities, but rather provides a few examples of storms which have occurred, and a few examples of storms which could occur. However, this analysis builds on the 2013 Isaac analysis as only one storm was modeled as part of that analysis.

3. ADCIRC Simulations of Betsy, Camille, Katrina, Rita, Gustav, Ike, Isaac and 10 Synthetic Storms

3.1 Introduction

In this chapter we present storm surge model results for the SL15-1965, SL15-2005, and SL15-2012 grids. Some validation data for Hurricanes Betsy and Camille are also presented. It is important to validate the simulations of Camille and Betsy on the SL15-1965 grid to show that the model reasonably reproduces measured peak water levels. Betsy flooded large portions of the Greater New Orleans area and it is important to quantify how well the ADCIRC modeling replicates this flooding.

3.2 Example Storm Surge Development for Hurricane Betsy

Figure 15 displays the simulated surge elevation time-series as Betsy makes landfall using the SL15-1965 ADCIRC grid. At midnight on 9/10/1965, strong winds begin to develop from the northeast, forcing water into Lake Borgne. By 6:00AM, a considerable surge of about 12.5 ft has developed in Lake Borgne causing the New Orleans East and St. Bernard existing levees to overtop and begin to flood. By 3:00PM, the eye of the storm has passed southeast Louisiana and New Orleans East and St. Bernard areas have substantial flooding. The modeled storm surge for Betsy is similar to what occurred in reality, although some interior flooding patterns are different. In reality, Betsy flooded New Orleans East, St. Bernard and portions of the New Orleans Metro areas. The model does not show all of these areas flooding exactly the way it happened in reality. However, the general pattern of modeled inundation is consistent with observations. The interior flooding is difficult to predict without more detailed model of the interior.

Figure 16 displays the wave height time series from the simulation of Hurricane Betsy using the SL15-1965 grid. The highest waves, with significant wave heights of roughly 7 to 9 ft, occur in Lake Pontchartrain. The wave development appears reasonable, although wave validation data is not available.

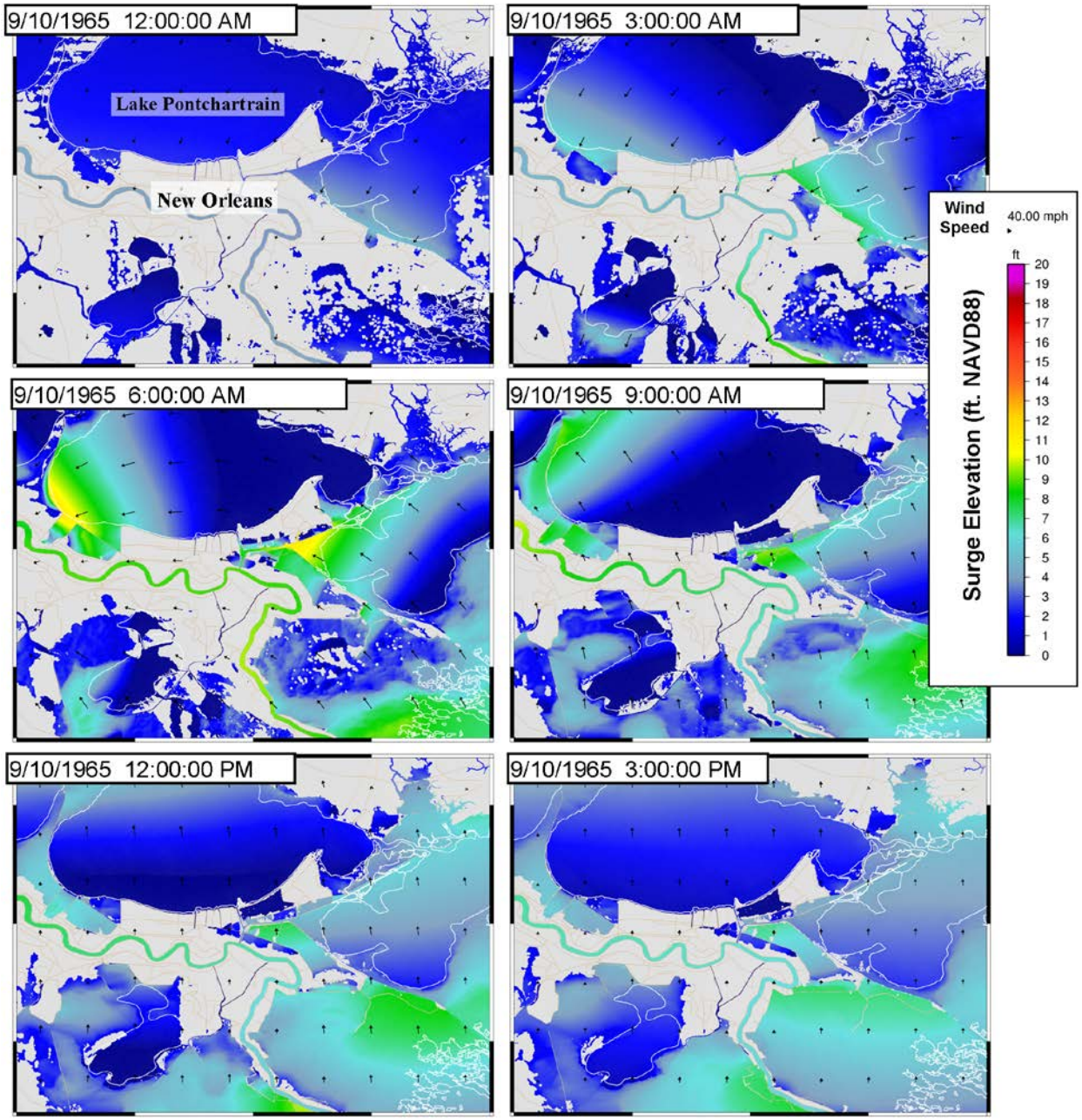


Figure 15 Storm Surge Development for Hurricane Betsy on the SL15-1965 Grid.

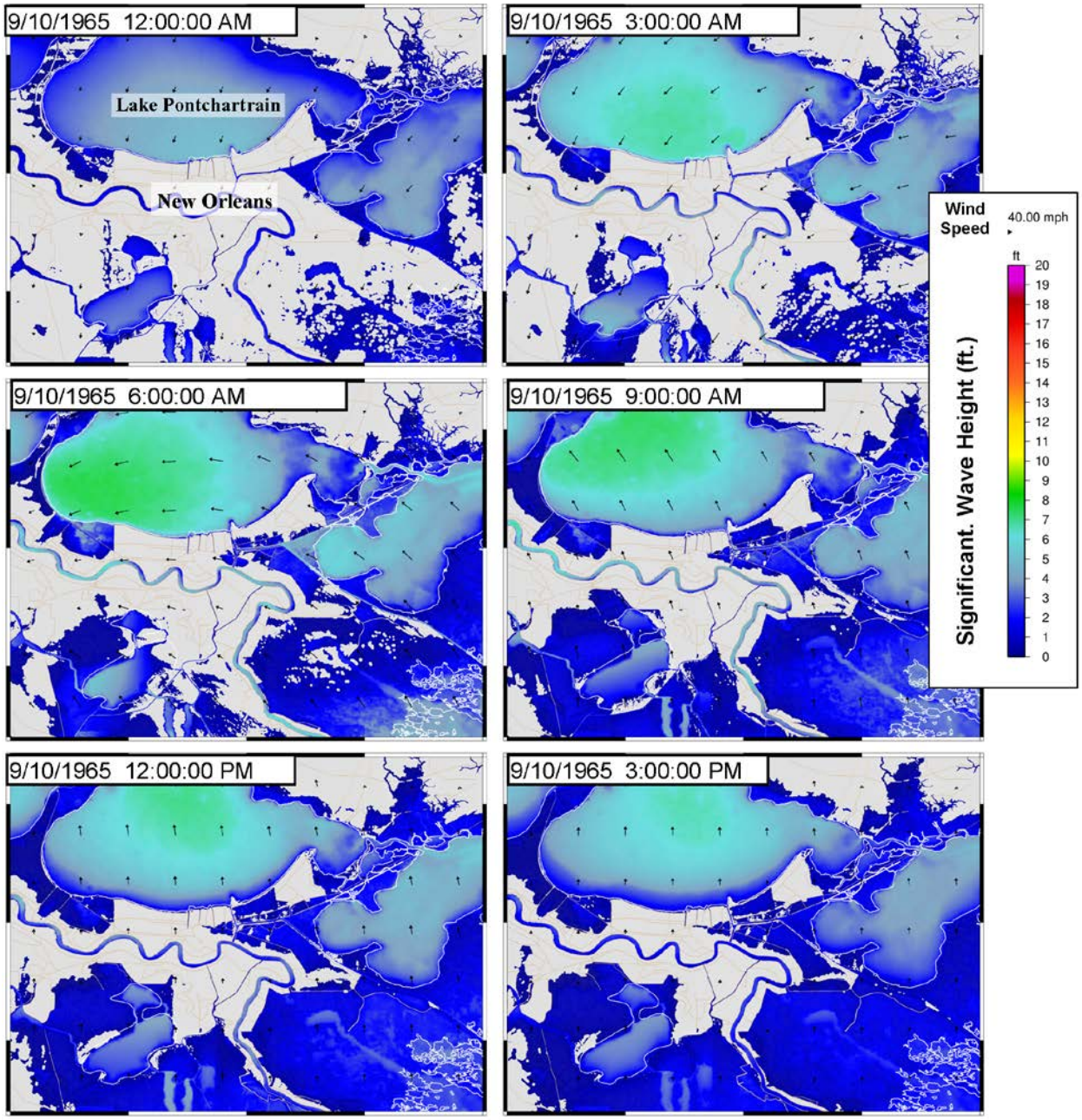


Figure 16 Wave Height Development for Hurricane Betsy on the SL15-1965 Grid.

3.3 Validation for Betsy and Camille

Figure 17 displays the observed high water mark data collected after the storm by USACE. A very dense network of high water mark data is useful for validation purposes. The data from the figure was extracted and converted to shapefile format. Figure 18 displays a validation plot, comparing modeled data to observed data. The plot presents scatter data of the difference between modeled and observed peak water surface elevation. The color of each scatter point corresponds to the error between the modeled high water mark and the observed high water marks. Warmer colors suggest model over prediction, while cooler colors suggest under-prediction. Overall ADCIRC seems to

under-predict the peak surge and also interior flooding, however in the location of interest (Lake Borgne, IHNC and Lake Pontchartrain), the model predicts peak surge to within 1 to 2 ft at most high water mark locations.

