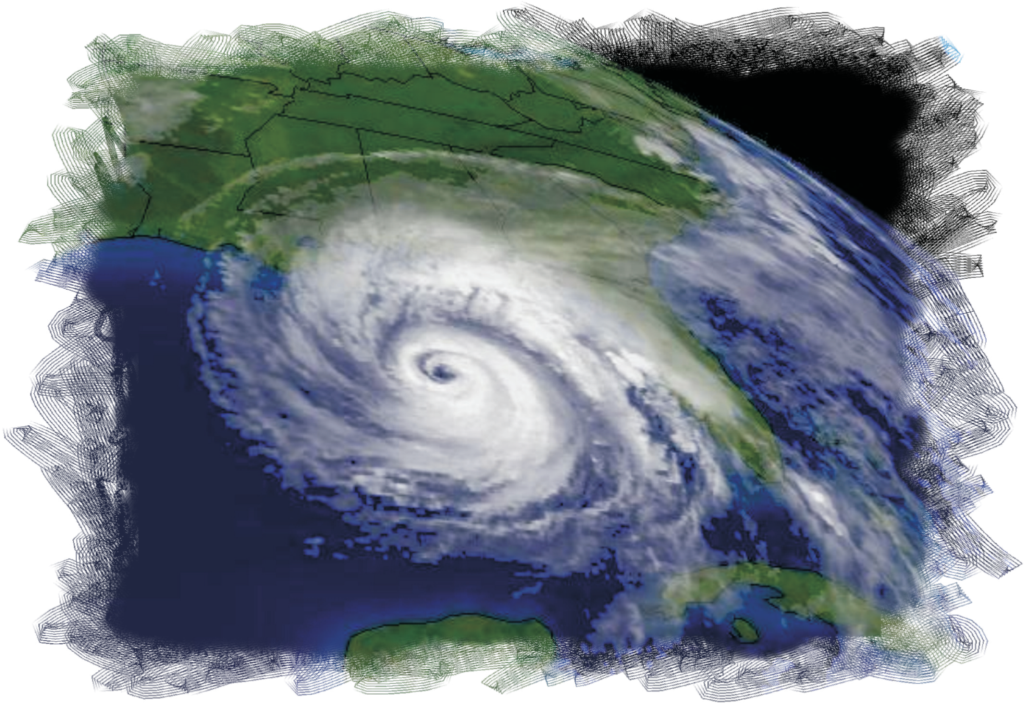
FINAL REPORT

THE DIRECT IMPACT OF THE MRGO ON HURRICANE STORM SURGE

Preformed under:

Contract No. 2503-05-39
Hydrodynamic Modeling Effort for MRGO Study



Prepared for:

State of Louisiana
Department of Natural Resources

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In March 2005 URS Corporation (URS) was tasked by the Louisiana Department of Natural Resources (LDNR) to evaluate the impact of the Mississippi River Gulf Outlet (MRGO) on regional hurricane storm surge by examining the *immediate and direct* effects using a hydrodynamic model of certain selected storms. In October 2005, LDNR requested that URS include modeling of Hurricane Katrina in this evaluation. The URS task follows a 2003 US Army Corps of Engineers (Corps) report on the effect of blocking the MRGO at Bayou La Loutre on hurricane storm surge.

The URS project team reviewed the 2003 Study results and identified seven additional factors for further study:

1. The impact of complete closure (i.e., filling in) of MRGO;
2. The effect on surge across the entire study area;
3. The influence on surge scour velocity;
4. The impact on storm surge arrival and draining;
5. The impact of a severe storm;
6. The sensitivity of storm surge to levee alignment; and
7. The effect of the MRGO on levee wave run-up.

URS conducted a total of seven simulations using three hurricanes—a 124-Knot-Fast Synthetic Storm, Hurricane Betsy, and Hurricane Katrina—including comparisons of MRGO Baseline versus Closure Scenarios. The simulations were conducted using the ADCIRC hydrodynamic model and the 2003 grid. MRGO closure was represented by filling in the channel to an elevation equivalent to approximately 1 foot above mean sea level. A levee alignment sensitivity simulation was conducted using the .levees along the south bank of the GIWW and the MRGO, and the intermediate levee at the 40 Arpent Canal. URS also provided a wave run-up analysis.

URS understands that public concern for the MRGO's *immediate and direct* contribution to storm surge is part of a broad interest in the full range of the MRGO's *long-term* impacts on the regional communities and environment. Especially given the effects of Hurricane Katrina, there is a justified interest in all measures that might protect human life and aid in restoring the economic, cultural, and ecological resources of the area for generations to come. This phase of work, however, only provides the findings and recommendations associated with modeling the surge impact of the MRGO for hurricanes under present conditions.

Major conclusions of this study are:

- The MRGO channel does not contribute significantly to peak surge during severe storms, when the conveyance of surge is dominated by flow across the entire surface of the coastal lakes and marsh. Nor does the channel contribute significantly to wave run-up.
- Complete filling of the MRGO—or blockage or partial filling—will not provide significant *immediate, direct* mitigation of severe storm surge.
- For a few locations outside the Hurricane Protection System (HPS) closure of the MRGO may reduce the peak surge for certain fast, low-to-moderate storms, when the surge is not dominated by flow across the open lakes and marsh, and may modestly delay the onset of surge.
- For some storms and locations MRGO closure would slightly *increase* storm surge peaks and impair draining of storm surge following the storm passage.
- MRGO closure would significantly reduce surge scour velocities at some channel locations, which is important to soft swamp and marsh organic soils.
- Natural and man-made landform alignments (passes, ridges, levees, etc.) can create surge concentration under certain storm conditions. The effect of the "funnel" formed by levees along the GIWW and MRGO in concentrating surge was evident in Hurricane Betsy but not in Hurricane Katrina. However, closure of the MRGO did not significantly impact the surge at the "funnel" for either storm. Widening the funnel in the sensitivity simulation actually resulted in an increase in surge at the IHNC.

The above findings on the role of the MRGO on storm surge imply that the surge conveyance of the MRGO is not an important factor in establishing *near-term* HPS requirements. *Near-term* HPS requirements should be based on a thorough analysis of surge height recurrence frequency—and those factors that can reasonably be expected to effect total surge heights—and the costs and benefits of alternative degrees of protection.

URS recommends that LDNR conduct further evaluations to better understand the *long-term* role of the MRGO on storm surges and the future implications of various closure scenarios of the MRGO, including:

- Develop an improved, high resolution ADCIRC grid of the MRGO and surrounding area, with accurate representation of the channel, and regional topography and bathymetry corrected to updated NAVD-88 benchmarks.

- Conduct calibration studies using the improved grid for a range of tidal and storm events.

- Perform surge simulations using the improved grid to better resolve locations of impact, and degrees of impact (positive and negative), for various MRGO baseline and closure scenarios.

- Evaluate the effect of various MRGO closure alternatives, subsidence, erosion, and sea level rise, and restoration measures—such as controlling saltwater intrusion and introducing freshwater from the Mississippi River—on the long-term regional landscape.

- Develop ADCIRC grids to represent long-term landscape scenarios and use them to study the future impact of natural processes, MRGO alternatives, regional wetland restoration alternatives, and other landscape changes on hurricane storm surge.

In March 2005 URS Corporation (URS) was tasked by the Louisiana Department of Natural Resources (LDNR) to evaluate the impact of the Mississippi River Gulf Outlet (MRGO) on regional hurricane storm surge by examining the *immediate and direct* effects using a hydrodynamic model of certain selected storms. In October 2005, LDNR requested that URS include modeling of Hurricane Katrina in this evaluation. This study was always intended as a preliminary evaluation of this specific issue, which—as this Introduction and Background show—is part of a broader, more fundamental, suite of concerns requiring careful examination. Nevertheless, a correct understanding of the MRGO's role in storm surge conveyance is one important key to establishing a sound scientific and engineering approach to protecting and restoring St. Bernard Parish and eastbank Orleans Parish.

1.1 OBJECTIVES AND ORGANIZATION

Due to the extensive media coverage and public attention directed at the impact of the MRGO on storm surge, it is important to understand the objectives and limited scope of this phase of work. The URS task is a follow-on to earlier modeling performed the US Army Corps of Engineers (Corps). In 2003 the Corps—as part of an assessment of options to reduce salinity intrusion caused by the MRGO—evaluated the impact of a saltwater barrier at Bayou LaLoutre on mitigating hurricane storm surge. The 2003 Study concluded that "the MRGO has minimal influence upon storm surge propagation." (A copy of the 2003 Study is included as Attachment 1 and is discussed in Section 2).

Since the 2003 Study only addressed blocking of the MRGO at Bayou La Loutre, the LDNR asked URS to evaluate the surge mitigation effects of totally filling the channel. The URS task examines this question with the following limitations:

- The URS simulations examine the impact of closing the MRGO channel—that portion which extends southeast from the Gulf Intracoastal Waterway (GIWW) to Breton Sound. The simulations do not look at possible impacts of filling or blocking the GIWW (e.g., at Paris Road).

- As an economical first effort the task was limited to the use of three "diagnostic" storms (one synthetic storm, Hurricane Betsy, and Hurricane Katrina), rather than a comprehensive suite of storms with widely varying intensities, sizes, tracks, and forward speeds. URS would recommend further simulations warranted by the results of this phase of work.

- The past and future effects of the MRGO on regional landforms (e.g., wetlands) and the impact of regional landform changes on storm surge are beyond the scope of this modeling task. This task examines only the *immediate* and *direct* impacts of MRGO closure on hurricane storm surge under current conditions.

The remainder of Section 1 provides background information for this report. The following topics are addressed in the ensuing sections:

Section 2.	The 2003 Corps Study
Section 3.	Factors for Further Study
Section 4.	Modeling of 124-Knot Synthetic Storm
Section 5.	Modeling of Hurricane Betsy
Section 6.	Modeling of Hurricane Katrina
Section 7.	Modeling of Levee Alignment Sensitivity
Section 8.	Wave Run-Up Analysis
Section 9.	Conclusions
Section 10.	Recommendations

1.2 THE MRGO AND VICINITY

The MRGO is a 76 mile man-made navigation channel bisecting the wetlands of St. Bernard Parish and connecting the GIWW in eastern New Orleans to Breton Sound and the Gulf of Mexico (see Figure 1). Construction of the 500-foot wide 36-foot deep MRGO was completed in 1968 by the Corps at a cost of $92 million. The MRGO facilitated the development of port facilities and expansion of commerce along the GIWW and Inner Harbor Navigation Canal (IHNC). The Corps has routinely performed dredging (typically to depths of 40 feet) to maintain the channel.

The region surrounding the MRGO is dominated by low-lying coastal wetlands, including cypress swamp, fresh-intermediate marsh, brackish marsh, and saline marsh. These wetlands are tidally connected to the adjacent coastal waterbodies—Lake Borgne and Breton Sound. Aside from minor remnant ridges, these wetlands are typically less than 2 feet above the local mean sea level (MSL) of the coastal lakes and bays.

The New Orleans urban area developed into eastern Orleans Parish and into St. Bernard Parish along the higher natural Mississippi River levee and swamp ridges, which commonly lie several feet above MSL. Development through the 20th Century expanded into adjacent swamps, which were drained by an extensive network of canals and pump stations.

Several small fishing villages, including Reggio, Yscloskey, Shell Beach, Hopedale, and Delacroix in St. Bernard Parish, arose near the coast. These communities, along with the roadways leading to them, were established on low natural ridges of abandoned deltaic distributaries at elevations a few feet above MSL.

1.3 LOCAL HURRICANE STORM SURGE THREAT

The more heavily developed portions of the New Orleans area are surrounded by a Hurricane Protections System (HPS) of levees and floodwalls. Major upgrades to the regional HPS were begun by the Corps in the 1960s in the wake of Hurricane Betsy. The HPS was typically designed to handle the surge from a "standard project hurricane" (equivalent to a fast-moving Category 3 hurricane). The HPS and floodgates are largely owned, operated, and maintained by local Levee Districts (e.g., Lake Borgne Levee District in St. Bernard Parish).

The coastal fishing villages lie outside the HPS. Given their low elevation, these communities are susceptible to significant damage from even minor tropical storm surge events. Moreover, evacuation in the face of a major hurricane is severely hampered by the advancement of high water and inundation of routes to safety.

Regional storm surge risks are magnified by the subsidence of the drained swamplands within the levee system. Such areas have subsided many feet below MSL, resulting in topography that resembles a large "bowl". Gradual post-construction settlement of the levees also exacerbates inundation risk. Communities and key evacuation roads outside of the levee system are also subsiding. Ironically, it is only those healthy coastal wetlands sustained by natural or simulated deltaic nourishment which maintain their elevation (primarily through the accretion of natural detritus).

Table 1 summarizes the basic characteristics of tropical cyclones based on the Saffir-Simpson Scale:

Table 1
Saffir-Simpson Scale for Tropical Cyclone Characteristics

Category	Winds (mph)	Central Pressure (mb)	Storm Surge (feet)
Tropical Depression	<39		
Tropical Storm	39-73		
1	74-95	> 980	3 to 5
2	96-110	979-965	6 to 8
3	111-130	964-945	9 to 12
4	131-155	944-920	13 to18
5	greater than 155	< 920	19+

The probability that any hurricane will pass within 75 miles of New Orleans in any given year is about 12.5 percent, or about once every 8 years. The odds of a major hurricane (Category 3 and above) passing within 75 miles are about 3.2 percent per year, or about once every 30 years (see Sheets, *Hurricane Watch*, Appendix D, 2001).

Following close calls with Hurricanes Andrew (1994), Georges (1998), Isadore (2003), and Lily (2003) there was increasing research attention, public awareness, and governmental concern for the threat to life, public health, and the regional economy posed by severe hurricane storm surge in southeast Louisiana. For example, the LSU Center for the Study of Public Health Impact of Hurricanes began a five-year study, *Assessment and Remediation of Public Health Impacts Due to Hurricanes and Major Flooding Events*. The ability of levees to withstand storm surge, problems of evacuation, and the catastrophic consequences of inundating the “bowl,” became front page news and a priority for federal, state, and local emergency planning and response officials. In February 2001, in response to post-Hurricane Georges assessments, the Corps drafted an“unwatering” plan for New Orleans. In June 2002 the New Orleans Times-Picayune ran a multi-day feature: *Special Report*: *Washing Away*. In July 2004 the Louisiana Office of Emergency Preparedness in conjunction with the Federal Emergency Management Agency (FEMA) conducted a planning exercise, which featured widespread inundation of the New Orleans area from a simulated Hurricane Pam, a slow-moving, large Category 3 hurricane.. In October 2004 Category 4 Hurricane Ivan threatened southeast Louisiana, precipitating a full-scale evacuation of hundreds of thousands of people.

Hurricane Katrina, a large storm with Category 5 winds up until a few hours before landfall, struck southeast Louisiana at dawn on August 29, 2005. The hurricane center passed due north through the eastern flank of St. Bernard Parish. In the ensuing, hours, days and weeks the storm's impacts far exceeded the preparations of all governments, private organizations, and individuals. As of this date the total storm related fatalities in Louisiana have reached 1,100—128 in St. Bernard Parish and 286 in the Lower 9th Ward. The number of area homes that may ultimately have to be demolished may reach the tens of thousands.

1.4 PREVIOUS STUDIES OF LOCAL HURRICANE STORM SURGE

Following Hurricane Betsy in 1965, the Corps calculated storm surge heights using a standard project hurricane—without the advantages of today's complex computer models. In the *1970 Flood Insurance Study for the Louisiana Gulf Coast*, the Corps estimated the 10, 50, 100, 200, and 500 years storm surge elevations in St. Bernard Parish south of Lake Borgne at 7.0, 11.1, 12.2, 13.0, and 13.7 feet MSL. The Corps designed floodwalls and levees in the MRGO-GIWW area to elevations of roughly 14 to 17.5 feet above NGVD-29. Pre-Katrina surveys have shown that some portions of the HPS were more than two feet below design grade (information provided by Lake Borgne Levee District).[*]

Beginning in the 1980s the FEMA and the National Oceanic and Atmospheric Administration (NOAA) began to undertake more sophisticated numerical computer modeling of storm surge (see Table 2). Throughout the 1990s models became more readily used by planning agencies, such as the *Southeast Louisiana Hurricane Preparedness Study* prepared by the Corps in 1994. Figure 2 shows Corps estimates of peak inundation for a Category 4 storm surge for southeastern Louisiana developed with the SLOSH model. [The inundation depths shown would not be produced from a single storm of a given track and forward speed, but are the depths each location could experience from a severe surge scenario for that area.]

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[*] Today most formal references to elevation are given in the North American Vertical Datum of 1988, (NAVD-88). In the New Orleans area references to the National Geodetic Vertical Datum of 1929 (NGVD-29) and NAVD-88 are nearly equal. Elevations in either the NGVD-29 or NAVD-88 are **not** equivalent to local MSL. An elevation of 0 feet in NGVD-29 or NAVD-88 is at about -1 foot <u>local</u> MSL. Thus, a reference to +1 foot NGVD-29 or NAVD-88 is roughly equal to local MSL. A levee height which is accurately surveyed to 15 feet NAVD-88 is about 14 feet above local MSL. Accurate elevation determinations in the New Orleans area must also be based on benchmarks that are valid at the time of survey.

Table 2
Overview of Storm Surge Models

Several different modeling techniques have been used to model storm surge in the coastal waters surrounding MRGO. These models are briefly reviewed.

SLOSH Model - A numerical-dynamic, tropical storm surge model, Sea, Lake, and Overland Surge from Hurricanes (SLOSH), was developed by Jelesnianski at the National Weather Service (NOAA) for real-time forecasting of hurricane storm surges on continental shelves, across inland water bodies, along coastlines and for inland routing of water. Overtopping of barriers such as levees, dunes, spoil banks, etc. is permitted. Also, channel flow and flow through barrier cuts are entertained. The model is two-dimensional, covering water bodies and inundated terrain and is applied on a polar coordinate system. The SLOSH model does not address wave set-up or wave run-up.

The SLOSH model is run to simulate the flooding caused by hurricanes. The model is designed for operational forecasting, and the model's input parameters that describe the hurricane are relatively simple and predictable. The hurricane's position, size and intensity all enter as input to the model. Verification runs of the SLOSH model indicate that the accuracy of storm surges prediction is +/- 20 %.

FEMA Model - An overland flooding model has been developed by the Federal Emergency Management Agency (FEMA) to predict hurricane flood elevations for the National Flood Insurance Program. The model uses an explicit, two dimensional, staggered finite difference scheme to simulate the flow of water caused by tides and wind systems. The inputs to the model include the bathymetry, coastline configuration, boundary conditions, and bottom friction and other flow resistance coefficients. Also required are the surface wind velocity and atmospheric pressure distributions of the hurricane. The model predicts water level elevation and water transport everywhere in the modeled region. The model uses a rectangular grid to discretize the simulated region of the ocean and coast. The model grid expands during a simulation to predict the flooding of low lying areas. Barriers and rivers which occur in the coastal zone have a controlling influence on flood levels. Barriers can include roadways, levees and natural features such as cheniers. Rivers include channels, canals and inlets. These features are typically much smaller in width than a typical grid cell, having widths that are about 100 to 1000 feet. These features can be included in the computations as sub-grid scale elements. The FEMA model also does not address wave set-up or wave run-up.

ADCIRC Model - The ADvanced CIRCulation model was developed by Westerink and Luettich as a two-dimensional depth integrated finite element hydrodynamic circulation code for ocean shelves, coasts, and estuaries. The finite element approach allows for modeling very large domains, with a flexible mesh that can provide coarse elements in open water far from areas of interest and fine resolution along areas of interest. Finite element also allows more accurate representation of interior features and model boundaries. The model incorporates recent developments in efficient finite element solution schemes and the code has been parallelized to run on commodity computer clusters. It includes wetting and drying algorithms and can represent hydraulic features such as levees, weirs, and culverts. The ADCIRC model does not address wave set-up or wave run-up.

Storm surge models were also used by university researchers. Figure 3 illustrates surge inundation estimates, prepared by Dr. Joseph Suhayda using the FEMA model, of the potential impact that the 1998 Hurricane Georges might have had on the New Orleans area had the storm not veered eastward (Louisiana Water Resources Research Institute, Louisiana State University).

These analyses fueled concern over hurricane storm surge risks and the need for further studies into the adequacy of levee protection. In 2002, the Corps completed a *Hurricane Protection Reconnaissance Study* to examine surge protection needs of the entire New Orleans area. The Corps recommended conducting an $8.6 million Feasibility Study to examine alternatives for upgrading protection—including the option of providing Category 5 protection throughout New Orleans. As of August 29, 2005 the Feasibility Study was awaiting funding. Following Hurricane Katrina, the Corps was authorized by Congress to prepare a Category 5 hurricane protection technical report for south Louisiana.

As part of their ongoing pre-Katrina levee assessment, the Corps funded development of a sophisticated computer storm surge model using ADCIRC (Westerink and Luettich). The finite element model provides several advances over the traditional FEMA and SLOSH storm surge models of southeast Louisiana. By facilitating large domains the model can more accurately represent hurricane storm surge in the Gulf of Mexico. At the same time, the model allows for high resolution of critical south Louisiana features, such as the HPS and the MRGO. Figure 4 illustrates the ADCIRC Grid developed for the Corps. The grid includes 600,331 elements and 314,442 nodes, with node spacing ranging from 15.5 miles in the mid-Atlantic to 330 feet in the New Orleans area. Simulations using this grid must be done in 1 to 2 second time-steps—with one day of simulation requiring tens of billions of node-steps. Multi-day hurricane simulations can be completed in a matter of hours on super computers utilizing parallel clusters of commodity processors (such as those typically operated by the Corps and universities).

In 2004 researchers at the LSU Hurricane Center (Kemp, Mashriqui, and van Heerden, in conjunction with Westerink) utilized the parallel version of ADCIRC and the 2003 Corps Grid to simulate a very large, slow-moving Category 3 storm (referred to as Hurricane Pam) on the LSU supercomputer “Super Mike” for a multi-agency emergency planning exercise. The synthetic storm portrayed the catastrophic inundation of the New Orleans area resulting from massive storm surge (see http://hurricane.lsu.edu/).

In addition to raising levees, the Corps, Levee Districts, and others began discussing potential alternatives for mitigating hurricane storm surge by restricting the penetration of surge at key locations. Such locations included the GIWW at Paris Road, which transmits surge westward into the IHNC, and the Rigolets and Chef Menteur Passes, through which surge enters Lake Pontchartrain.

In the wake of Hurricane Georges and the Hurricane Pam exercise, one conveyance feature which received significant attention, particularly by residents and officials of St. Bernard and Orleans Parishes, was the MRGO. The conventional opinion has been that the MRGO facilitates the transmittal of storm surge from Breton Sound into St. Bernard Parish and upward into the GIWW and IHNC, placing these areas under an increased threat.

1.5 RELATED ISSUES

By way of background, there are the several environmental and economic issues which are related to concerns over the role of the MRGO in storm surge conveyance. While these issues are not the subject of this report, they are important to acknowledge.

- The erosion of the MRGO banks. Bank erosion is estimated at up to 15 feet/year, widening the channel to as much as twice its original design in some places, and over time significantly increasing conveyance. Erosion is primarily due to ship wave action (Britsch and Ratcliff, 2001). The Corps and the LDNR are investigating methods to improve bank stabilization using articulated concrete mattresses, rock dikes, and other armoring techniques (e.g., CWPPRA Project PO-32).

- The increased salinity in the upper estuaries. Increased salinity is occurring in part due to the introduction of saltwater via the MRGO channel, causing rapid disappearance of surrounding fresh and brackish coastal wetlands. Some locations have seen a 3 to 4 fold increase in salinity during the decades since the MRGO was opened. An estimated 11,000 acres of fresh/intermediate marsh and cypress swamps have converted to brackish marsh and 19,000 acres of brackish marsh have converted to saline marsh. Land losses include fresh/intermediate marsh (3,400 acres), brackish marsh (10,300 acres), saline marsh (4,200 acres), and freshwater swamps (1,500 acres). The Coast 2050 Plan and the Louisiana Coastal Area (LCA) Feasibility Study acknowledged the role of the MRGO in contributing to major coastal degradation and targeted reversing associated wetland loss in St. Bernard Parish as a critical objective. Local officials have asked if the MRGO's role in damaging regional wetlands increases the long-term threat of hurricane storm surge. Methods to control salinities in the MRGO, such as the installation of a saltwater barrier (sill or gate) near Bayou La Loutre are being assessed by the Corps in a *MRGO Re-Evaluation Study* and by the Corps and LDNR in a *MRGO Ecosystem Restoration Study*.

- The continued economic viability of a deep channel in the face of light cargo traffic. An average of five cargo vessels per day utilize the MRGO (R. Caffey, 2002). The Corps has been evaluating long-term alternatives including modifying the MRGO to a shallow barge channel (*MRGO Reevaluation Study*, in progress as of August 2005).

- Regional rates of subsidence, sea level rise, and changing ocean climate. Within St. Bernard Parish, benchmarks along the natural levee of the Mississippi River are subsiding at a rate of 3 feet/century. Benchmarks along Paris Road near the GIWW (across former wetlands) are subsiding at 6 feet/century (Shinkle and Dokka, 2004). Natural geologic processes contribute significantly to subsidence in the St. Bernard Parish area. In some locations—such as drained swamps—natural subsidence rates are exacerbated by human intervention. Gulf Coast eustatic sea levels are estimated to be rising at a rate of about 1 foot per century (R. Twilley, 2001). Moreover, hurricane researchers theorize that the Atlantic Basin is experiencing increasing frequency and intensity of hurricanes. Regional vulnerability to storm surge may therefore be increasing.

Concern over the contribution of MRGO conveyance to local hurricane storm surge inundation led the Corps in 2003 to expand their study of a Bayou La Loutre Saltwater Barrier concept to include an evaluation of whether such a Barrier might mitigate storm surge. The Corps conducted this assessment using the ADCIRC storm surge model (a copy of the 2003 Study is included as Attachment 1).

2.1 2003 ADCIRC GRID

The 2003 Grid was prepared by Dr. Joannes Westerink of Notre Dame for the Corps (also referred to by the Corps as Grid SO8). Figure 5 shows the density of ADCIRC grid nodes for the MRGO and surrounding area. In addition, the figure illustrates the location of weirs used to represent elevated levees and roads incorporated into the model. Figure 6 depicts the ADCIRC model terrain of the area, including the MRGO and levees, in a 3D oblique view. The terrain model appears to be a reasonable coarse representation of regional topography and bathymetry. URS did not perform a detailed check of terrain values during this phase of work. We understand that several sources of topographic and bathymetric data were utilized and that accurate reconciliation of datums was not always possible. Certain features (e.g. portions of levees) are known to be off by a couple of feet. All ADCIRC simulations were conducted with the starting still water surface at model elevation 0.0—which we refer to as MSL. The surge results are not readily convertible to NGVD-29 or NAVD-88 due to the variety of datums reflected in the grid topographic and bathymetric elevations.

It is interesting to note that the ADCIRC grid used in the 2003 Study represented the MRGO channel cross-sectional area at roughly twice the Corps' most recent surveyed cross-sectional area. Figures 7 and 8 present plan and cross-section comparisons of recent surveys versus ADCIRC representations of the MRGO near Shell Beach. This comparison is typical of the entire surveyed and modeled channel. The larger representation of the MRGO in the 2003 grid results from using a number of minimum-sized elements in representing the channel width, which in needed to control numerical stability. Thus, the 2003 Study ADCIRC grid *significantly over-represents* the conveyance of the MRGO. As shown in Figure 5, the 2003 Grid also has the alignment of MRGO slightly off, to the south, but the discrepancy in overall channel length and orientation with the coast is very minor.