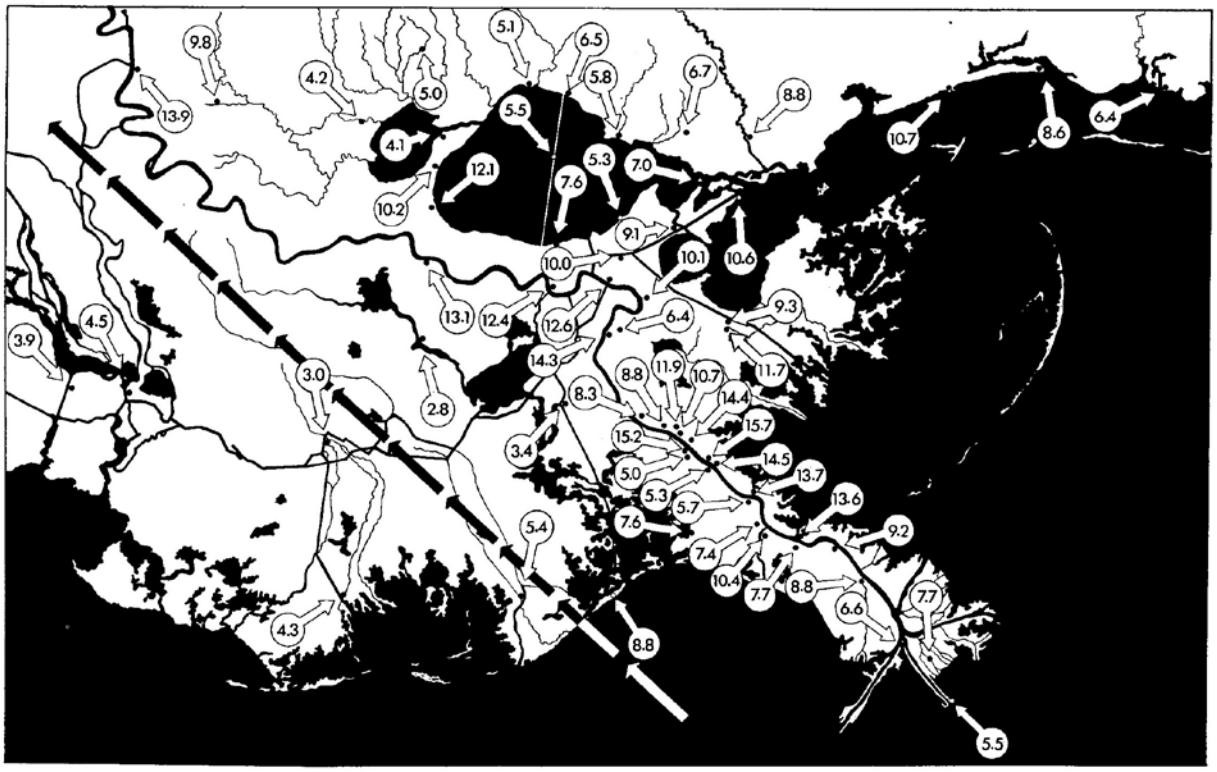


Figure 17 Hurricane Betsy Observed High Water Marks

Figure 19 displays a high water mark profile plot for Hurricane Camille taken from a May 1970 corps report, produced by the USACE Mobile District, entitled “Hurricane Camille 14 – 22 August 1969”. The profile is plotted along the Gulf Coast from the Rigolets pass in Louisiana to Perdido Pass, FL. The observed data shows a peak surge near Pass Christian, MS of approximately 22.5 ft. M.S.L. The data from this plot is extracted using a similar technique as used to extract the levee elevation data from the GDMs. The surge is adjusted to the NAVD88 datum. Figure 20 is a validation plot for Hurricane Camille. The top portion of Figure 20 shows the maximum surge elevation for Camille using the SL15-1965 grid. The black line represents a transect where peak surge is extracted from the simulation. The bottom portion of the figure compares the modeled peak surge to the observed peak surge. The model provides a reasonable reproduction of surge for the area of impact, although modeled peak surge is under-predicted by approximately 2-3 ft west of Bay St. Louis. The quality of wind data applied in the simulation of Camille might explain some of the differences between modeled and observed. H*Wind or other data-assimilated wind products are not available for Camille.

The high water mark data used for validation of Hurricanes Betsy and Camille is from the 1960s and it is difficult to know whether or the surveyed marks include the effects of

wave run-up. The data is taken as-is because very little documentation is available to verify these high water marks.

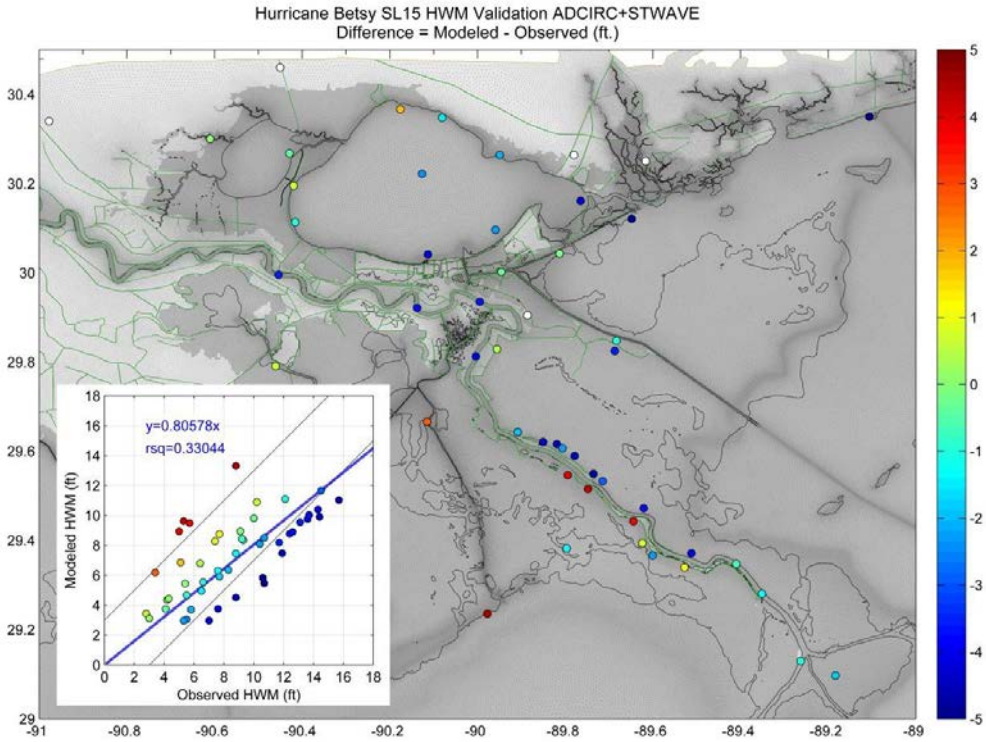


Figure 18 Hurricane Betsy High Water Mark Validation in SE Louisiana

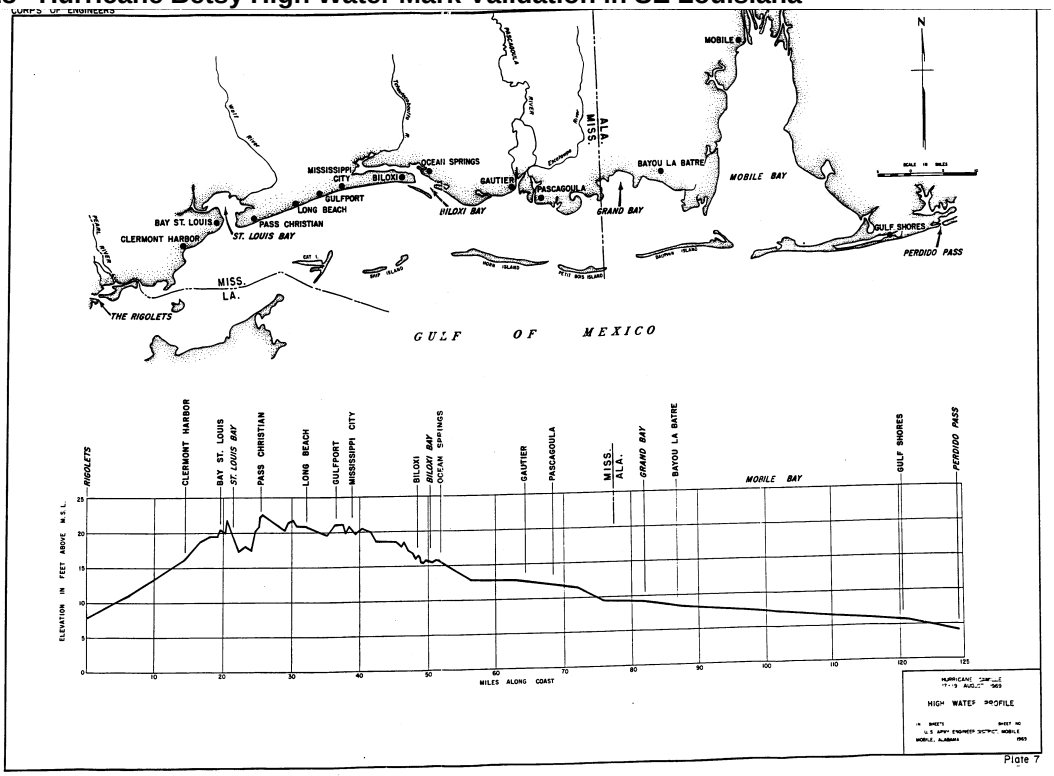


Figure 19 Hurricane Camille Observed High Water Profile along the MS, GA, FL Coast

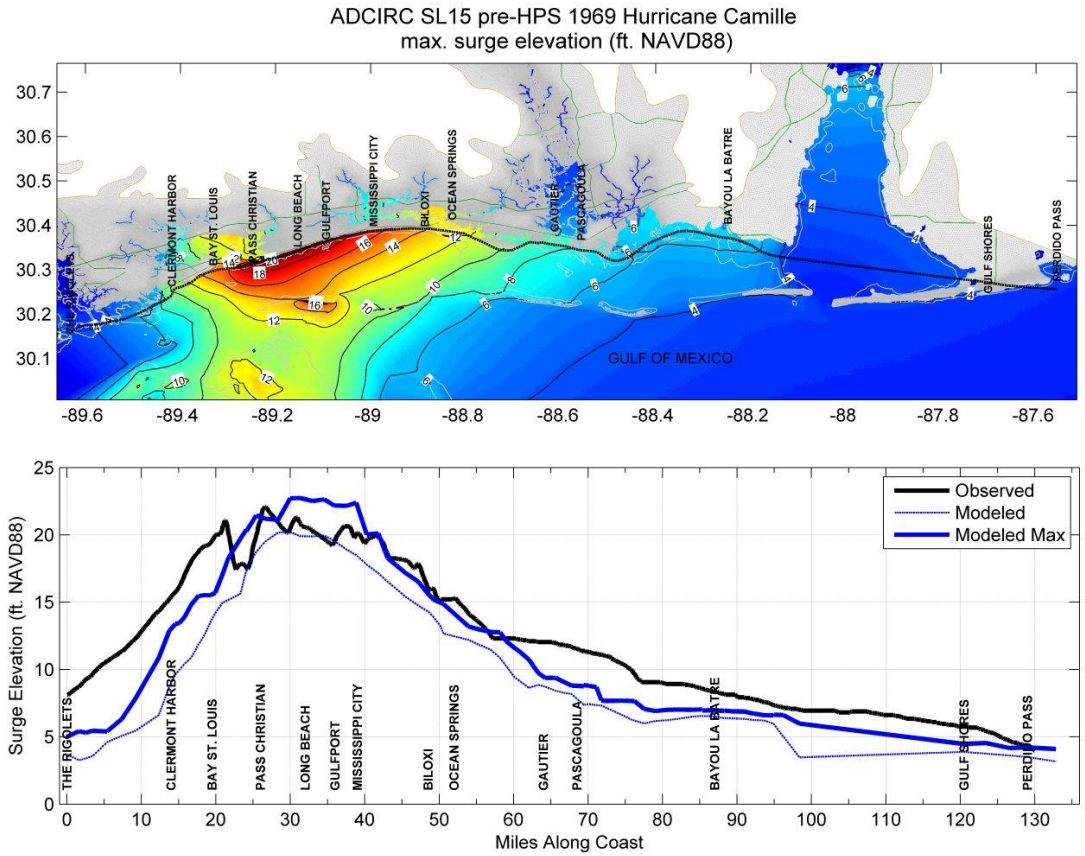


Figure 20 Hurricane Camille Validation of High Water Profile along the MS, GA, FL Coast

3.4 Impacts to Surrounding Communities

Figure 21 displays the maximum surge elevation for the Hurricane Betsy simulation on the SL15-1965 grid. Without post-Betsy federal levees in place around St. Bernard and New Orleans East, substantial flooding occurs in these areas. This result is similar to what occurred in reality during Betsy. Figure 22 displays the maximum surge plot for Hurricane Betsy on the SL15-2005 grid. With the federal levees post-Betsy in place, the St. Bernard and New Orleans East areas do not flood for the Betsy simulation, although some minor overtopping seems to occur at isolated locations. Figure 23 displays the maximum surge of Hurricane Betsy using the SL15-2012 grid. With this grid, the features of GNO HSDRRS, including the IHNC Surge Barrier, IHNC Seabrook Closure and West Closure Complex prevent major interior flooding in the Betsy simulation. Maximum surge elevation plots for all 17 storms are presented in Appendix A.