The Bayou La Loutre Barrier was represented in model simulations by raising several grid nodes in the MRGO where it bisects the Bayou La Loutre ridge—in effect restoring the ridge across the MRGO. The remainder of the grid was not altered for the Barrier Scenario.

2.2 SUMMARY OF 2003 CORPS STUDY

In order to evaluate potential storm surge effects of the Barrier, the 2003 Study utilized nine synthetic storms (see Table 3) and one historic storm, Hurricane Betsy (1965). The Betsy simulation represented the storm with top winds of 135 knots and a forward speed of about 20 knots at landfall, and included tides. The storm tracks are shown on Figure 9. All ten storms were simulated for the Baseline Scenario (without-Barrier) versus with-Barrier Scenario.

Table 3
Characteristics of Nine Synthetic Hurricanes

Top Winds	Forward Speed	Central Pressure (mb)
124-Knot	Fast, 20 Knots	934
124-Knot	Medium, 15 Knots	934
124-Knot	Slow, 5 Knots	934
100-Knot	Fast, 20 Knots	955
100-Knot	Medium, 15 Knots	955
100-Knot	Slow, 5 Knots	955
65-Knot	Fast, 20 Knots	989
65-Knot	Medium, 15 Knots	989
65-Knot	Slow, 5 Knots	989

1 knot equals 1.155 miles per hour.

Hydrographs for the two scenarios (Baseline versus Barrier) were presented in the 2003 study for four locations:

- IHNC
- GIWW at Paris Road
- Bayou Dupre
- Shell Beach

Comparison of the maximum water surface elevation (WSE) in MSL at each location for four of the nine synthetic storms plus Betsy is re-produced as Table 4. (The hydrographs are included in the copy of the report in Attachment 1). Table 4 shows that there were two reductions in maximum storm surge over 0.5 feet. These reductions represented about a 27 percent reduction of Baseline peak surge (in the case of the 65-Knot-Fast storm at Bayou

Dupre) and 16 percent reduction (for the 124-Knot-Fast storm at Shell Beach). Reductions in the range of 0.3 to 0.5 feet were also seen at Shell Beach for the Betsy simulation and for the other three locations for the 65-Knot-Fast storm. The reductions in peak surge for the other 16 data points on Table 4 were all less than 0.3 feet. In six of these the maximum surge was slightly increased by the Barrier.

Table 4
Difference in Maximum WSE (ft)
Baseline MRGO versus Bayou La Loutre Barrier

Hurricane	Surge Range (ft MSL)	IHNC	GIWW @ Paris Road	MRGO @ Bayou Dupre	MRGO @ Shell Beach
124-Knot-Fast	<5	-0.16	-0.19	-0.16	**-0.53**
124-Knot-Slow	<10	-0.11	-0.13	-0.14	-0.26
65-Knot-Fast	<3	-0.3	-0.33	**-0.54**	-0.37
65-Knot-Slow	<4	0.03	0.02	0.02	0.02
Betsy	<12	0.03	-0.01	0.02	-0.3

A positive value is an increase in surge associated with the Barrier and a negative value is a decrease in surge.

Examination of the hydrographs for the 124-Knot-Fast and Betsy storms for Shell Beach and Bayou Dupre reveal that the Barrier Scenario had a noticeable negative impact by impeding draining of storm surge.

The 2003 Study showed that, at most, blocking the MRGO would only slightly reduced peak surge, with the most reduction occurring for a fast storm. For the higher surge simulations, conveyance across the entire marsh appears to dominate the propagation of surge. The 2003 Study concluded that “the MRGO has minimal influence upon storm surge propagation.” This inference is buttressed by the very conservative representation of the channel cross section in the 2003 model grid. Representing the MRGO channel in the 2003 grid at almost twice the cross-sectional area causes the model to over-estimate the role of MRGO conveyance. Thus, the reductions noted in Table 4 with the Bayou La Loutre Barrier simulations are probably over-predicted.

The URS project team reviewed the 2003 Study results and identified seven factors that should be evaluated in order to establish a more complete and definitive set of findings with regard to the immediate and direct impact of the MRGO on storm surge:

8. Complete closure of MRGO. Significant conveyance from Lake Borgne to the GIWW, upstream of Bayou La Loutre via the MRGO, might still be occurring in the 2003 Barrier Scenario. To better assess the role of the MRGO in contributing to storm surge, modeling of a complete closure (filling-in) of the MRGO should be performed. (This factor was also noted by several local St. Bernard officials in their review of the 2003 Study.).

9. The potential for surge reductions throughout the area. The potential for storm surge reduction should be assessed more systematically across the surrounding area, and not be limited to the four locations.

10. Possible impacts to surge scour velocity. Closing the MRGO may impact surge velocities within the MRGO footprint and these should be examined.

11. The timing of storm surge arrival. Impacts to the timing of surge can be critical for the evacuation of areas. The evaluation of MRGO contribution to surge threats needed to also address the timing of storm surge onset.

12. Wave run-up analysis. In addition to modeling these surge issues a wave run-up analysis for the St. Bernard HPS should be performed to determine if regeneration of waves in the Baseline versus Closed MRGO has a significant impact. (ADCIRC only models the mean sea level during surge.)

These first five factors were incorporated into the URS evaluation of the Baseline versus Closure scenarios for the hurricane simulations discussed in Sections 4 and 5..

13. Assessment of impacts with a severe storm. None of the surges for the nine synthetic storms used in the 2003 Study reached elevations that would threaten to overtop the HPS. Therefore, URS recommended that a simulation should be conducted with a storm that generated a surge approaching the height of the MRGO levee. Hurricane Katrina struck just after the review of the initial simulation results and it was chosen for this assessment.

14. Evaluation of the sensitivity of storm surge to levee alignment. While this was not initially a focus of the URS effort, results of initial simulations and concerns over the role of levee alignments for Hurricane Katrina suggested that a simulation to examine this issue was needed.

URS conducted a total of seven simulations and Table 5 presents a summary of the grids and time-steps utilized. A one second time-step was used for the Hurricane Katrina runs to provide added assurance of model stability given the higher surge levels.

Table 5
Summary of URS Simulations

Hurricane Simulation	Scenarios	Grid	Time Step
124-Knot-Fast (Synthetic)	Baseline MRGO	2003 ADCIRC Grid	2 seconds
	Closed MRGO	2003 ADCIRC Grid with MRGO Filled In	2 seconds
Betsy	Baseline MRGO	2003 ADCIRC Grid	2 seconds
	Closed MRGO	2003 ADCIRC Grid with MRGO Filled In	2 seconds
Katrina	Baseline MRGO	2003 ADCIRC Grid	1 second
	Closed MRGO	2003 ADCIRC Grid with MRGO Filled In	1 second
	Modified Levees	2003 ADCIRC Grid with MRGO Filled In Height of Levee on South Bank of MRGO and GIWW Reduced Height of Interior Levee Increased	1 second

The first simulation pair was performed using the 124-Knot Fast synthetic hurricane from the 2003 Study. This storm was chosen as an initial test for five reasons:

- Use of one of the previous storm scenarios would allow direct comparison of a Closed MRGO and a Bayou La Loutre Barrier simulation.
- The 2003 Study showed that this storm produced one of the highest (albeit still modest) reductions of surge of any of the Barrier simulations—i.e., 0.53 feet at Shell Beach. This reduction was greater than that seen for Betsy.
- The MRGO is probably a more important factor in surge conveyance for fast storms than for slow storms (due to the greater head differential created in the MRGO by fast storms).
- A strong, fast storm seemed most likely to create the greatest head gradient along the MRGO.
- The fast storm scenario was relatively quick to run.

4.1 SIMULATION MODELS

URS utilized the same parallelized version of ADCIRC and the same 314,442 node grid used in the 2003 Study. Runs were performed on an 8-node cluster owned by WorldWinds, Inc. at Stennis, Mississippi. (WorldWinds had previously run parallel ADCIRC to assess storm surge scenarios on the Mississippi Gulf Coast in 2004.)

To compare the Baseline MRGO scenario URS undertook two pairs of simulations—with the MRGO channel represented as it had been in the 2003 Study—to a *fully* Closed MRGO scenario—in which the grid nodes within the footprint of the MRGO were changed to the elevation of the surrounding marsh (approximately 1 foot above MSL). Figure 10 illustrates the 2003 ADCIRC terrain configuration with the Closed MRGO.

4.2 QA CHECK

URS first re-ran the Baseline 124-Knot-Fast storm and compared results to the 2003 Study in order to confirm that the model and grid were performing correctly on the WorldWinds cluster. Results of the “QA Check” run are provided in Table 6 using a comparison of maximum surge WSE and show that the WorldWinds parallel version of ADCIRC was performing properly.

Table 6
QA Check Comparison of Maximum Surge WSE
URS/WorldWinds ADCIRC Run versus 2003 Study Using the 124-Knot-Fast Storm

Location	URS Maximum WSE (ft MSL)	2003 Corps Maximum WSE (ft MSL)
IHNC	4.18	4.1
Paris Road	4.41	4.3
Bayou Dupre	3.85	3.9
Shell Beach	3.31	3.5

4.3 SIMULATION RESULTS

The 124-Knot-Fast storm was then run with the Closed MRGO grid. Maximum WSE within the area surrounding the MRGO for the Baseline and Closed MRGO simulations for the 124-Knot Fast storm are provided on Figures 11 and 12. Figure 13 depicts the difference between the two simulations.

Table 7 compares the maximum inundation for the Closure Scenario at the six locations—the four locations from the 2003 Study, plus Caernarvon and the MRGO Mouth—with maximum inundations for the Baseline and Bayou La Loutre Barrier Scenarios. (The latter data is taken from the 2003 Study.) Stage hydrographs for both simulations at the six locations are included on Figure 14.

The Caernarvon location was added in order to examine a lag in storm surge peak reported by local St. Bernard Parish officials for this area. The lag is clearly seen when comparing the hydrographs on Figure 14 and is attributable to the westerly driven emptying of the surge from the Lake Pontchartrain/Borgne waterbodies, combined with the southwestern movement in the Gulf below New Orleans in the post-storm period.

Table 7
Difference in Maximum WSE for Baseline, MRGO Closure, and Bayou La Loutre Barrier Scenarios, 124-Knot-Fast Storm

Location	Maximum WSE (ft MSL)		Difference in Max WSE (ft)		Difference in Max WSE (Percent)	
	Baseline	MRGO Closure	MRGO Closure	Barrier	MRGO Closure	Barrier
IHNC	4.18	4.15	-0.03	-0.16	-0.7	-3.8
Paris Road	4.41	4.33	-0.08	-0.19	-1.8	-4.3
Bayou Dupre	3.85	4.02	0.17	-0.16	4.5	-4.2
Shell Beach	3.31	2.70	-0.62	-0.53	-18.6	-16.0
Caernarvan	2.78	2.76	-0.03	NA	-0.9	NA
MRGO Mouth	3.96	3.99	0.03	NA	0.7	NA

A positive value is an increase in surge associated with the Barrier or Closure and a negative value is a decrease in surge.

4.4 DISCUSSION OF RESULTS

Figures 11 and 12 show similar patterns of maximum inundation for the Baseline and Closure Scenarios. Figure 13 highlights a few small areas for which the Closure Scenario has a lower surge peak:

- Along the MRGO north of Hopedale, upstream of the Bayou La Loutre ridge, and
- Sporadic, isolated pockets of marsh.

There are two areas for which the Closure Scenario exhibited higher surge peak:

- Near Chef Menteur Pass, and
- Along the MRGO from the GIWW to just above Shell Beach.

Table 7 shows that at three of the four locations (IHNC, Paris Road, and Bayou Dupre), simulation of full MRGO Closure produced less reduction in peak storm surge (one was actually an increase) than the Bayou La Loutre Barrier. The one location that showed a greater reduction of peak storm surge with full closure, Shell Beach, saw a slight increase in the peak reduction from 16 percent to 19 percent.

The Baseline versus Closure hydrographs for the 124-Knot-Fast storm (Figure 14) provide further evidence of little difference in storm surge for these locations except Shell Beach. The onset of surge at Shell Beach under the Closure Scenario is delayed—with the arrival of a 1 foot surge lagging by 5 hours. However, the draining leg of the storm surge at Shell Beach is negatively impacted. Fifteen hours after the peak, the surge remains 1 foot higher under the Closure compared to the Baseline Scenario. (Note: the 2003 grid does not include Bayou Yscloskey. An improved grid which includes Bayous Yscloskey and Bayou La Loutre might show different results.)

To further assess the effect of full MRGO closure, URS modeled the Baseline and Closure Scenarios using the Hurricane Betsy simulation, but without tides. Not including tides shortened the model time by several days (and reduced simulation cost) and was not expected to affect the relative comparison of scenarios. Hurricane Betsy was chosen because it produced the highest surge peaks of any of the 2003 Study storms. The same grids that were used in the 124-Knot-Fast Storm were used for Betsy.

5.1 SIMULATION RESULTS

Maximum inundations within the area for the Baseline and Closed MRGO simulations for Betsy are provided on Figures 15 and 16. Figure 17 depicts the difference between the two simulations. Table 8 compares the maximum inundation for the Baseline and Closure Scenarios for Betsy. Stage and current speed hydrographs are presented on Figures 18 and 19.

Table 8
Difference in Maximum Surge WSE for Baseline and Closure Scenarios
Hurricane Betsy

Location	Maximum WSE (ft MSL)		Difference in Max WSE (ft)	Difference in Max WSE (Percent)
	Baseline	Closure		
IHNC	10.13	10.44	0.31	3.1
Paris Road	10.35	10.80	0.45	4.3
Bayou Dupre	7.47	7.54	0.08	1.1
Shell Beach	5.58	5.50	-0.08	-1.4
Caernarvan	8.24	8.28	0.04	0.4
MRGO Mouth	6.47	6.51	0.04	0.6

A positive value is an increase in surge associated with Closure and a negative value is a decrease in surge.

5.2 DISCUSSION OF RESULTS

Figures 15 and 16 again show similar patterns of peak surge for the Baseline and Closure Scenarios. Figure 17 shows that the Closure Scenario produced no areas in which surge reduction reached one foot. However, three areas of higher surge peaks occurred under the Closure Scenario:

- Hopedale,
- East of the MRGO at the confluence with the GIWW,

- Along the MRGO near Proctor Point. area for the Closure Scenario;

Five of the six locations on Table 8 indicate increases, albeit slight, in surge peak for Hurricane Betsy Closure versus Baseline Scenarios. Only Shell Beach saw a decrease in the peak, 1.4 percent, a much smaller reduction than the 19 percent for the 124-Knot-Fast storm.

The Hurricane Betsy stage hydrographs (Figure 18) for Baseline versus Closure Scenarios again are nearly identical at each location, with the exception of Shell Beach. Similar to the 124-Knot-Fast storm, surge onset is slightly delayed as Shell Beach under the Closure Scenario, and the draining leg is negatively impacted.

Figure 19 provides a comparison of Betsy Baseline versus Closure current speed hydrographs for the six locations. In the case of the MRGO closure scenarios this current is for overland flow. The speed hydrographs are similar for four locations (IHNC, Paris Road, MRGO Mouth, and Caernarvon), but are significantly different for Bayou Dupre and Shell Beach. At Bayou Dupre the maximum current for Closure is lower by about 0.5 fps (on a Baseline peak flow of about 2.2 fps) and the duration over which the current exceeds 1 fps is cut by over half. At Shell Beach the maximum current for Closure is halved, from 7 to 3.5 fps. The Baseline Scenario depicted Shell Beach currents above 3.5 fps for 6 hours. This is a significant difference considering the scouring impact of the higher currents on the adjacent marsh. Moreover, actual velocities are higher due to added energy of wave action.

The Hurricane Betsy simulation surge elevations did not approach the current HPS elevations, reaching 10.35 feet above MSL in the GIWW at Paris Road. URS therefore recommended performing a simulation with a truly severe storm to confirm the preliminary conclusion. Following the surge impact of Hurricane Katrina on the study area on August 29, 2005, URS, at LDNR's direction, undertook to use Katrina as a diagnostic storm to further assess the role of MRGO channel conveyance on peak surge. URS conducted Hurricane Katrina MRGO Baseline and Closure simulations using the same ADCIRC Baseline and MRGO Closure grids used for the 124-Knot Fast Storm.

6.1 HURRICANE KATRINA

The track of Hurricane Katrina is shown in Figure 9. Katrina's forward speed was about 17.4 miles per hour as it was crossing St. Bernard Parish. The URS simulations used a synthetic wind-field file prepared by Dr. Pat Fitzpatrick of WorldWinds, Inc.. Top winds and central pressure on which the simulations were based are shown in Figure 20. The simulated top winds following landfall at Buras, Louisiana are more than 10 knots higher than the revised values provided by the National Hurricane Center in their December 20, 2005 report. The WorldWinds wind model does not take into account structural changes that the hurricane was undergoing at the time of landfall—including degradation of the southern eyewall. As a result the modeled Katrina is a more powerful storm than the actual one. The model does not include tides, and as with the earlier runs, uses a reference datum of MSL.

The URS ADCIRC Katrina simulations allow HPS overtopping but do not include HPS breaches and failures. These simulations examine the relative impact of MRGO closure for a severe storm and are not meant as a detailed reproduction of actual Katrina events and conditions.

6.2 SIMULATION RESULTS

Table 9 compares the maximum inundation for the Hurricane Katrina Baseline versus Closure scenarios. Figures 21 and 22 illustrate the maximum water surface elevation (WSE) for the MRGO Baseline and Closed scenarios. Figure 23 depicts the difference in peak surge between the two simulations. Stage and current speed hydrographs for selected locations are provided in Figures 24 and 25.

Table 9
Difference in Maximum Surge Water Surface Elevations
for Hurricane Katrina Simulation of MRGO Baseline and Closure

Location	Maximum WSE (ft. MSL)		Difference in Max WSE (ft)	Difference in Max WSE (Percent)
	Baseline	Closure		
IHNC	16.1	16.1	-0.05	-0.31
Paris Road	19.8	19.2	-0.57	-2.86
Bayou Dupre	22.3	22.2	-0.03	-0.12
Shell Beach	20.6	20.3	-0.26	-1.24
Caernarvon	19.5	19.3	-0.20	-1.04
MRGO Mouth	19.8	19.9	0.07	0.36

A positive value is an increase in surge associated with Closure and a negative value is a decrease in surge.

6.3 DISCUSSION OF RESULTS

As shown in Table 9 and in Figures 21, 22, 23, and 24, the Katrina simulations demonstrated nearly identical patterns in surge WSE for the Baseline and Closure scenarios. The figures clearly show that a massive wall of surge advanced entirely across the surrounding lakes and marsh. There were only very slight reductions in peak WSE—amounting to less than 3 percent—with the closure scenario at Paris Road, Shell Beach, and Caernarvon (0.6, 0.3 and 0.2 ft, respectively). The peak surge was unaffected at the IHNC and Bayou Dupre by closure, and was slightly increased at the Mouth of the MRGO.

Figure 23 shows that the difference in peak surge for the two scenarios was less than 0.5 ft over the vast majority of the region. The 0.6 ft reduction at Paris Road is indicated on Figure 23 by the yellow area, which extends into portions of New Orleans East. The reduction in New Orleans East under the closure scenario is attributable to the slightly lower water levels in the GIWW at Paris Road, which resulted in slightly reduced overtopping of the GIWW levee.

The stage hydrographs in Figure 24 further demonstrate that the Hurricane Katrina simulations did not produce any significant instances of surge increase or delay with the MRGO closure scenario. Nor do the stage hydrographs show any evidence of impeded drainage with the closure scenario.

The vertical scales on the individual current speed hydrographs in Figure 25 show that the rate of surge flow throughout the system is highly variable. Maximum velocities at the

MRGO Mouth, Caernarvon, Shell Beach, and Bayou Dupre are all in the range of 3.5 to 6 ft/sec. The maximum velocity in the IHNC is about 1.5 ft/sec under both scenarios (the simulations do not include breaching of the floodwalls). The highest velocity occurred at Paris Road—12.5 ft/sec, which is reduced slightly to 11.6 ft/sec under the closure scenario. The largest impact to velocity from closure occurs at Shell Beach, with an *increase* from 3.8 to 5.9 ft/sec. Closure of the MRGO channel does reduce the duration of flow above 1 ft/sec at Bayou Dupre.

The modeled current speeds discussed here represent basic *longitudinal* flows (up and down the channel), and do not include the additional energy of wave action. High surge longitudinal flow will cause scour along soft, unarmored channel bank and bottom soils. The HPS scouring observed as a result of Katrina was reportedly due to *lateral* flow, which occurred when water levels exceeded the height of HPS structures and they were overtopped. URS understands that there have been no major reports of longitudinal scouring of HPS structures to date. This is likely attributable to the fact that most of the HPS structures are typically located hundreds of feet from the channel bank. High longitudinal currents do have the potential to cause scour damage at structures supported by the channel bank and bottom—such as bank revetments and piers for docks and bridges.

Since Hurricane Katrina, there has been significant attention given to the potential concentration of surge (and aggravation of surge peaks) by the location and orientation of regional landforms. Landforms with the potential to concentrate surge include both natural passes and shoreline bends, and man-made constrictions formed by road embankments and levees. One such feature of concern has been the "funnel" created by levees along the south bank of the MRGO and the north bank of the GIWW, (see Figure 1).

Figures 15 and 16 show that this constriction caused the Hurricane Betsy surge to pile up at the funnel vertex near the Paris Road bridge over the GIWW. *It is important to note that in the Hurricane Betsy simulations, filling in the MRGO had no impact on this "funnel" effect.*

For Hurricane Katrina, the shape of the WSE contours on Figures 21 and 22 shows that surge piles up against the MRGO levee to the south in a nearly identical fashion for both the Baseline and Closed scenarios. Interestingly, there is no exaggerated surge gradient at the throat of the "funnel" as there was with the Hurricane Betsy scenarios. This is likely due to Katrina's track, and the shift in winds as the eye passed to the east.

At LDNR's request, URS conducted a single simulation of a modified levee alignment in order to assess the effect of levee alignments on surge elevations in the MRGO, GIWW, and IHNC. This single simulation was performed as an initial "sensitivity evaluation" and was not intended as a comprehensive evaluation of the local levee alignments and designs. A study of levee improvements would require a complete range of storm surge simulations and levee alignment/design scenarios

7.1 SIMULATION MODEL

URS conducted the Hurricane Katrina Modified Levee simulation using the ADCIRC MRGO Closure grid described in Section 4, with the MRGO filled-in to approximately one foot above MSL. The alignment and height of levees, which are simulated as weirs in ADCIRC, were the same for all previous scenarios and are shown on Figure 26. The levee alignment and height for the Modified Levees Scenario are shown on Figure 27. The major changes included:

- Reducing the levee height along the south bank of the GIWW and MRGO to the general height of the land grids behind the levee. (Note: for the purposes of this sensitivity assessment URS used the existing land elevations in the ADCIRC model. No adjustments to the grid topography were made.) As illustrated in Figure 27, this resulted in reducing the levees along the MRGO from 17.5 ft to mostly 6.5 ft. Levees along the GIWW (east of Paris Road) were reduced from 14 ft to mostly 6.5 ft, with one stretch at 2.5 ft.

- Increasing the height of the intermediate levee (north of the 40 Arpent Canal) to 17.5 ft.

The effect of this modification was to widen the "funnel" and shift the vertex from the Paris Road bridge westward to the IHNC. Given the roughly 20 ft surge in this area associated with the Hurricane Katrina MRGO Closure Scenario, these simple grid changes were thought to be one way to initially gauge the sensitivity of surge to levee alignment.

7.2 SIMULATION RESULTS

Table 10 compares the maximum inundation for the Hurricane Katrina Baseline versus Modified Levee scenarios. Figure 28 illustrates the maximum water surface elevation (WSE) for the Modified Levees scenario. Figure 29 depicts the difference in peak surge between the Baseline (no MRGO closure) and Modified Levees simulations. Stage hydrographs comparing the Baseline and Modified Levee results for selected locations is provided in Figure 30.

Table 10
Difference in Maximum Surge Water Surface Elevations
for Hurricane Katrina Simulation of MRGO Baseline and Modified Levees

Location	Maximum WSE (ft. MSL)		Difference in Max WSE (ft.)	Difference in Max WSE (Percent)
	Baseline	Modified Levees		
IHNC	16.1	18.9	2.80	17.4%
Paris Road	19.8	19.1	-0.67	-3.4%
Bayou Dupre	22.3	20.7	-1.54	-6.9%
Shell Beach	20.6	19.7	-0.87	-4.2%
Caernarvon	19.5	19.6	0.07	0.4%
MRGO Mouth	19.8	19.9	0.06	0.3%

A positive value is an increase in surge associated with Modified Levees and a negative value is a decrease in surge.

7.3 DISCUSSION OF RESULTS

As shown in Table 10 and in Figures 28, 29, and 30 the Modified Levees simulation resulted in a significant increase in surge in the IHNC (17.4 percent), and modest increases along the MRGO and GIWW, compared to the Baseline Scenario (no MRGO closure). Figures 28, 29, and 30 show a marked change in the peak surge distribution, with levels increased across the area south of the MRGO and the GIWW. Surge levels to the north of the MRGO were reduced. Higher surge in the MRGO, GIWW and especially IHNC also resulted in greater interior flooding of the three major eastbank areas protected by levees.

Given the intensity and particular track of Katrina, this modification clearly facilitated greater westward conveyance of surge. The increased volume of surge then resulted in a higher setup at the IHNC. This result may seem counter-intuitive because one might expect that widening the funnel should give the surge more room to spread out. However, this simulation clearly illustrates the need to carefully consider the sensitivity of peak surge to changes in alignments.

One of the processes that may contribute to the flooding of coastal areas protected by levees is wave run-up (see Figure 31). As storm waves approach a levee they undergo breaking and the broken wave runs up the face of the levee to an elevation well above the storm surge. If the levee is at a lower height than the maximum run-up, then the levee will be overtopped, even though the mean storm surge elevation may actually be below the levee crest.

The MRGO—as a wide, long water body with moderate fetch—has the potential to create or regenerate storm waves which can reach the St. Bernard Parish levees, and thus to impact the magnitude of the wave run-up. Therefore, URS undertook an analysis of the effect of MRGO on storm wave run-up. This section presents results of wave generation and wave run-up calculations based upon preliminary hypothetical wind and surge data. The methodology used in the analysis is taken from the Corps' Shore Protection Manual (SPM) and illustrates the influence of the various factors controlling the magnitude of the wave run-up.

8.1 SELECTION OF LOCATION FOR INITIAL CALCULATION

For these preliminary calculations a single levee location was selected as an example. The levee location selected is near Bayou Dupre, as shown in Figure 1. This location is at a mid-way point along the St. Bernard Parish HPS and is where the amount of marsh separating Lake Borgne and MRGO is minimal.

Data giving the height and shape of the St. Bernard Levees were obtained from the Lake Borgne Levee District. The levee cross section used in the calculations was taken at Station 673+00 and is shown in Figure 32. At this station the levee crest is about 350 ft from MRGO. The levee has a crest elevation of 17.0 feet NGVD-29 and foreslope of about 1:4. In front of the levee is a berm having a width of about 60 foot and elevation of about 8 feet NGVD-29, with a foreslope of about 1:8. The ground between the toe of the berm and MRGO has an elevation is about 3 to 4 feet NGVD-29, and at the bank of MRGO there is a rubble mound structure with a height of about 8 feet NGVD-29. Levee cross sections at other locations along the St. Bernard HPS have different characteristics than those of Station 673+00 and can be evaluated further if warranted.