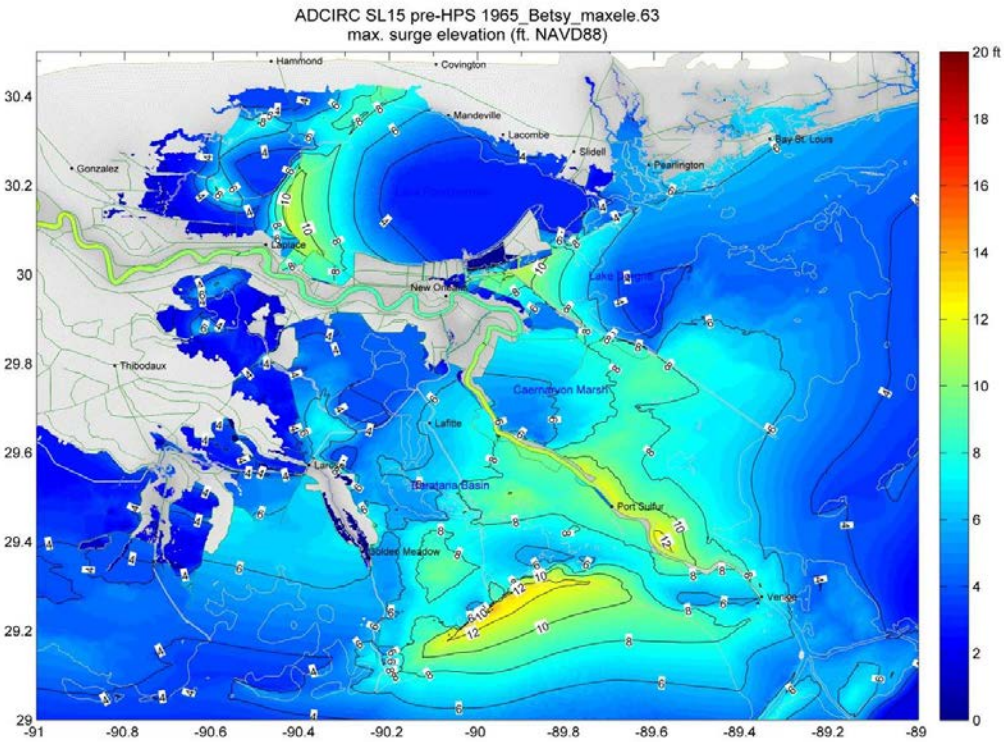


Figure 21 Hurricane Betsy Maximum Surge Elevation on SL15-1965 Grid

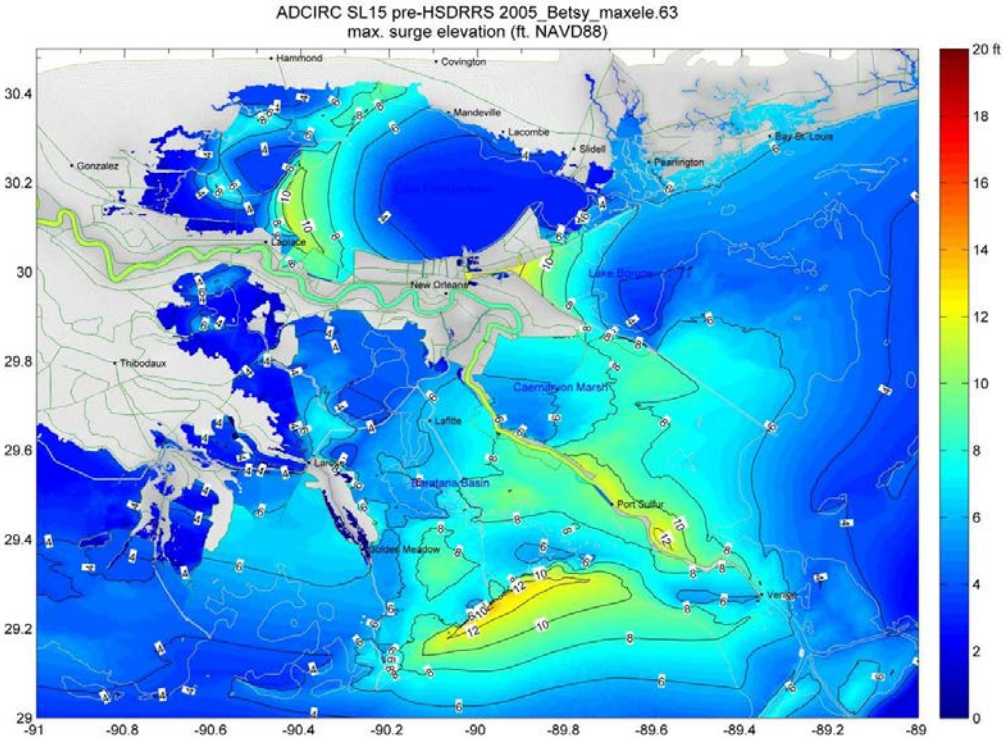


Figure 22 Hurricane Betsy Maximum Surge Elevation on SL15-2005 Grid

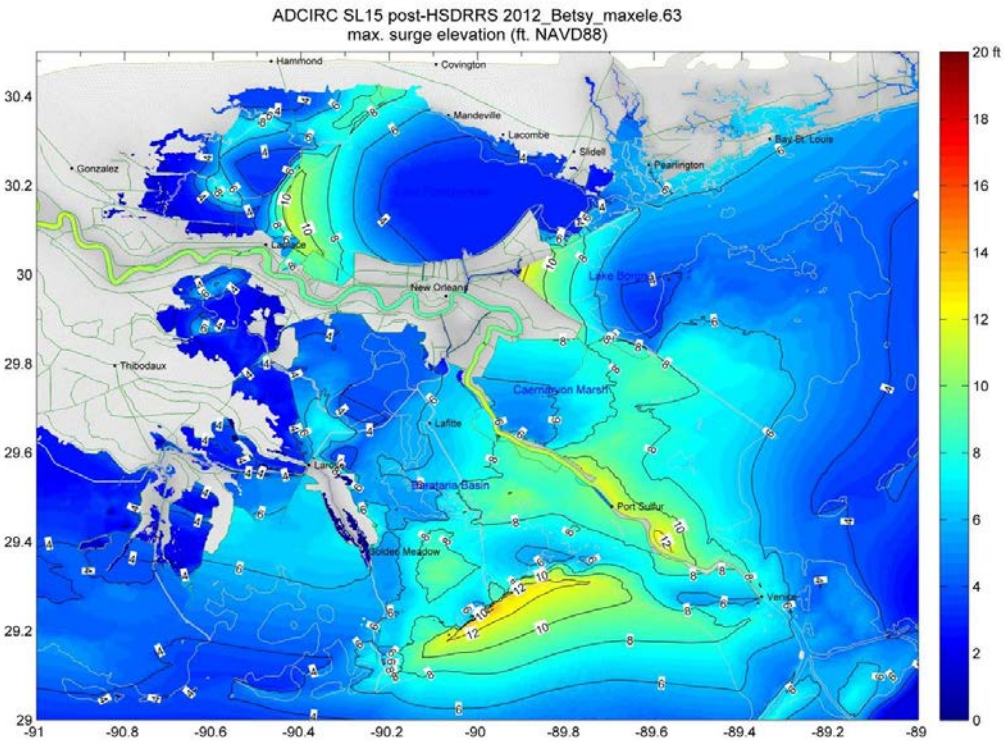


Figure 23 Hurricane Betsy Maximum Surge Elevation on SL15-2012 Grid

To help visualize the impact on surge patterns due to the post-Betsy federal levees and the GNO HSDRRS, difference plots for each storm have been created. Figure 24 displays the difference in maximum surge produced for Betsy between the SL15-2005 and SL15-2012 grids. The difference surface is color coded, with warmer color representing an increase in water level due to the GNO HSDRRS project features. The figure suggests that the project features of GNO HSDRRS increase water level very modestly between the 2005 and 2012 conditions. A roughly 1.0 inch increase in water level is observed near Eden Isle, Slidell, LA, while a reduction of approximately 1.0 inch is observed in Lake Pontchartrain near Mandeville, LA. The reduction in peak water surface can be attributed to the closure of the IHNC corridor, which prevents some flow into Lake Pontchartrain through Seabrook. With the IHNC Surge Barrier in place, the hydraulic conductivity between the source of the surge (the Gulf of Mexico / Lake Borgne) and Lake Pontchartrain is reduced, reducing the overall volume entering Lake Pontchartrain. This behavior is not unique to Betsy, and similar results are produced for Isaac and other storms. The WBV levees, including the West Closure Complex, reduce interior flooding, and increase exterior water levels immediately outside the system. As distance from the WCC increases, the increase in water level is diminished. Difference plots for the SL15-2005 and SL15-2012 grids for all 17 modeled storms are presented in Appendix B.

Figure 25 is a difference plot for Hurricane Betsy comparing the peak surge produced on the SL15-1965 grid and peak surge produced on the SL15-2012 grid. This comparison shows the impact on surge patterns due to construction of the post-Betsy federal levees and GNO HSDRRS, or the changes to the system between 1965 and

2012. As expected, the changes to surge patterns are more intense, although still a modest increase in water level is observed. Simulation of Betsy on the SL15-1965 grid shows a tremendous amount of water volume entering St. Bernard, New Orleans East and the eastern side of the New Orleans metropolitan area. With the GNO HSDRRS in place, the volume no longer enters the areas, but it causes a minor increase in surge levels on the exterior of the system. Most of this increase in water level is immediately adjacent to the GNO HSDRRS (in Lake Borgne and to the east of New Orleans within the levee system). An approximate 2.0 inch increase in water level is observed near the Rigolets, while water levels are unchanged near Mandeville, LA and Eden Isle, Slidell, LA. Lake Pontchartrain generally shows a reduction in water level since the hydraulic connectivity to the Gulf is reduced with the New Orleans East levees in place. In the Betsy simulations, construction of the GNO HSDRRS on the westbank prevents the interior flooding and raises exterior water levels about 7 inches in the immediate vicinity of the West Closure Complex. The increase in water level is diminished with increased distance from the system. At Lafitte, the increase is less than 1 inch.

To demonstrate how the differences in water level evolve throughout time, a time series difference plot has been created and presented in Figure 26. The plot shows that as water surface elevation is reduced in the interior, the exterior is increased. The largest increase in water level occurs in Lake Borgne, immediately east of the IHNC Surge Barrier. Near Slidell and more specifically Eden Isle, the increase is nearly zero, but further east near Pearlington, MS the increase in roughly 2.0 inches or less.