For the Bayou Dupre transect, a fetch trending northeast across Lake Borgne and Mississippi Sound was selected as having the greatest length and deepest water, as shown in Figure 33. The fetch length is 150,000 ft long. The trend of the fetch is roughly perpendicular to the route of MRGO. The marsh segment between Lake Borgne and MRGO has a width of about

2,000 feet along the fetch, and MRGO has a width of about 1,500 feet. In the case of a closure of MRGO, the channel would be replaced by an additional length of marsh of 1,500 feet.

8.2 WAVE GENERATION AND ATTENUATION CALCULATION

Severe storm waves affecting the St. Bernard HPS could potentially occur with strong winds coming from the east and northeast. The height of the waves depends primarily upon four factors:

- wind speed,
- wind duration,
- water depth, and
- bottom roughness.

Wave properties along the selected fetch depend upon the processes of generation and attenuation. Wave generation will occur along the fetch until the marsh segment is encountered, and then wave attenuation will occur as they cross over the marsh segment. The storm waves will re-generate slightly as the waves cross the MRGO before reaching the west bank of the MRGO. The effect of these processes on wave height is illustrated in Figure 34.

The MRGO will have an effect on wave run-up because there will be a wave height difference at the west bank of MRGO between the case with MRGO open and with it closed. The deep open water associated with MRGO allows for some regeneration of the wave heights during the storm. A closed MRGO channel would be replaced by marsh which would further attenuate the storm waves.

In order to determine the magnitude of the storm wave height difference, wave forecasts were made for Baseline and Closed MRGO Scenarios. The first step was to forecast a storm wave height at the location of the eastern bank of MRGO using a hypothetical storm. This forecast was based upon an average storm wind speed of 60 mph and a storm surge of 10 ft. The fetch consisted of 130,000 feet of water having an average depth of 10 ft and a marsh segment 2,000 feet long. This calculation resulted in significant wave heights of 5.1 feet (above still water) at the end of the open water fetch and 4.0 feet at the east bank of the MRGO (following attenuation in the 2,000 feet of marsh).

The next step was to calculate the re-growth of the storm waves as they pass across the Baseline versus closed MRGO. Using the SPM methodology, the wave height is forecast to increase under the Baseline Scenario to 4.1 feet at the west bank of MRGO. Under the Closed MRGO Scenario the wave height is forecast to be 3.8 feet. The results of the calculations indicate that the significant wave height at the western bank of MRGO would be about 0.3 feet higher in the Baseline versus the Closed MRGO Scenario.

8.3 RUN-UP CALCULATION

In order to asses the effect of the wave height increase associated with the Baseline versus Closed MRGO Scenarios, wave run-up calculations were made for the two wave height cases. The run-up calculations were made using the SPM methodology. Run-up depends on:

- shape and roughness of the levee,
- water depth at the toe of the levee,
- bottom slope in front of the levee, and
- incident wave characteristics.

Because of the variety of levee designs and storm conditions, a complete theoretical description of all of run-up may not be available for a particular levee and storm. Numerous laboratory investigations have been conducted of run-up on smooth, impermeable slopes. Because these studies are at a different physical scale than the prototype structures, the laboratory results need to be adjusted for scale effects.

The wave run-up calculation indicates that the run-up on the selected location of St. Bernard HPS is about 1.5 times the incoming wave height. This produces run-up values of 6.2 feet (above still water) for the Baseline Scenario and 5.7 feet for the Closed MRGO Scenario. These results indicate that the run-up on the St. Bernard HPS will be about 0.5 feet higher for the Baseline versus the Closed MRGO Scenario.

The following findings can be drawn regarding the *immediate* and *direct* impact of the MRGO on storm surge from the combined results of the 2003 Study and this study's ADCIRC simulations and wave run-up analysis.

- The MRGO channel does not appear to contribute significantly to peak surge during severe storms, when the conveyance of surge is dominated by flow across the entire surface of the coastal lakes and marsh. This conclusion is reinforced by the very conservative representation of the MRGO channel cross section in the Baseline model grid.

- Closure of the MRGO channel by complete filling will not provide significant *immediate, direct* mitigation of severe hurricane storm surge. Likewise, other closure scenarios—such as blockage or partial filling—will not directly mitigate storm surge.

- The contribution of the MRGO to surge peaks is likely to be most significant when the peak is low-to-moderate and flow across the marsh does not overwhelm the fraction of flow conveyed through the MRGO. Preliminary results suggest that closure of the MRGO may reduce the peak surge on the order of 15 to 30 percent in a few locations for certain fast, low-to-moderate storms.

- In a few locations, for particular storms, closure of MRGO may modestly delay the onset of surge, but would probably not reduce the peak. No delay is expected for severe surges.

- MRGO closure would slightly *increase* storm surge peaks in some areas for some storms.

- Closure of the MRGO may impair draining of storm surge for some storms following the storm passage in some areas (e.g., Shell Beach, depending on the effect of Bayou Yscloskey). This effect is probably not as significant for severe storms due the size of surge.

- Closure of the MRGO would significantly reduce storm surge scour velocities at some locations. This is particularly important to soft swamp and marsh organic soils.

- The circulation of surges is highly complex and is affected by many features, including the natural topography and waterbodies, and man-made embankments, walls, and channels. Curving and intersecting landform alignments can create surge concentration at vertices under certain storm conditions. Modifications of natural and man-made landforms and waterbodies can cause significant changes in peak surges, which may only be evident for particular storms.

The above findings on the role of the MRGO on storm surge have many implications:

- The surge conveyance of the MRGO is not an important factor in establishing *near-term* HPS requirements. *Near-term* HPS requirements should be based on a thorough analysis of surge height recurrence frequency—and those factors that can reasonably be expected to effect surge—and the costs and benefits of alternative degrees of protection.

- Wave run-up, as well as wave set-up, should be included in any estimate of total surge height and specifically in evaluating the occurrence frequency of surge heights.

- *Long-term* HPS requirements need to consider the impact of wetland damage on storm surge. Certain closure scenarios for the MRGO may help preserve the surrounding swamps and marsh, and thus, *indirectly* mitigate surges in the decades ahead. This issue was not addressed in this phase of work.

- Appropriate surge models—taking into account future broad topographic and bathymetric conditions—should be used to estimate the future recurrence frequency of various total surge heights.

- The impact of the MRGO's role in increasing low-to-moderate surge, particularly on low lying communities and wetlands outside the HPS, should be addressed. This is especially important considering that low-to-moderate surge events occur much more frequently than severe surges and may have a significant cumulative impact. The localized increases in WSE associated with low-to-moderate hurricane surges also occur during other wind driven high WSE events.

- Scouring of the soft swamp and marsh banks during surge events should be addressed, including the additional effect of wave energy.

- Modifications to HPS and regional landforms should be carefully considered to avoid exacerbating surge. Efforts to relax or smooth-out landform constrictions (or funnels) can potentially raise surge heights at points of surge concentration (vertices) given particular storm tracks.

URS offers the following recommendations for further evaluation of the *long-term* role of the MRGO on storm surges and the future implications of various closure scenarios of the MRGO:

- Develop an improved ADCIRC grid for the MRGO and surrounding area that provides a more accurate representation of the channel and surrounding topography and bathymetry corrected to updated NAVD-88 benchmarks. Figure 35 illustrates a recent update of the grid prepared by Dr. Westerink of the University of Notre Dame. A study of the regional terrain should be conducted to identify key areas for improved grid resolution.

- Conduct calibration studies using the improved grid with a range of tidal and storm events. The starting mean water level for the simulations should be the actual sea level in NAVD-88. Calibrations should examine the full stage and velocity hydrographs of the simulation period at representative locations.

- Perform surge simulations using the improved grid to better resolve locations of impact, and degrees of impact (positive and negative), for various MRGO baseline and closure scenarios. Among the diagnostic storms that should be considered is a fast, moderate storm which proceeds along a northwest track west of the MRGO. This storm would likely maximize the head difference between the GIWW and Breton Sound, and thus the conveyance role of the MRGO.

- Evaluate the role of the swamps and marshes surrounding Lake Borgne and Breton Sound on reducing local hurricane storm surge and the value of various measures—such as controlling saltwater intrusion and introducing freshwater from the Mississippi River—to preserve these features. Geomorphic and ecological models (incorporating subsidence, erosion, and eustatic sea-level rise) should be used to predict future landforms given various MRGO closure and other restoration scenarios. Future landform (terrain) grids can then be used to simulate the impact of future landscapes on hurricane storm surge.

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FIGURES

ATTACHMENT 1

NUMERICAL MODELING OF STORM SURGE EFFECT OF MRGO CLOSURE

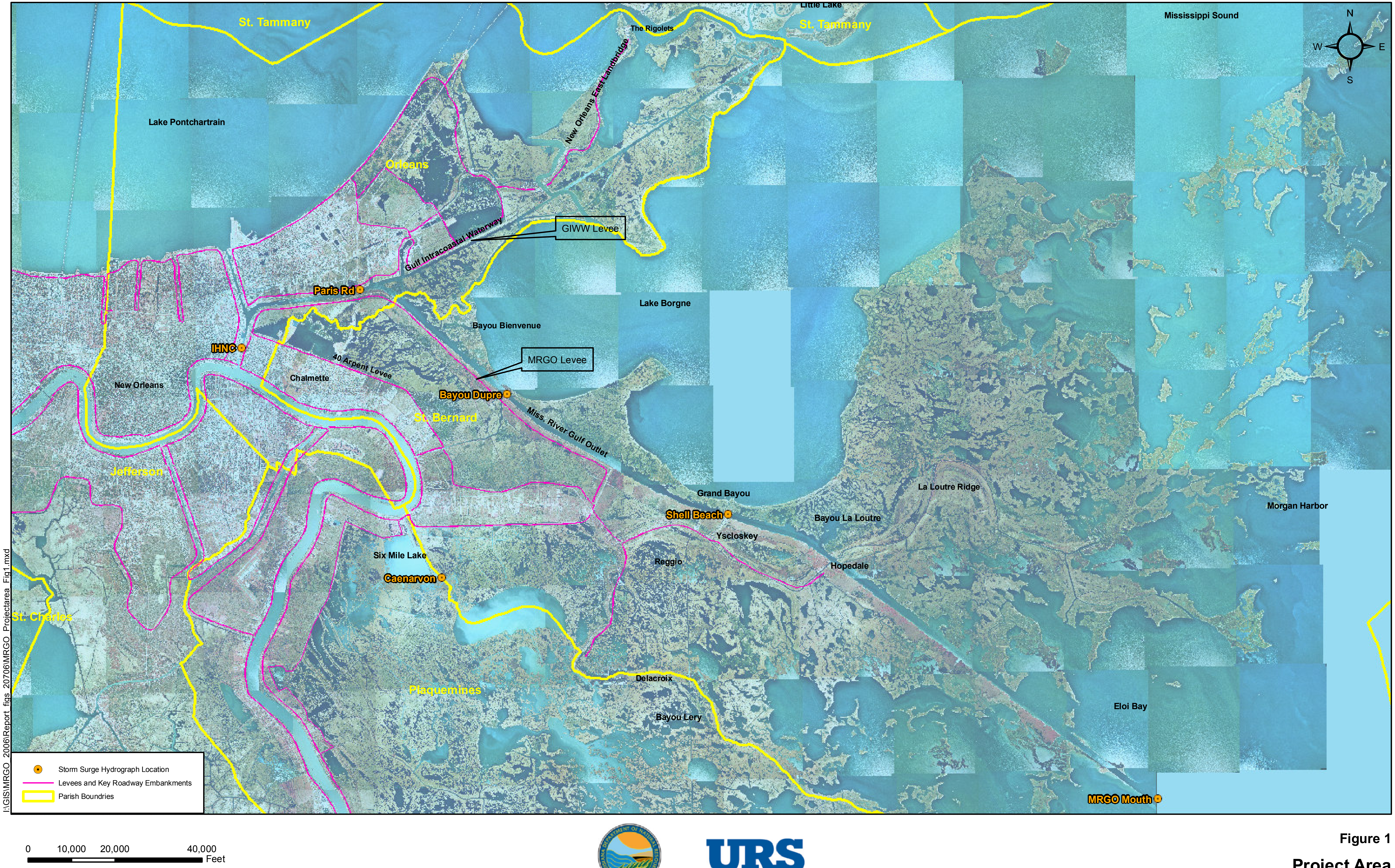

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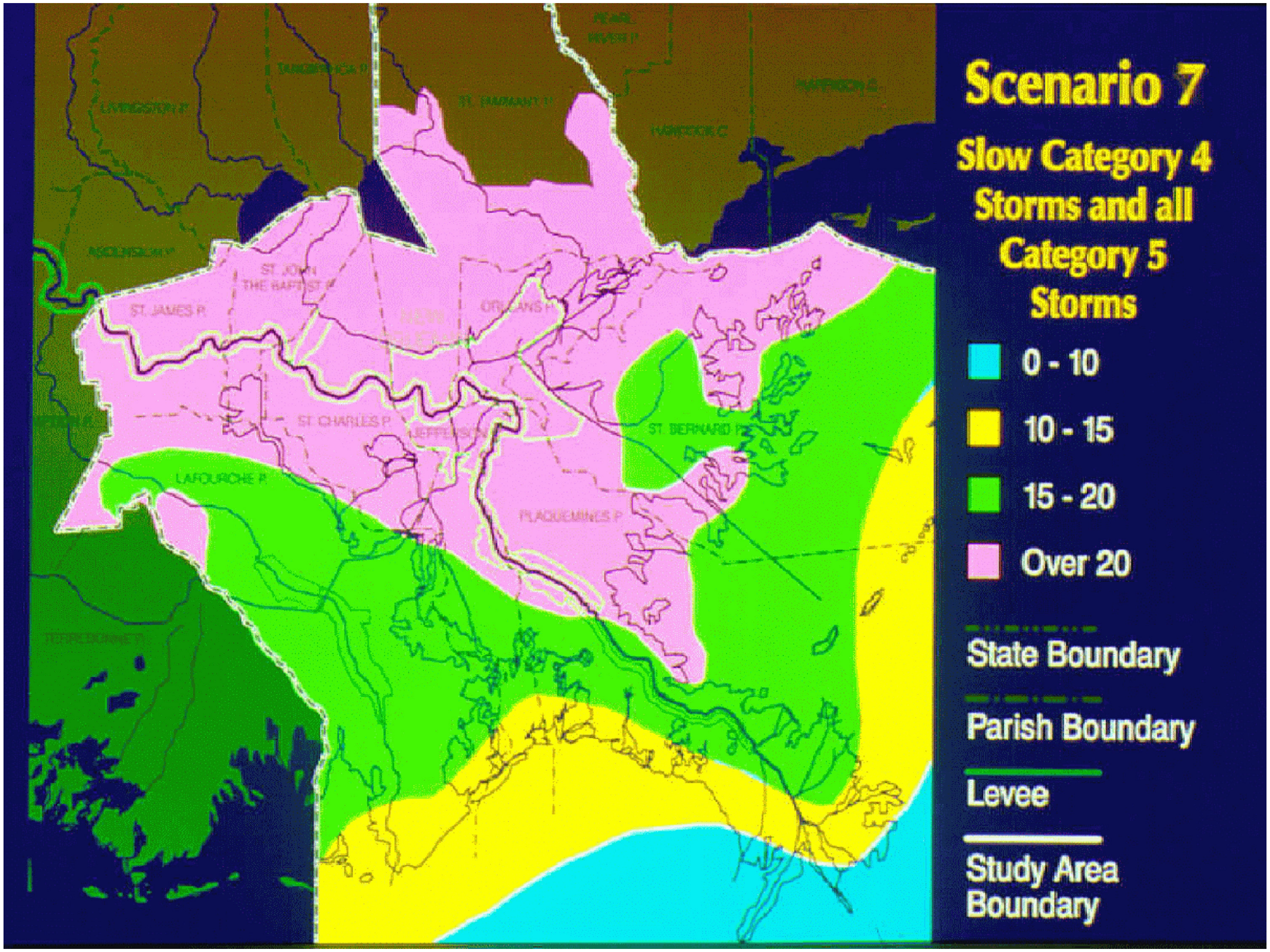
Figure 1

Project Area

Corps Estimate of Regional Inundation from Slow Category 4 Storm Surge



Source: US Army Corps of Engineers, 1998 inundation in feet MSL

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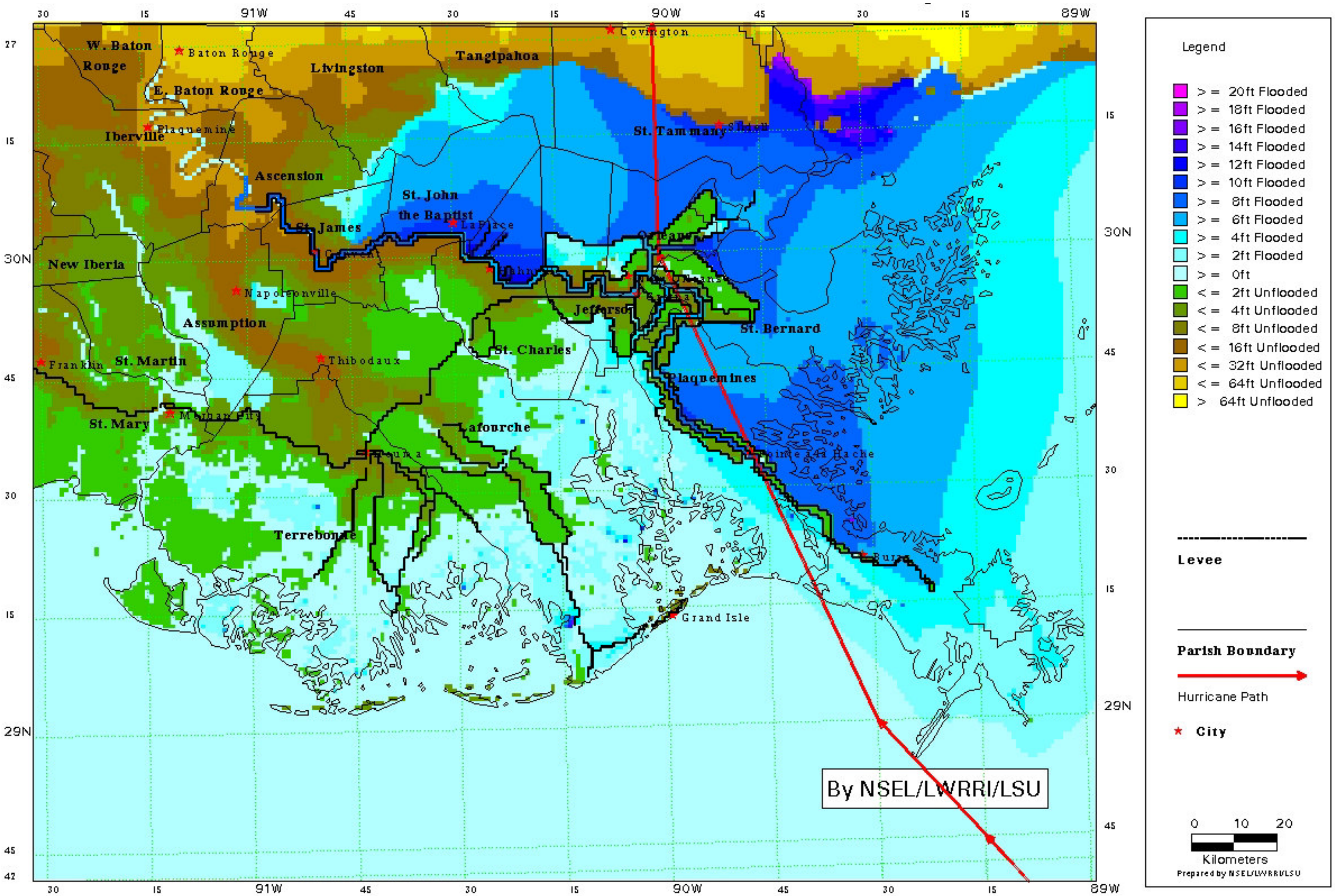
Figure 2

Estimate of Regional Inundation from Hurricane Georges (1998) Prior to Track Turn