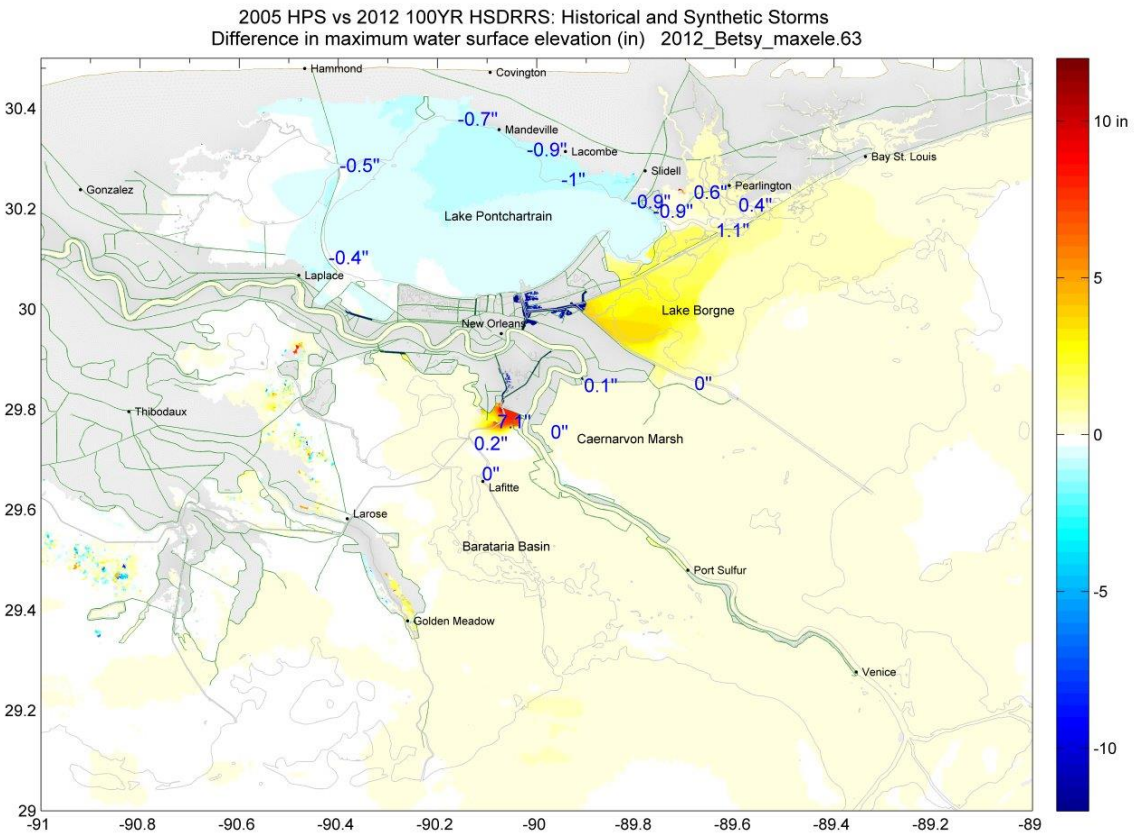


Figure 24 Peak Surge Difference Between SL15-2005 and SL15-2012

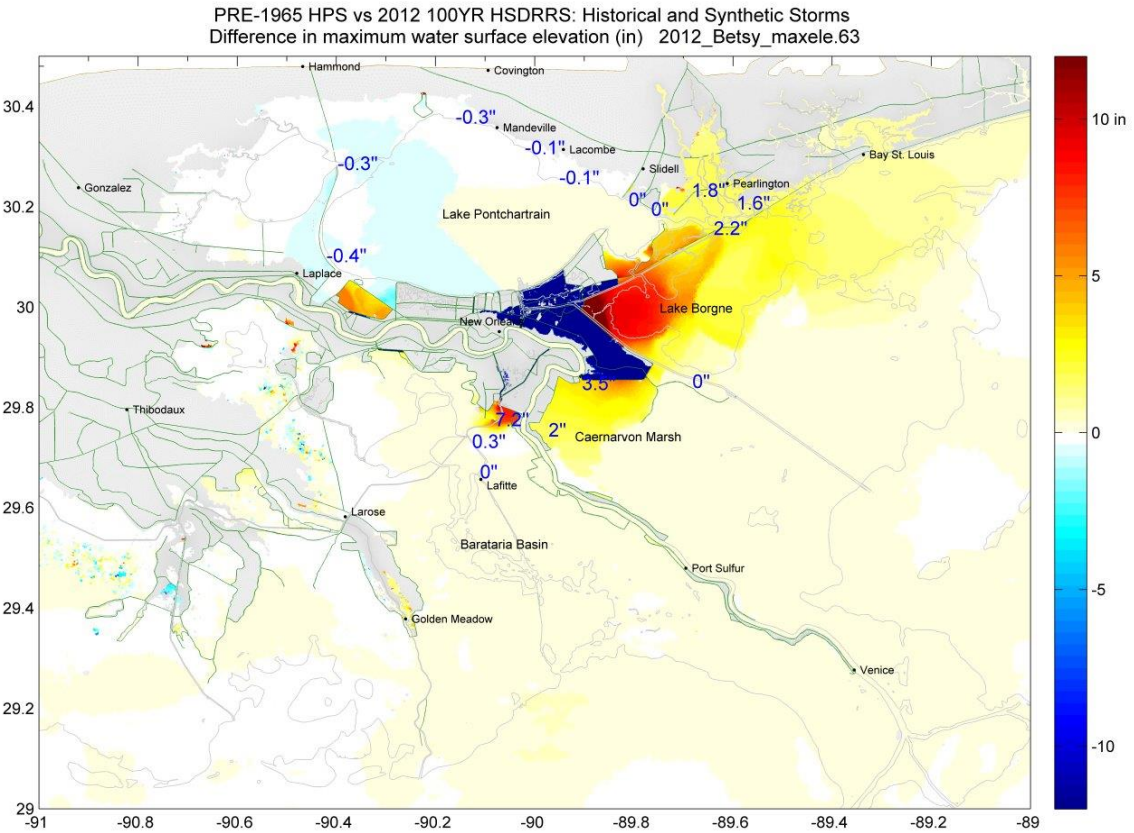


Figure 25 Peak Surge Difference Between SL15-1965 and SL15-2012

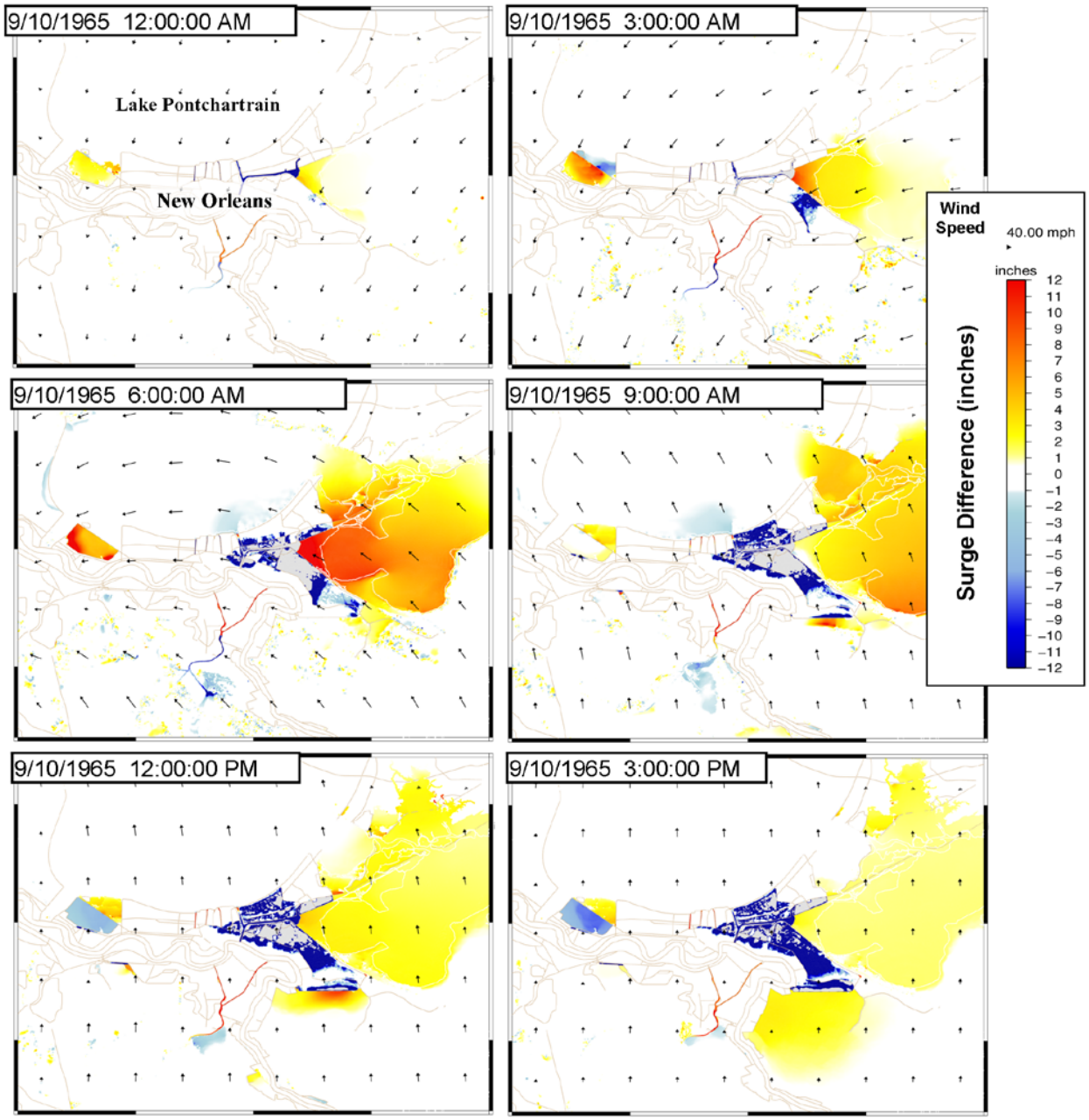


Figure 26 Time Series of Differences in Peak Surge between SL15-1965 and SL15-2012

Figure 27 displays the selected output locations where peak surge values for all simulations have been extracted.