Source: LWRRI, 1997 based on advisory 44 inundation in feet MSL

Figure 3

Full 2003 ACIRC Grid

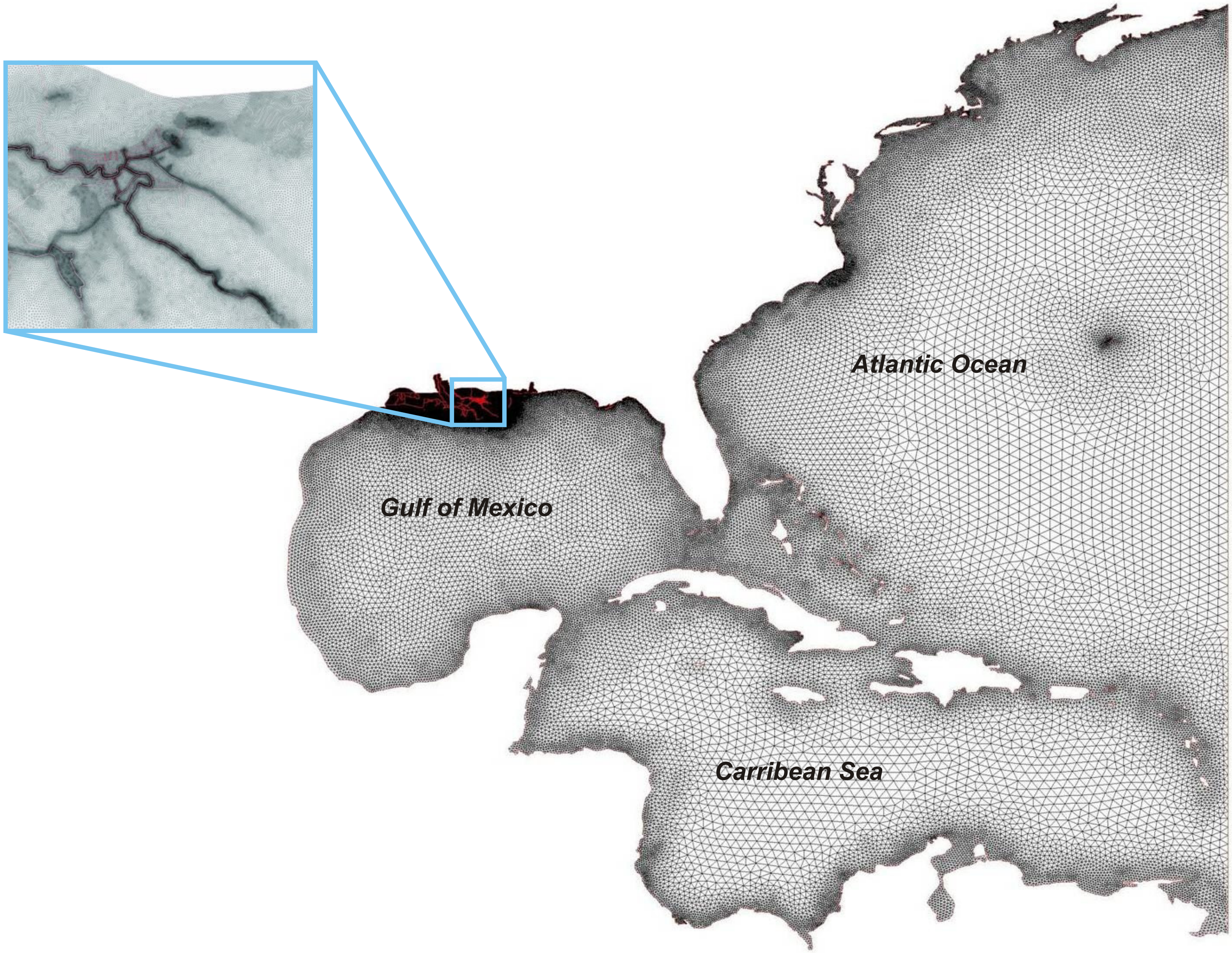


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Figure 4

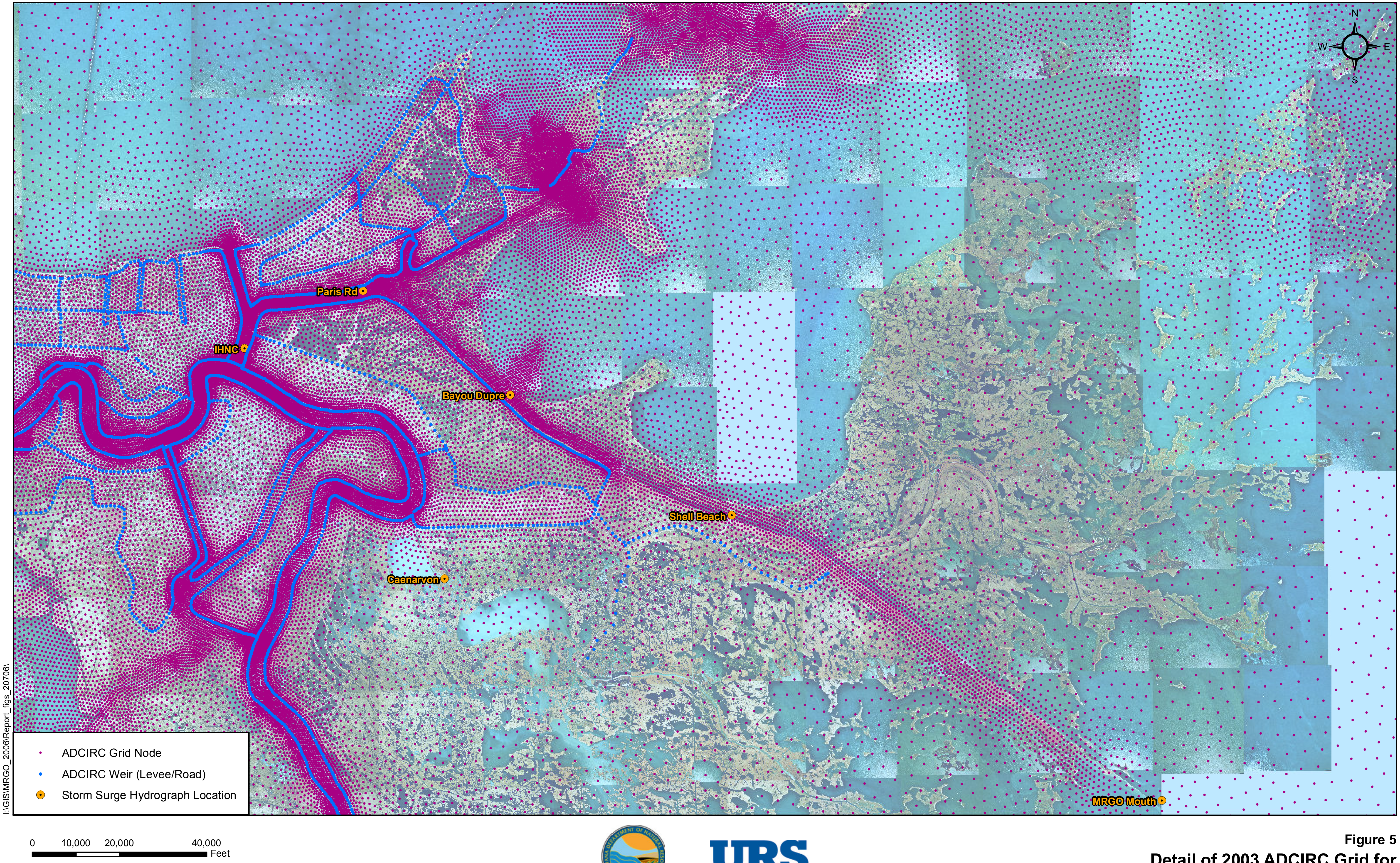

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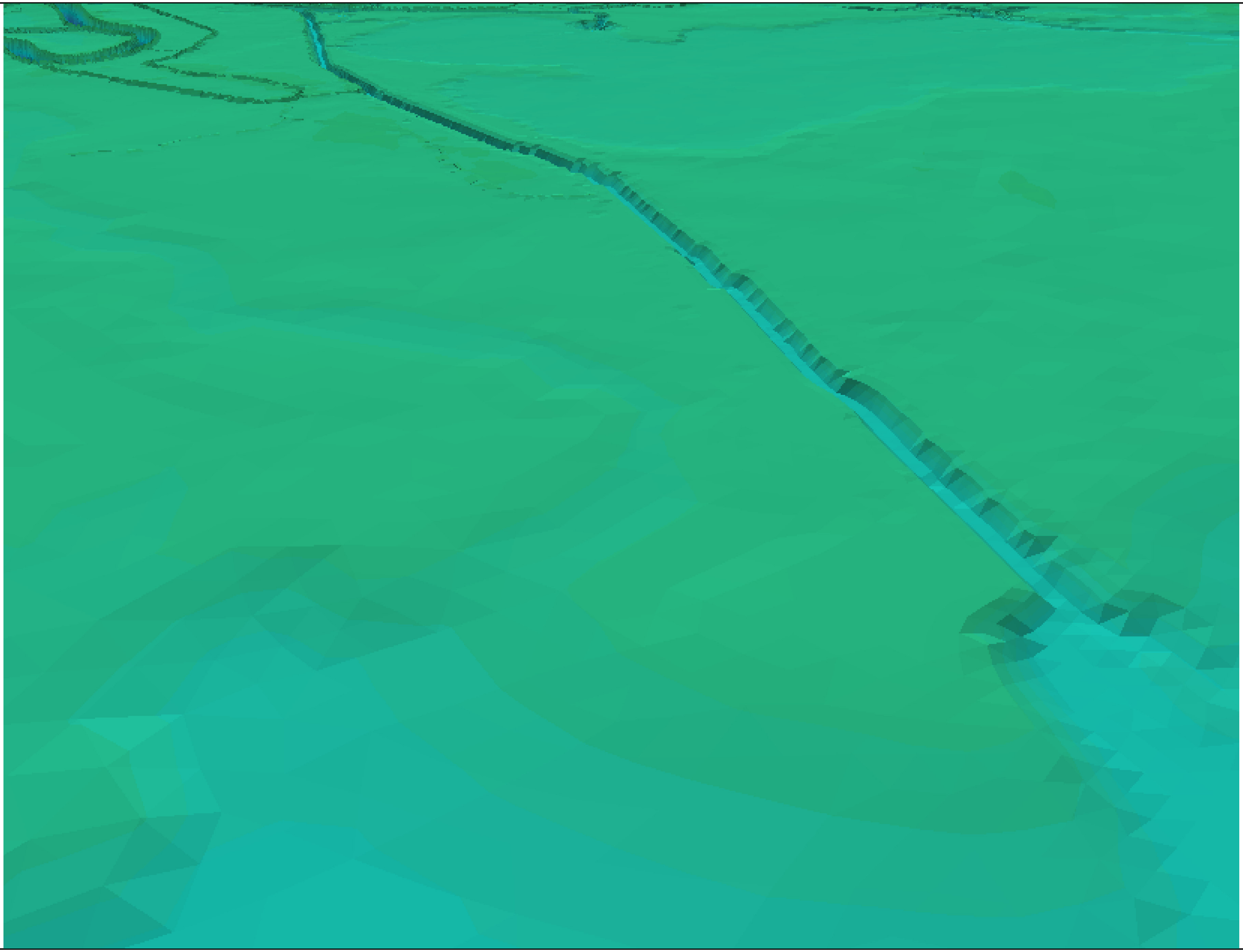
Figure 5

Detail of 2003 ADCIRC Grid for MRGO and Surrounding Area



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Note: Image created in ArcScene. Vertical Exaggeration 25x.
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Figure 6
3D Depiction of 2003 ADCIRC Terrain for MRGO and Surrounding Area

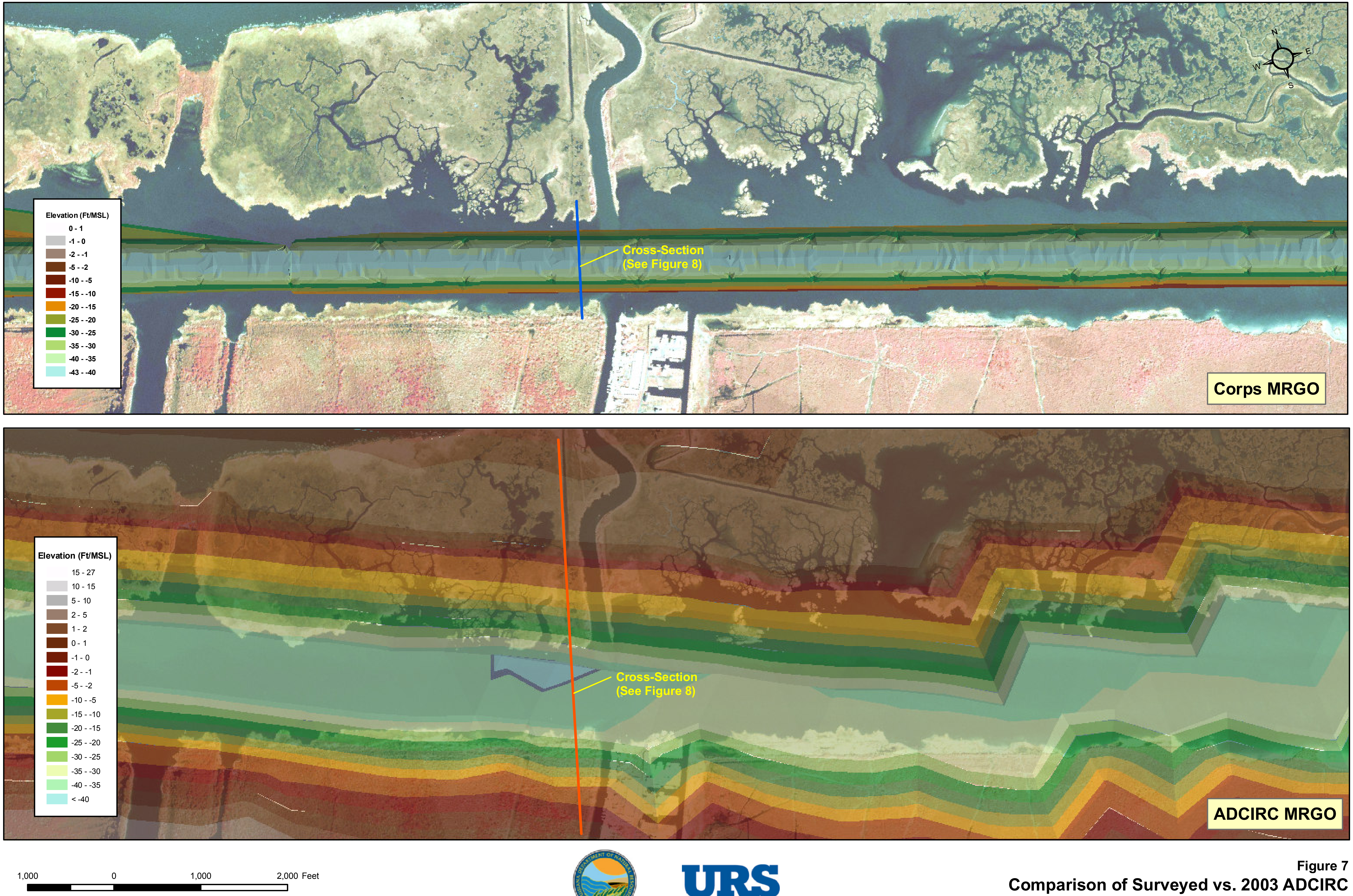

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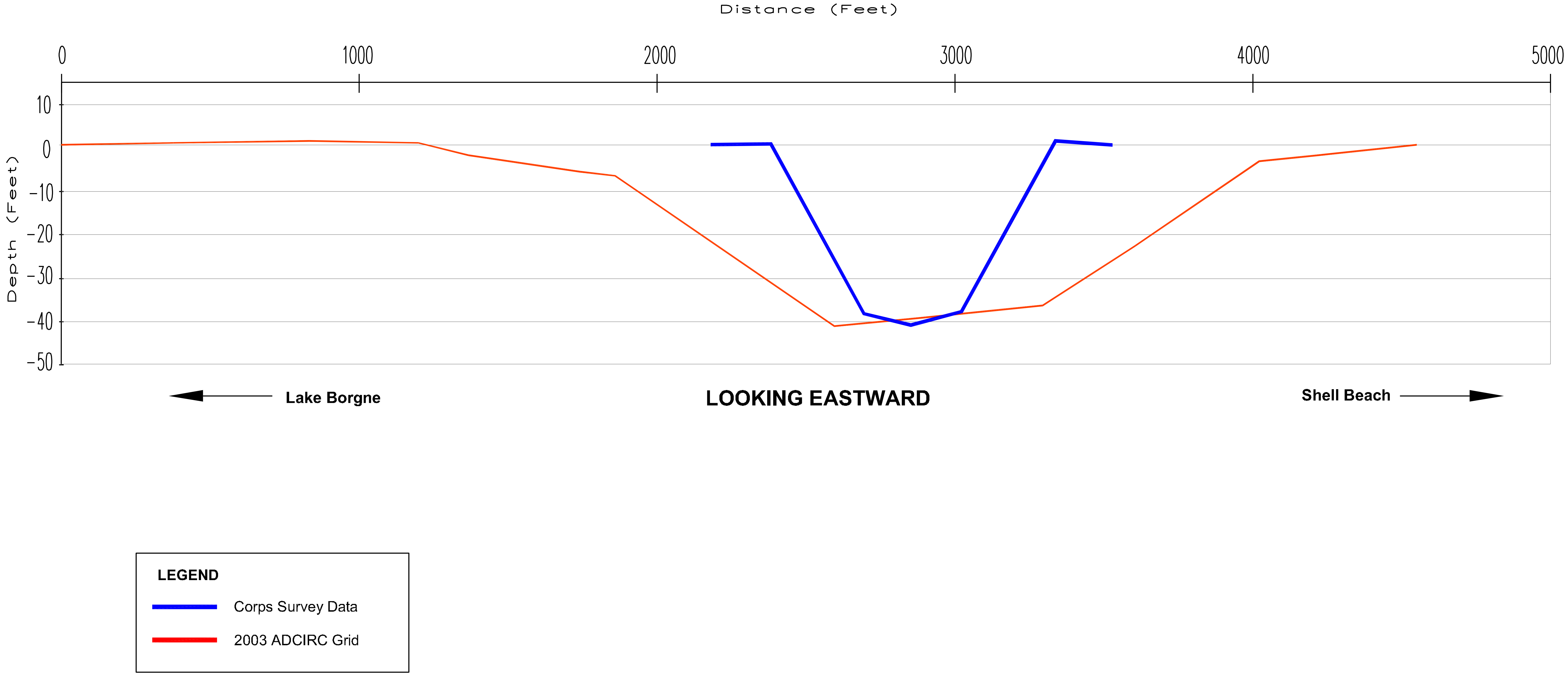
Figure 7

Comparison of Surveyed vs. 2003 ADCIRC MRGO Channel Near Shell Beach, Plan View



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NOTE: Corps survey depth is in NAVD-88 and ADCIRC Grid is MSL.
Differences in datum have been ignored for purposes of this figure.

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Figure 8

Comparison of Surveyed vs. 2003 ADCIRC MRGO Channel Near Shell Beach, Cross-Section

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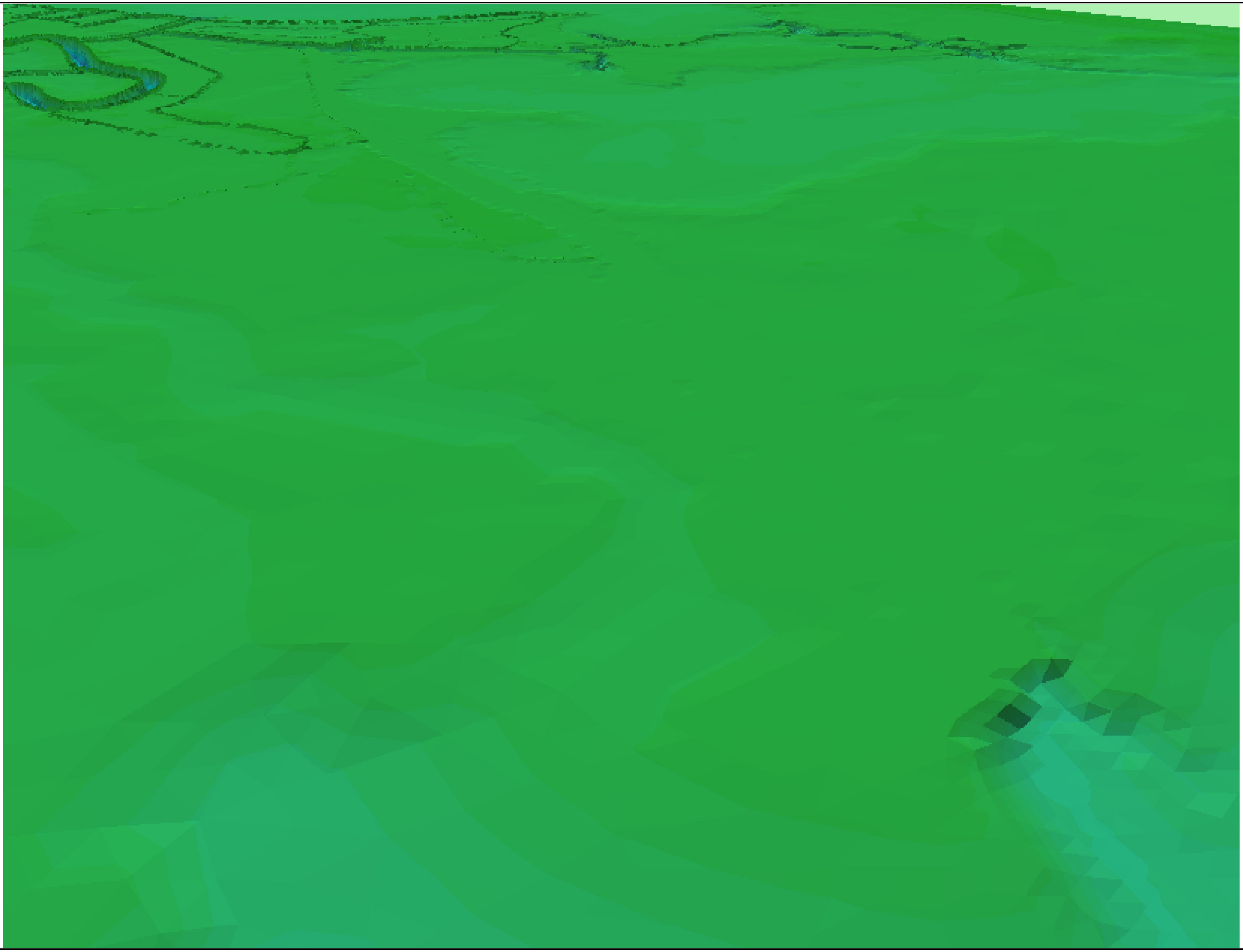
Figure 9