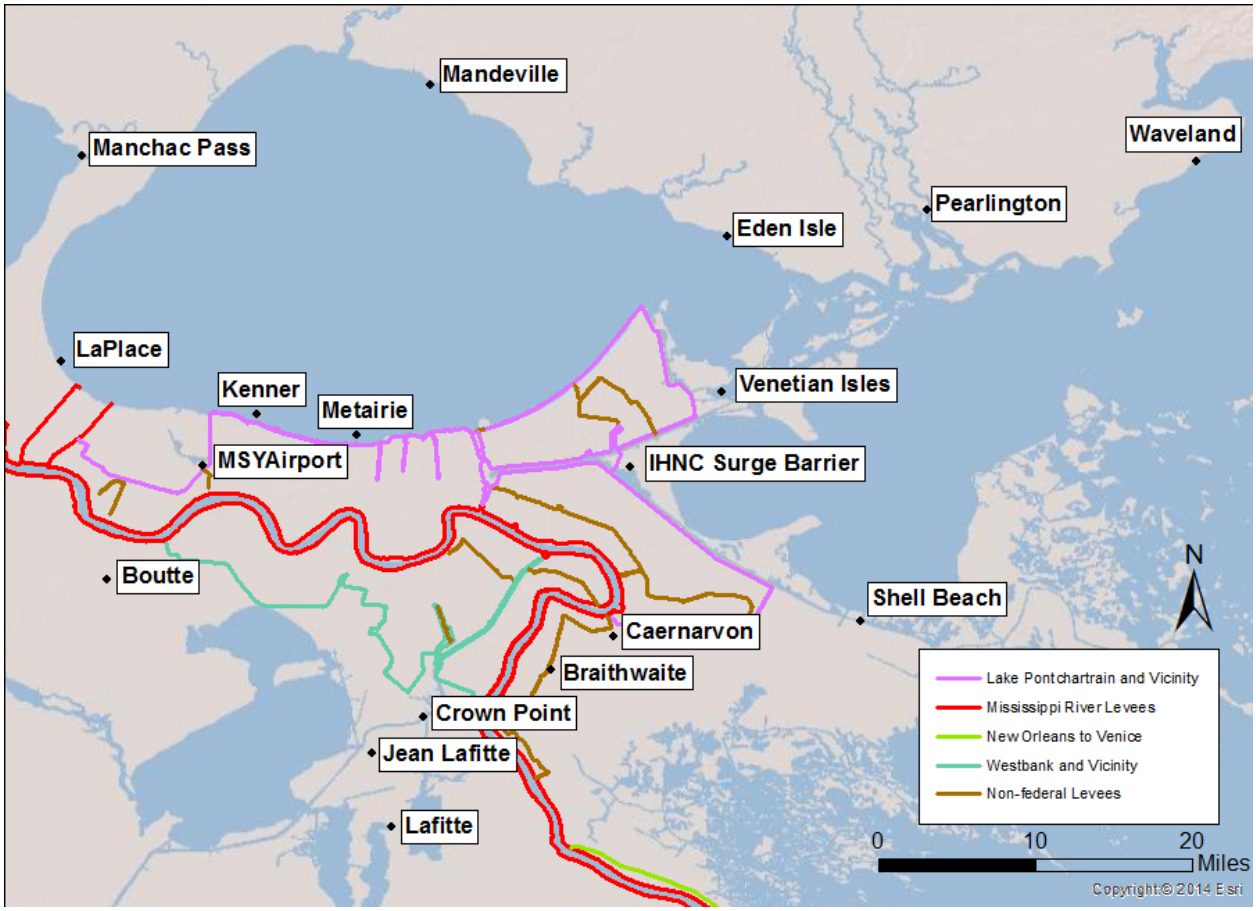


Figure 27 Selected Output Locations

Table 3 displays the maximum surge values at the selected output points for all storms for the SL15-1965, SL15-2005 and SL15-2012 grids. The table also displays the difference in peak surge elevation between the SL15-2005 and SL15-2012 grids, and the SL15-1965 and SL15-2012 grids. Positive difference values represent an increase in water level due to the federal project. A percentage change has also been calculated. For example, at Eden Isle, Slidell, LA, storm S094 produced a 10.4 ft NAVD88 storm surge on the SL15-1965 grid, a 10.4 ft NAVD storm surge on the SL16-2005 grid, and a 10.9 ft NAVD88 storm surge on the SL15-2012 grid. The difference between the peak water level produced on the SL15-1965 grid and SL15-2012 grid is 0.48 ft, which is a 4.6% increase. Table 3 shows that the maximum increase at Eden Isle between peak water levels produced on the SL15-1965 and SL15-2012 is 0.48 ft and occurs with storm S094, a storm which floods major portions of New Orleans in the SL15-1965 grid and SL15-2005 grid, but does not flood New Orleans in the SL15-2012 grid.

At Crown Point, which is located in the Barataria Basin, the maximum increase in surge between the SL15-1965 grid and the SL15-2012 grid occurs for storm S146. For this specific storm, the peak surge level increases 1.35 ft, which is a 13.3% increase. With increased distance from the West Closure Complex, the increase in peak surge in reduced. At Lafitte, the increase in peak surge is reduced to 0.41 ft, or a 4.6% increase.

At the IHNC Surge Barrier location, the differences between maximum surge produced on the SL15-1965 and SL15-2012 grids are much greater. At this location, the peak surge increases by about 4.56 ft for storm S023, an approximate 33% increase. The results in Table 3 show that the impact to peak surge values depends heavily on storm characteristics and location. In general, larger impacts occur at locations that are immediately adjacent to the GNO HSDRRS, such as the area immediately adjacent to the IHNC Surge Barrier or the West Closure Complex.

Table 3 Comparison of Peak Surge at Eden Isles, Chef Pass, and IHNC Surge Barrier for SL15-1965, SL15-2005, and SL15-2012

Metairie	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	4.7		2.3		4.8		4.8		6.8		8.4		5.2		6.3		6.2		6.4		8.4		4.9		8.3		8.4		9.1		7.3		8.4	
2005 Peak Surge (ft. NAVD88)	4.7		2.3		4.9		4.8		6.8		8.5		5.3		6.4		6.3		6.6		8.4		5.0		8.4		7.7		8.7		7.3		8.1	
2012 Peak Surge (ft. NAVD88)	4.6		2.3		4.8		4.7		6.8		8.4		5.2		6.4		6.2		6.6		8.4		4.9		8.3		7.7		8.8		7.3		8.2	
Difference 1965 to 2012 (ft.)	-0.04	-0.9%	0.01	0.4%	0.00	0.0%	-0.06	-1.3%	0.01	0.1%	0.01	0.1%	-0.03	-0.6%	0.09	1.4%	0.05	0.8%	0.15	2.3%	-0.05	-0.6%	0.03	0.6%	0.01	0.1%	-0.68	-8.1%	-0.26	-2.9%	-0.03	-0.4%	-0.24	-2.9%
Difference 2005 to 2012 (ft.)	-0.03	-0.6%	0.01	0.4%	-0.07	-1.5%	-0.08	-1.7%	-0.06	-0.9%	-0.07	-0.8%	-0.05	-1.0%	-0.08	-1.3%	-0.08	-1.3%	-0.05	-0.8%	-0.09	-1.1%	-0.05	-1.0%	-0.04	-0.5%	0.03	0.4%	0.13	1.4%	-0.03	-0.4%	0.04	0.5%

Kenner	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	6.1		1.8		4.9		4.9		6.8		7.7		5.2		6.3		6.2		7.3		9.5		4.9		8.6		9.8		9.1		7.5		8.5	
2005 Peak Surge (ft. NAVD88)	6.1		1.8		4.9		5.0		6.9		7.8		5.2		6.5		6.3		7.3		9.6		5.0		8.7		10.0		9.3		7.6		8.5	
2012 Peak Surge (ft. NAVD88)	6.1		1.8		4.9		4.9		6.8		7.7		5.2		6.4		6.2		7.2		9.5		5.0		8.6		10.0		9.3		7.5		8.4	
Difference 1965 to 2012 (ft.)	-0.04	-0.7%	0.01	0.5%	0.00	0.0%	-0.05	-1.0%	0.01	0.1%	-0.02	-0.3%	-0.03	-0.6%	0.08	1.3%	0.04	0.6%	-0.07	-1.0%	-0.02	-0.2%	0.03	0.6%	-0.04	-0.5%	0.22	2.2%	0.17	1.9%	-0.04	-0.5%	-0.02	-0.2%
Difference 2005 to 2012 (ft.)	-0.03	-0.5%	0.01	0.5%	-0.08	-1.6%	-0.07	-1.4%	-0.07	-1.0%	-0.08	-1.0%	-0.05	-1.0%	-0.08	-1.3%	-0.08	-1.3%	-0.09	-1.2%	-0.07	-0.7%	-0.04	-0.8%	-0.06	-0.7%	0.02	0.2%	0.00	0.0%	-0.08	-1.1%	-0.05	-0.6%

Caernarvon	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	7.1		3.0		8.3		8.2		15.1		10.7		9.5		15.0		13.9		16.8		11.7		13.6		10.0		21.9		20.9		18.3		20.6	
2005 Peak Surge (ft. NAVD88)	7.3		3.0		8.6		8.4		15.8		10.8		9.7		15.8		14.7		17.7		12.5		14.5		10.0		22.0		21.0		18.9		20.9	
2012 Peak Surge (ft. NAVD88)	7.4		3.0		8.6		8.4		15.9		10.8		9.7		15.8		14.8		17.9		12.5		14.5		10.0		23.2		21.9		19.2		21.6	
Difference 1965 to 2012 (ft.)	0.29	4.1%	0.00	0.0%	0.25	3.0%	0.14	1.7%	0.81	5.4%	0.11	1.0%	0.20	2.1%	0.82	5.5%	0.82	5.9%	1.06	6.3%	0.82	7.0%	0.94	6.9%	0.09	0.9%	1.27	5.8%	0.97	4.6%	0.91	5.0%	0.98	4.7%
Difference 2005 to 2012 (ft.)	0.01	0.1%	0.00	0.0%	0.01	0.1%	0.01	0.1%	0.06	0.4%	0.07	0.7%	0.01	0.1%	0.04	0.3%	0.04	0.3%	0.20	1.2%	0.04	0.3%	0.02	0.1%	0.06	0.6%	1.17	5.3%	0.92	4.4%	0.32	1.7%	0.76	3.7%

IHNC Surge Barrier	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	10.6		2.0		9.3		7.1		11.8		12.5		7.9		11.4		10.9		12.4		14.0		10.6		12.8		17.8		18.1		13.6		16.1	
2005 Peak Surge (ft. NAVD88)	11.7		2.0		9.7		7.1		12.6		15.5		8.0		12.8		11.9		14.6		17.9		11.6		15.9		19.2		19.9		15.7		17.9	
2012 Peak Surge (ft. NAVD88)	11.9		1.9		9.8		7.2		12.7		15.8		8.1		13.0		12.0		14.9		18.6		11.9		16.3		20.5		21.4		16.2		18.5	
Difference 1965 to 2012 (ft.)	1.36	12.9%	-0.09	-4.4%	0.54	5.8%	0.11	1.6%	0.94	8.0%	3.32	26.6%	0.21	2.7%	1.64	14.4%	1.16	10.7%	2.53	20.4%	4.56	32.5%	1.28	12.1%	3.53	27.6%	2.62	14.7%	3.27	18.0%	2.58	19.0%	2.45	15.2%
Difference 2005 to 2012 (ft.)	0.29	2.7%	-0.09	-4.4%	0.16	1.7%	0.07	1.0%	0.14	1.2%	0.34	2.7%	0.09	1.1%	0.23	2.0%	0.17	1.6%	0.37	3.0%	0.72	5.1%	0.28	2.6%	0.42	3.3%	1.21	6.8%	1.48	8.2%	0.41	3.0%	0.60	3.7%

Shell Beach	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	5.8		7.7		7.7		5.9		9.1		14.1		6.3		8.4		7.8		8.4		10.5		5.7		13.2		13.8		14.6		11.4		13.2	
2005 Peak Surge (ft. NAVD88)	5.8		7.7		7.9		5.9		9.6		14.9		6.4		8.8		8.3		9.0		11.3		6.0		14.1		14.5		15.6		12.1		14.1	
2012 Peak Surge (ft. NAVD88)	5.9		7.7		7.9		6.0		9.7		15.0		6.4		8.9		8.4		9.1		11.5		6.1		14.2		15.2		16.2		12.3		14.4	
Difference 1965 to 2012 (ft.)	0.04	0.7%	0.00	0.0%	0.24	3.1%	0.08	1.4%	0.65	7.2%	0.94	6.7%	0.14	2.2%	0.53	6.3%	0.57	7.3%	0.70	8.3%	1.02	9.7%	0.40	7.1%	1.05	8.0%	1.37	9.9%	1.54	10.5%	0.88	7.7%	1.21	9.2%
Difference 2005 to 2012 (ft.)	0.03	0.5%	0.00	0.0%	0.08	1.0%	0.04	0.7%	0.09	1.0%	0.11	0.8%	0.05	0.8%	0.09	1.1%	0.08	1.0%	0.14	1.7%	0.19	1.8%	0.02	0.4%	0.16	1.2%	0.71	5.1%	0.52	3.6%	0.22	1.9%	0.35	2.7%

Venetian Isles	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	6.7		2.8		7.5		5.5		9.3		12.3		6.1		8.7		8.6		9.5		11.0		7.9		9.2		15.1		15.3		11.2		13.2	
2005 Peak Surge (ft. NAVD88)	7.1		2.8		7.7		5.5		9.8		12.5		6.2		9.3		9.1		10.6		12.8		8.4		10.4		15.6		16.2		12.1		14.1	
2012 Peak Surge (ft. NAVD88)	7.3		2.7		7.8		5.5		9.8		12.6		6.2		9.5		9.2		10.8		13.1		8.5		10.7		16.3		16.9		12.3		14.5	
Difference 1965 to 2012 (ft.)	0.59	8.8%	-0.08	-2.9%	0.28	3.7%	0.07	1.3%	0.54	5.8%	0.28	2.3%	0.14	2.3%	0.75	8.6%	0.61	7.1%	1.25	13.1%	2.17	19.8%	0.58	7.3%	1.49	16.2%	1.21	8.0%	1.62	10.6%	1.11	9.9%	1.28	9.7%
Difference 2005 to 2012 (ft.)	0.16	2.4%	-0.05	-1.8%	0.07	0.9%	0.01	0.2%	0.07	0.8%	0.06	0.5%	0.03	0.5%	0.13	1.5%	0.10	1.2%	0.20	2.1%	0.36	3.3%	0.15	1.9%	0.27	2.9%	0.68	4.5%	0.75	4.9%	0.22	2.0%	0.35	2.7%

Eden Isle	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	3.1		6.1		4.9		4.7		7.3		12.1		5.2		6.5		7.2		7.4		11.7		7.6		6.9		11.5		10.4		7.4		8.6	
2005 Peak Surge (ft. NAVD88)	3.1		6.1		4.9		4.7		7.4		12.4		5.2		6.7		7.4		7.7		12.0		7.7		7.2		11.0		10.4		7.5		8.6	
2012 Peak Surge (ft. NAVD88)	3.1		6.1		4.9		4.7		7.3		12.3		5.2		6.6		7.3		7.7		12.0		7.7		7.2		11.2		10.9		7.6		8.8	
Difference 1965 to 2012 (ft.)	0.00	0.0%	0.01	0.2%	0.01	0.2%	-0.04	-0.8%	0.01	0.1%	0.19	1.6%	-0.04	-0.8%	0.11	1.7%	0.11	1.5%	0.24	3.2%	0.26	2.2%	0.07	0.9%	0.30	4.4%	-0.30	-2.6%	0.48	4.6%	0.22	3.0%	0.19	2.2%
Difference 2005 to 2012 (ft.)	-0.07	-2.3%	0.01	0.2%	-0.05	-1.0%	-0.06	-1.3%	-0.07	-1.0%	-0.03	-0.2%	-0.07	-1.3%	-0.08	-1.2%	-0.07	-1.0%	-0.03	-0.4%	0.02	0.2%	-0.06	-0.8%	0.01	0.1%	0.24	2.1%	0.51	4.9%	0.08	1.1%	0.23	2.7%

Table 3 Continued

Pearlington, MS	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	5.8		2.4		8.0		5.6		9.5		16.3		6.2		10.1		10.2		11.6		15.9		11.4		8.6		15.0		14.4		11.5		12.5	
2005 Peak Surge (ft. NAVD88)	5.9		2.4		8.2		5.6		9.7		16.6		6.3		10.4		10.4		12.0		16.2		11.6		8.9		15.4		14.9		12.0		13.0	
2012 Peak Surge (ft. NAVD88)	5.9		2.4		8.2		5.6		9.8		16.6		6.3		10.5		10.4		12.1		16.3		11.6		8.9		15.8		15.3		12.2		13.2	
Difference 1965 to 2012 (ft.)	0.14	2.4%	0.00	0.0%	0.19	2.4%	0.04	0.7%	0.25	2.6%	0.37	2.3%	0.09	1.5%	0.43	4.3%	0.26	2.6%	0.52	4.5%	0.47	3.0%	0.22	1.9%	0.35	4.1%	0.71	4.7%	0.89	6.2%	0.70	6.1%	0.73	5.9%
Difference 2005 to 2012 (ft.)	0.04	0.7%	0.00	0.0%	0.07	0.9%	0.01	0.2%	0.05	0.5%	0.03	0.2%	0.03	0.5%	0.08	0.8%	0.04	0.4%	0.11	0.9%	0.09	0.6%	0.07	0.6%	0.04	0.5%	0.39	2.6%	0.41	2.8%	0.15	1.3%	0.22	1.8%

Manchac Pass	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	4.3		2.2		3.8		4.4		6.7		4.0		4.7		6.4		5.2		7.5		4.6		8.6		3.2		11.6		9.1		6.8		9.0	
2005 Peak Surge (ft. NAVD88)	4.4		2.2		3.9		4.4		6.9		4.1		4.7		6.5		5.2		7.5		4.7		8.6		3.3		11.2		8.7		6.9		8.8	
2012 Peak Surge (ft. NAVD88)	4.3		2.2		3.8		4.4		6.8		4.1		4.6		6.4		5.2		7.5		4.7		8.5		3.3		11.3		8.9		6.8		8.8	
Difference 1965 to 2012 (ft.)	-0.02	-0.5%	0.01	0.5%	-0.01	-0.3%	-0.04	-0.9%	0.06	0.9%	0.10	2.5%	-0.04	-0.9%	-0.01	-0.2%	-0.02	-0.4%	-0.02	-0.3%	0.11	2.4%	-0.07	-0.8%	0.11	3.4%	-0.30	-2.6%	-0.23	-2.5%	0.03	0.4%	-0.18	-2.0%
Difference 2005 to 2012 (ft.)	-0.04	-0.9%	0.01	0.5%	-0.04	-1.0%	-0.05	-1.1%	-0.12	-1.8%	-0.02	-0.5%	-0.06	-1.3%	-0.11	-1.7%	-0.08	-1.5%	-0.08	-1.1%	0.00	0.0%	-0.06	-0.7%	0.00	0.0%	0.10	0.9%	0.17	1.9%	-0.05	-0.7%	0.02	0.2%

Mandeville	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	5.0		2.0		5.2		5.3		8.5		6.5		5.8		7.0		8.0		8.6		7.6		9.9		4.8		13.2		11.2		7.9		9.7	
2005 Peak Surge (ft. NAVD88)	5.1		2.0		5.3		5.3		8.6		6.8		5.9		7.2		8.1		8.8		7.8		10.0		5.0		12.4		10.7		7.9		9.4	
2012 Peak Surge (ft. NAVD88)	5.0		2.0		5.3		5.3		8.5		6.8		5.8		7.1		8.0		8.7		7.8		9.9		5.0		12.6		10.9		7.9		9.4	
Difference 1965 to 2012 (ft.)	-0.02	-0.4%	0.02	1.0%	0.01	0.2%	-0.05	-0.9%	0.04	0.5%	0.24	3.7%	-0.05	-0.9%	0.12	1.7%	0.06	0.8%	0.12	1.4%	0.28	3.7%	-0.02	-0.2%	0.25	5.2%	-0.60	-4.5%	-0.32	-2.9%	-0.01	-0.1%	-0.28	-2.9%
Difference 2005 to 2012 (ft.)	-0.07	-1.4%	0.02	1.0%	-0.06	-1.1%	-0.07	-1.3%	-0.08	-0.9%	-0.06	-0.9%	-0.09	-1.5%	-0.11	-1.6%	-0.11	-1.4%	-0.09	-1.0%	0.02	0.3%	-0.09	-0.9%	0.00	0.0%	0.16	1.2%	0.16	1.4%	-0.03	-0.4%	0.02	0.2%

LaPlace	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	11.5		1.4		5.9		5.4		8.4		6.4		5.8		10.8		8.4		12.9		10.5		11.2		9.6		14.9		12.1		12.6		12.0	
2005 Peak Surge (ft. NAVD88)	11.5		1.4		5.9		5.4		8.6		6.5		5.9		10.8		8.4		13.0		10.6		11.2		9.6		15.0		12.4		12.6		12.3	
2012 Peak Surge (ft. NAVD88)	11.5		1.4		5.8		5.3		8.5		6.5		5.8		10.7		8.3		12.9		10.6		11.1		9.5		15.1		12.4		12.6		12.3	
Difference 1965 to 2012 (ft.)	-0.03	-0.3%	0.00	0.0%	-0.07	-1.2%	-0.06	-1.1%	0.06	0.7%	0.03	0.5%	-0.05	-0.9%	-0.04	-0.4%	-0.05	-0.6%	-0.03	-0.2%	0.01	0.1%	-0.06	-0.5%	-0.06	-0.6%	0.20	1.3%	0.29	2.4%	0.01	0.1%	0.23	1.9%
Difference 2005 to 2012 (ft.)	-0.03	-0.3%	0.00	0.0%	-0.06	-1.0%	-0.08	-1.5%	-0.09	-1.1%	-0.05	-0.8%	-0.09	-1.5%	-0.07	-0.6%	-0.09	-1.1%	-0.06	-0.5%	-0.02	-0.2%	-0.06	-0.5%	-0.07	-0.7%	0.06	0.4%	0.04	0.3%	-0.03	-0.2%	0.00	0.0%

MSY Airport	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	7.6		1.4		4.8		4.8		6.5		9.5		5.1		6.4		6.4		8.4		11.8		5.0		11.2		11.7		11.4		9.5		10.4	
2005 Peak Surge (ft. NAVD88)	7.5		2.1		4.9		4.9		6.7		9.7		5.2		6.4		6.6		8.7		11.9		5.0		11.2		11.8		11.5		9.5		10.4	
2012 Peak Surge (ft. NAVD88)	7.5		2.1		4.8		4.8		6.6		9.7		5.1		6.3		6.5		8.6		12.5		5.0		11.6		12.5		12.0		9.8		10.7	
Difference 1965 to 2012 (ft.)	-0.13	-1.7%	0.70	49.3%	0.02	0.4%	-0.06	-1.2%	0.09	1.4%	0.19	2.0%	-0.04	-0.8%	-0.08	-1.3%	0.03	0.5%	0.17	2.0%	0.61	5.2%	0.03	0.6%	0.40	3.6%	0.81	6.9%	0.58	5.1%	0.30	3.2%	0.35	3.4%
Difference 2005 to 2012 (ft.)	-0.02	-0.3%	0.01	0.7%	-0.08	-1.7%	-0.09	-1.9%	-0.12	-1.9%	-0.06	-0.6%	-0.06	-1.2%	-0.09	-1.4%	-0.11	-1.7%	-0.05	-0.6%	0.58	4.9%	-0.03	-0.6%	0.40	3.6%	0.71	6.1%	0.48	4.2%	0.27	2.8%	0.28	2.7%

Braithwaite	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	6.5		2.0		8.3		8.4		15.5		9.4		9.7		15.3		13.6		16.6		10.8		12.5		10.9		23.0		21.1		18.9		21.7	
2005 Peak Surge (ft. NAVD88)	6.7		2.0		8.6		8.5		16.2		9.5		9.9		16.1		14.4		17.4		11.3		13.4		11.0		23.2		21.2		19.6		21.9	
2012 Peak Surge (ft. NAVD88)	6.7		2.0		8.6		8.5		16.3		9.6		9.9		16.1		14.4		17.5		11.4		13.4		10.9		23.9		21.7		19.8		22.4	
Difference 1965 to 2012 (ft.)	0.21	3.2%	0.00	0.0%	0.24	2.9%	0.14	1.7%	0.77	5.0%	0.18	1.9%	0.17	1.7%	0.76	5.0%	0.81	6.0%	0.96	5.8%	0.54	5.0%	0.91	7.3%	0.02	0.2%	0.88	3.8%	0.64	3.0%	0.83	4.4%	0.70	3.2%
Difference 2005 to 2012 (ft.)	0.01	0.2%	0.00	0.0%	0.00	0.0%	0.01	0.1%	0.05	0.3%	0.07	0.7%	0.00	0.0%	0.04	0.3%	0.03	0.2%	0.12	0.7%	0.04	0.4%	0.02	0.2%	-0.01	-0.1%	0.73	3.2%	0.56	2.7%	0.22	1.2%	0.45	2.1%

Jean Lafitte	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	5.1		2.2		3.0		3.6		4.9		1.3		3.9		5.5		4.3		6.7		2.4		8.3		2.3		13.9		4.1		5.9		8.5	
2005 Peak Surge (ft. NAVD88)	5.1		2.2		3.0		3.6		4.9		1.3		3.9		5.5		4.3		6.7		2.4		8.3		2.3		14.0		4.2		5.9		8.6	
2012 Peak Surge (ft. NAVD88)	5.2		2.2		3.1		3.6		5.1		1.3		3.9		5.6		4.3		6.7		2.5		8.5		2.3		14.8		4.5		5.9		9.1	
Difference 1965 to 2012 (ft.)	0.03	0.6%	0.01	0.5%	0.02	0.7%	0.02	0.6%	0.11	2.2%	0.00	0.0%	0.02	0.5%	0.03	0.5%	0.02	0.5%	0.02	0.3%	0.04	1.7%	0.20	2.4%	0.00	0.0%	0.95	6.8%	0.36	8.7%	0.00	0.0%	0.63	7.4%
Difference 2005 to 2012 (ft.)	0.02	0.4%	0.01	0.5%	0.02	0.7%	0.02	0.6%	0.11	2.2%	0.00	0.0%	0.02	0.5%	0.02	0.4%	0.01	0.2%	0.01	0.1%	0.04	1.7%	0.20	2.4%	0.00	0.0%	0.78	5.6%	0.28	6.8%	0.00	0.0%	0.51	6.0%

Table 3 Continued

Lafitte	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	6.2		1.5		3.5		3.8		5.5		1.3		4.2		6.6		5.0		7.8		2.8		8.7		2.6		14.9		5.0		7.4		8.9	
2005 Peak Surge (ft. NAVD88)	6.2		1.5		3.5		3.8		5.5		1.3		4.2		6.6		5.0		7.8		2.7		8.7		2.6		15.0		5.0		7.4		9.0	
2012 Peak Surge (ft. NAVD88)	6.2		1.5		3.5		3.8		5.5		1.3		4.2		6.6		5.0		7.8		2.8		8.7		2.6		15.7		5.2		7.4		9.3	
Difference 1965 to 2012 (ft.)	0.01	0.2%	-0.01	-0.7%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.02	0.2%	0.00	0.0%	0.82	5.5%	0.20	4.0%	0.00	0.0%	0.41	4.6%
Difference 2005 to 2012 (ft.)	0.01	0.2%	-0.01	-0.7%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	-0.01	-0.2%	0.00	0.0%	0.01	0.4%	0.02	0.2%	0.00	0.0%	0.66	4.4%	0.15	3.0%	0.00	0.0%	0.31	3.5%

Crown Point	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	5.4		1.8		3.0		3.8		5.7		1.3		3.9		5.7		4.4		7.2		2.2		9.2		2.0		15.5		5.8		5.9		10.2	
2005 Peak Surge (ft. NAVD88)	5.4		1.8		3.0		3.8		5.7		1.3		3.9		5.7		4.4		7.2		2.2		9.2		2.0		15.7		5.9		5.9		10.3	
2012 Peak Surge (ft. NAVD88)	6.0		2.4		3.2		3.9		6.2		1.3		4.2		6.1		4.9		7.5		2.4		9.6		2.0		17.0		6.7		6.4		11.5	
Difference 1965 to 2012 (ft.)	0.57	10.6%	0.57	31.0%	0.21	6.9%	0.05	1.3%	0.53	9.3%	0.00	0.0%	0.25	6.4%	0.39	6.9%	0.50	11.4%	0.32	4.5%	0.21	9.4%	0.38	4.1%	0.03	1.5%	1.53	9.9%	0.93	16.1%	0.49	8.3%	1.35	13.3%
Difference 2005 to 2012 (ft.)	0.57	10.6%	0.57	31.0%	0.21	6.9%	0.05	1.3%	0.53	9.3%	0.00	0.0%	0.25	6.4%	0.38	6.7%	0.49	11.2%	0.31	4.3%	0.21	9.4%	0.37	4.0%	0.03	1.5%	1.31	8.5%	0.77	13.3%	0.49	8.3%	1.20	11.8%

Waveland	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	6.2		13.1		9.4		5.4		8.4		24.5		6.0		10.2		9.5		11.6		18.3		11.4		15.7		13.5		13.6		11.6		11.5	
2005 Peak Surge (ft. NAVD88)	6.3		13.1		9.5		5.4		8.6		24.7		6.0		10.3		9.6		11.8		18.5		11.4		15.8		13.7		13.9		11.8		11.8	
2012 Peak Surge (ft. NAVD88)	6.3		13.1		9.5		5.4		8.6		24.7		6.0		10.3		9.6		11.8		18.6		11.5		15.8		13.9		14.0		11.9		11.9	
Difference 1965 to 2012 (ft.)	0.08	1.3%	0.00	0.0%	0.03	0.3%	0.01	0.2%	0.21	2.5%	0.22	0.9%	0.02	0.3%	0.13	1.3%	0.12	1.3%	0.19	1.6%	0.25	1.4%	0.08	0.7%	0.09	0.6%	0.41	3.0%	0.41	3.0%	0.26	2.2%	0.34	3.0%
Difference 2005 to 2012 (ft.)	0.03	0.5%	0.00	0.0%	0.01	0.1%	0.01	0.2%	0.03	0.4%	0.02	0.1%	0.01	0.2%	0.04	0.4%	0.03	0.3%	0.04	0.3%	0.04	0.2%	0.03	0.3%	0.02	0.1%	0.16	1.2%	0.12	0.9%	0.06	0.5%	0.07	0.6%

Boutte	Betsy		Camille		Gustav		Ike		Isaac		Katrina		Rita		S008		S012		S014		S023		S069		S077		S085		S094		S126		S146	
1965 Peak Surge (ft. NAVD88)	3.7		1.9		2.9		3.6		4.0		1.9		3.8		5.4		3.2		5.0		1.9		7.2		2.2		1.9		2.1		5.0		4.9	
2005 Peak Surge (ft. NAVD88)	3.7		1.9		2.9		3.6		4.0		1.9		3.8		5.4		3.2		5.0		1.9		7.2		2.2		1.9		2.1		5.0		5.0	
2012 Peak Surge (ft. NAVD88)	3.7		1.9		2.9		3.7		4.1		1.9		3.8		5.4		3.3		5.0		1.9		7.5		2.2		1.9		2.2		5.0		5.2	
Difference 1965 to 2012 (ft.)	0.00	0.0%	0.00	0.0%	0.01	0.3%	0.02	0.6%	0.05	1.2%	0.00	0.0%	0.02	0.5%	0.03	0.6%	0.02	0.6%	0.04	0.8%	0.00	0.0%	0.33	4.6%	0.01	0.5%	0.00	0.0%	0.06	2.8%	0.01	0.2%	0.34	7.0%
Difference 2005 to 2012 (ft.)	-0.01	-0.3%	0.00	0.0%	0.00	0.0%	0.01	0.3%	0.05	1.2%	0.00	0.0%	0.01	0.3%	0.02	0.4%	0.02	0.6%	0.04	0.8%	0.00	0.0%	0.32	4.5%	0.01	0.5%	0.00	0.0%	0.06	2.8%	0.00	0.0%	0.28	5.7%

Figure 30 displays a regression plot comparing individual peak storm surge values from the SL15-2012 grid against the SL15-1965 grid at the IHNC Surge Barrier location. The small red dots represent the peak surge values. A 2nd order polynomial trendline, which is plotted as a green line, has been fitted to the data. Fifty (50)-year, 100-year, 200-year and 500-year statistics from the IHNC Surge Barrier frequency analysis are plugged into the trendline to estimate the corresponding statistics that would be produced on the SL15-1965 grid. The IHNC Surge Barrier frequency analysis was conducted to determine with-project design water levels for the IHNC Surge Barrier and surrounding GNO HSDRRS components. Figure 28 shows the 100-year from the SL15-2012 condition is roughly 17.5 ft NAVD88, while the estimated 100-year surge from the SL15-1965 grid is 14.7 ft NAVD88. Using this approach, one can estimate that the post-Betsy federal levees and GNO HSDRRS have increased the 50-year surge by 2.0 ft, increased the 100-year by 2.8 ft, increased the 200-year by 3.3ft, and increased the 500-year by 4.0 ft at the immediate location of the IHNC Surge Barrier. These estimates are based on a simple trend between surge values produced on the SL15-1965 and SL15-2012 grids.

Figure 29 displays the same regression analysis, but at the Venetian Isles, New Orleans, LA location. The estimates show that the 50-year surge is increased 1.0 ft, the 100-year is increased by 1.2 ft, the 200-year is increased 1.4 ft, and the 500-year is increased 1.6 ft at the immediate location of Venetian Isles. These increases can be attributes to the combined effects of construction of the post-Betsy federal levees and the GNO HSDRRS.

Figure 30 displays the same regression analysis, but at the Eden Isle, Slidell, LA location. Here regression analysis estimates a smaller increase between the SL15-1965 and SL15-2012 statistical surge estimates. The estimates show that the 50-year surge is increased 0.1 ft, the 100-year is increased by 0.2 ft, the 200-year is increased 0.2 ft, and the 500-year is increased 0.2 ft.

Table 4 contains the results of the regression analysis at all locations of interest. The results in Table 4 show that the impact to peak surge values depends heavily on location and proximity to the GNO HSDRRS. In general, the impacts are greatest in the areas immediate adjacent to the GNO HSDRRS; impacts diminish as the distance from the GNO HSDRRS increases. Table 4 shows that the absolute change in water level depends also on the return period, although the percent change is similar across all return periods.

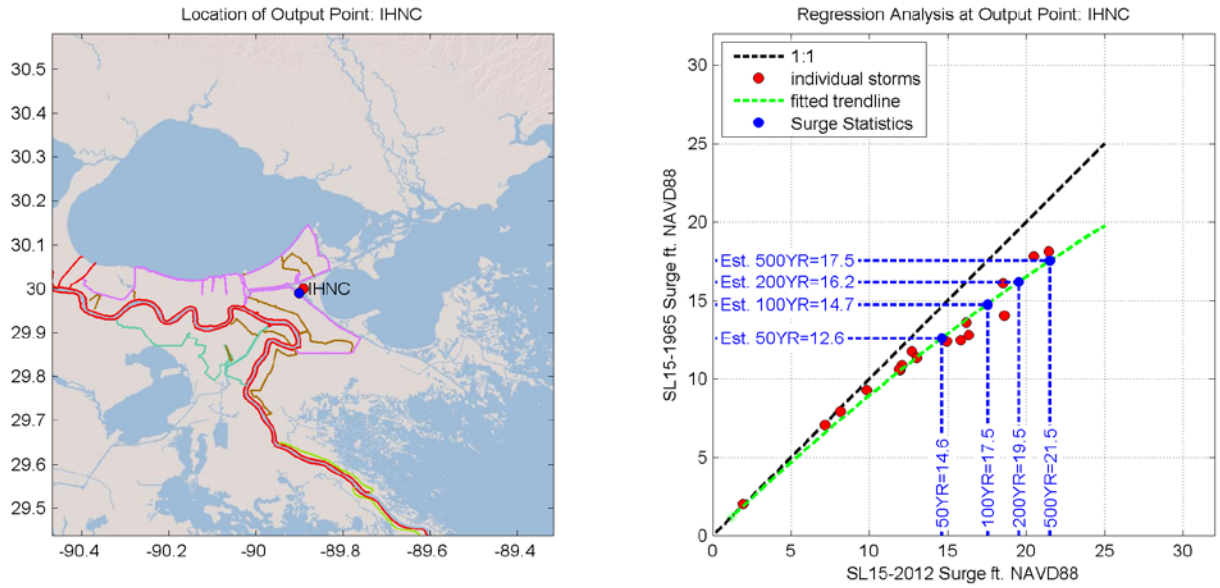


Figure 28 Surge Frequency Regression Analysis at IHNC

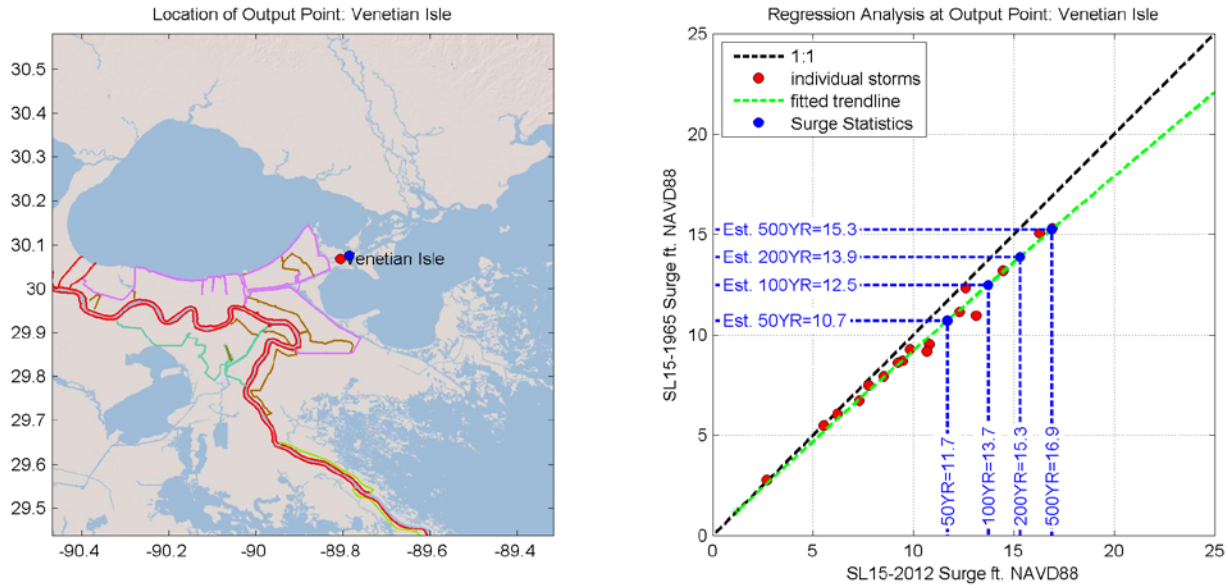


Figure 29 Surge Frequency Regression Analysis at Venetian Isle

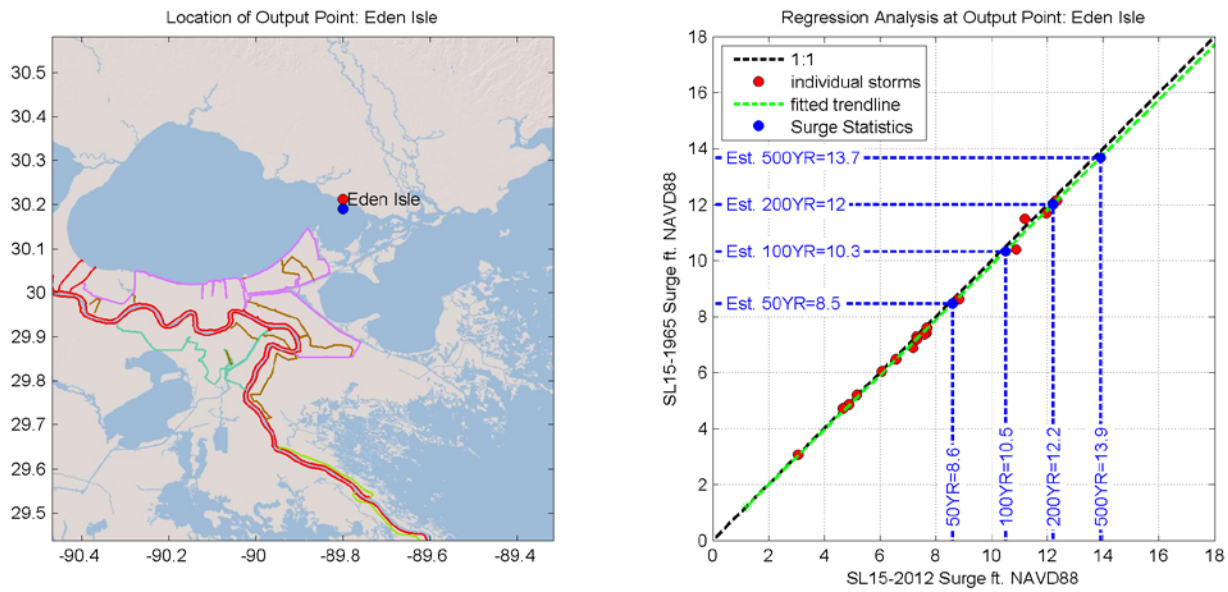


Figure 30 Surge Frequency Regression Analysis at Eden Isle

Table 4 Summary of Regression Analysis at all Output Locations

			Sl15-2012 Stage-frequency (ft. NAVD88 2004.65)				Sl15-1965 Est. Stage-frequency (ft. NAVD88 2004.65)				Difference (ft) and Percent Difference for various return periods							
Location	Long	Lat	50 YR	100 YR	200 YR	500 YR	50 YR	100 YR	200 YR	500 YR	50 Yr Dif	50 Yr %Dif	100 Yr Dif	100 Yr %Dif	200 Yr Dif	200 Yr %Dif	500 Yr Dif	500 Yr %Dif
Metairie	-90.144	30.028	7.8	9.1	10.2	11.5	7.9	9.3	10.5	12.0	-0.1	-1%	-0.2	-2%	-0.3	-3%	-0.5	-4%
Kenner	-90.236	30.047	7.9	9.1	10.2	11.3	7.9	9.0	10.1	11.1	0.0	0%	0.1	1%	0.1	1%	0.2	2%
Caernarvon	-89.906	29.842	14.6	17.7	19.8	21.9	14.0	16.9	18.8	20.8	0.6	4%	0.8	5%	1.0	5%	1.1	5%
IHNC Surge Barrier	-89.891	29.999	14.6	17.5	19.5	21.5	12.6	14.7	16.2	17.5	2.0	16%	2.8	19%	3.3	20%	4.0	23%
Shell Beach	-89.678	29.856	10.7	12.5	14.1	16.0	10.0	11.6	13.0	14.6	0.7	7%	0.9	8%	1.1	8%	1.4	10%
Venetian Isles	-89.807	30.069	11.7	13.7	15.3	16.9	10.7	12.5	13.9	15.3	1.0	9%	1.2	10%	1.4	10%	1.6	10%
Eden Isle	-89.801	30.212	8.6	10.5	12.2	13.9	8.5	10.3	12.0	13.7	0.1	1%	0.2	2%	0.2	2%	0.2	1%
Pearlington, MS	-89.616	30.236	11.6	13.9	16.0	18.4	11.2	13.4	15.4	17.6	0.4	4%	0.5	4%	0.6	4%	0.8	5%
Manchac Pass	-90.397	30.286	7.1	8.3	9.3	10.3	7.1	8.4	9.5	10.5	0.0	0%	-0.1	-1%	-0.2	-2%	-0.2	-2%
Mandeville	-90.075	30.351	8.2	9.6	10.7	11.8	8.2	9.7	10.9	12.2	0.0	0%	-0.1	-1%	-0.2	-2%	-0.4	-3%
LaPlace	-90.416	30.096	7.3	9.6	11.3	13.0	7.3	9.6	11.3	12.9	0.0	0%	0.0	0%	0.0	0%	0.1	1%
MSYAirport	-90.285	30.001	9.3	11.0	12.3	13.8	9.1	10.6	11.7	13.0	0.2	2%	0.4	4%	0.6	5%	0.8	6%
Braithwaite	-89.963	29.811	14.4	17.7	20.0	22.1	13.8	17.0	19.2	21.2	0.6	4%	0.7	4%	0.8	4%	0.9	4%
Jean Lafitte	-90.129	29.734	5.3	7.0	8.4	9.9	5.2	6.8	8.1	9.5	0.1	2%	0.2	3%	0.3	4%	0.4	4%
Lafitte	-90.112	29.667	6.0	7.8	9.3	11.0	6.0	7.7	9.1	10.7	0.0	0%	0.1	1%	0.2	2%	0.3	3%
Crown Point	-90.081	29.769	5.7	7.5	9.1	10.9	5.3	6.9	8.3	9.9	0.4	8%	0.6	9%	0.8	10%	1.0	10%
Waveland	-89.368	30.280	13.1	15.6	17.8	20.2	12.9	15.4	17.6	20.0	0.2	2%	0.2	1%	0.2	1%	0.2	1%
Boutte	-90.374	29.895	3.2	3.6	4.0	4.3	3.2	3.6	4.0	4.2	0.0	0%	0.0	0%	0.0	0%	0.1	2%

4.0 Conclusions and Discussion

The purpose of this modeling is to assess the impacts to surge levels due to construction of the GNO HSDRRS on communities inside and outside the system. The analysis evaluates the projected storm surge levels in areas outside the GNO HSDRRS as the levee system existed in the years 1965 (pre-Betsy, pre-federal levees), 2005 (pre-Katrina) and 2012 (post-GNO HSDRRS construction). The analysis describes and evaluates the past, present and potential cumulative storm surge impacts of the completed GNO HSDRRS on the surrounding areas. Prior to construction of the post-Betsy federal levees, local levees existed in many areas including New Orleans East and the New Orleans metropolitan area. Prior to construction of the post-Betsy federal levees, the St. Bernard area had no levees along the MRGO, although surveys show a spoil bank with modest elevation. The SL15-1965 grid is simply a version of the SL15-2005 grid with elevations lowered to match pre-Betsy surveys of St. Bernard, New Orleans East and the east side of the New Orleans metropolitan area. The SL15-1965 and SL15-2005 grids are the same in the WBV project area, as very little levee construction occurred on the west bank during this time period.

Flood risk reduction features, including levees, floodwalls, floodgates and surge barriers reduce the risk of flooding in the Greater New Orleans area. When these features prevent water from flowing into the interior, the surrounding surge levels are amplified. This effect is most pronounced in the immediate vicinity of major modifications to the existing levee elevations such as the IHNC Surge Barrier and West Closure Complex. The effect is less pronounced with increased distance from the major modifications. This analysis provides estimates of these impacts for a variety of past and synthetic storms. The storms which have the most impact are the intense synthetic storms which follow critical tracks for the New Orleans area.

The analysis provides some examples of past storms, and a small sample of synthetic storms. From this small subset of 17 storms, we can estimate the changes to surge frequency at the surrounding communities using a regression analysis. The surge frequency regression analysis, presented in Figures 29 through Figure 30 and summarized in Table 4, shows that the changes to the stage-frequency depend heavily on location. In general, the impacts are greatest in the areas immediate adjacent to the GNO HSDRRS; impacts diminish as the distance from the GNO HSDRRS increases.

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APPENDIX A
Maximum Elevation Plots SL15-1965, SL15-2005, SL15-2012

APPENDIX B
Difference Plots SL15-1965 vs SL15-2012

APPENDIX C
Difference Plots SL15-2005 vs SL15-2012