Tracks for Hurricane Simulations



Note: Image created in ArcScene. Vertical Exaggeration 25x.
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Figure 10
3D Depiction of 2003 ADCIRC Terrain for MRGO and Surrounding Area with Closed MRGO

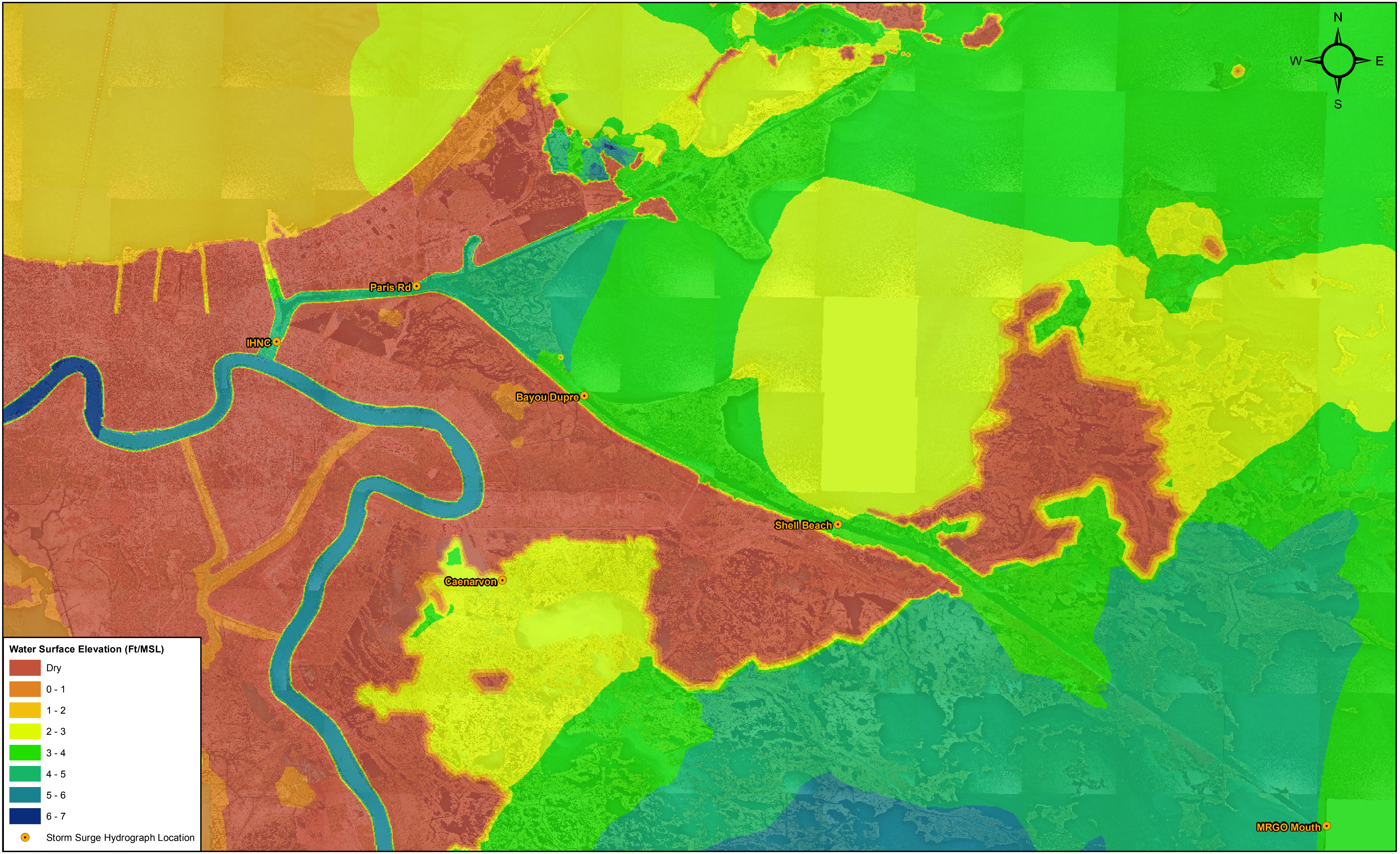

Figure 11
Maximum Water Surface Elevation for
124-Knot-Fast Storm, Baseline MRGO

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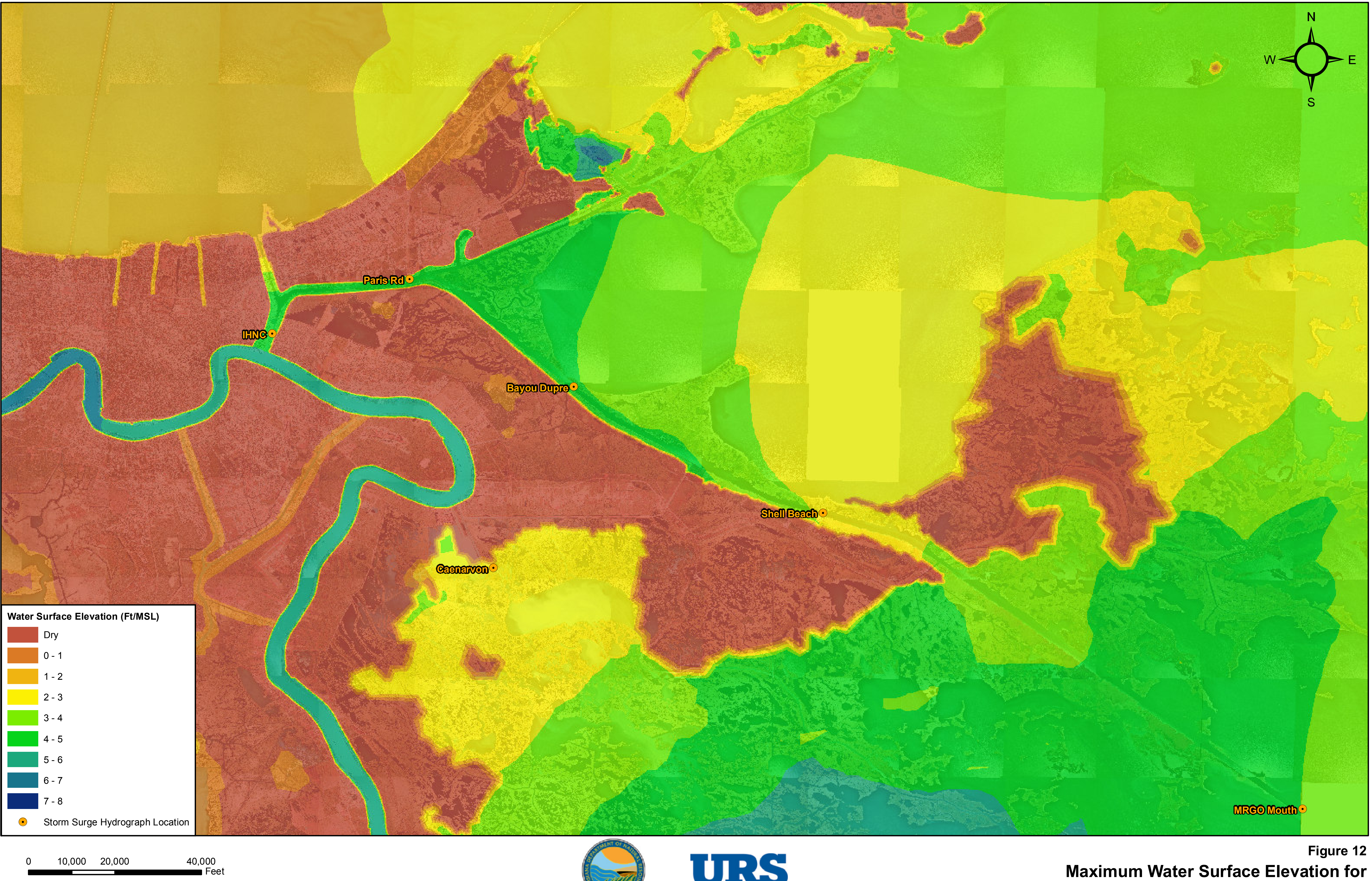

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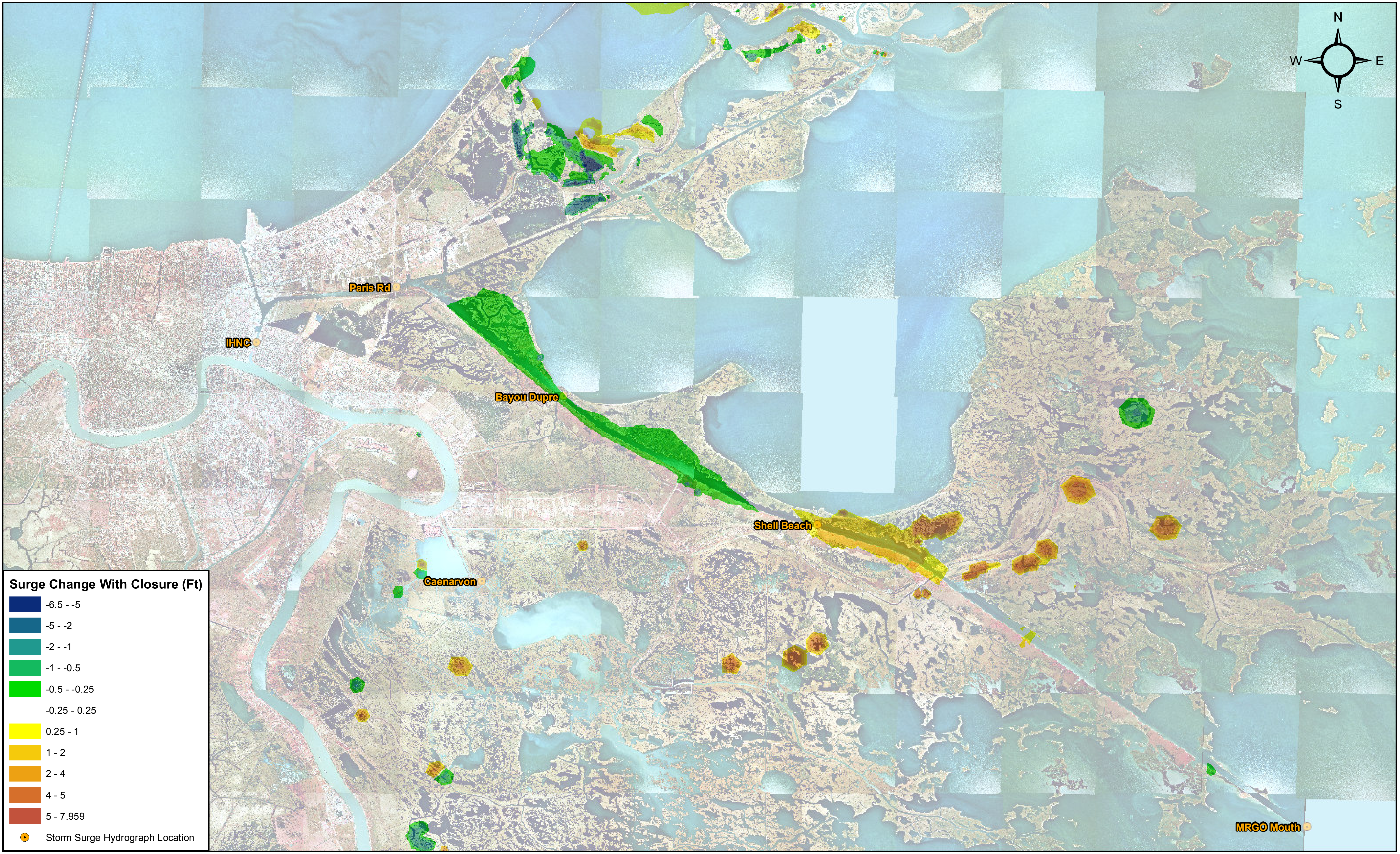
Figure 12

Maximum Water Surface Elevation for 124-Knot-Fast Storm, Closed MRGO



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NOTE: Surge Reduction with Closure is Negative (Green).
Surge Increase with Closure is Positive (Red).

URS

Figure 13

Difference in Maximum Water Surface Elevation for 124-Knot-Fast Storm, Baseline vs. Closed MRGO

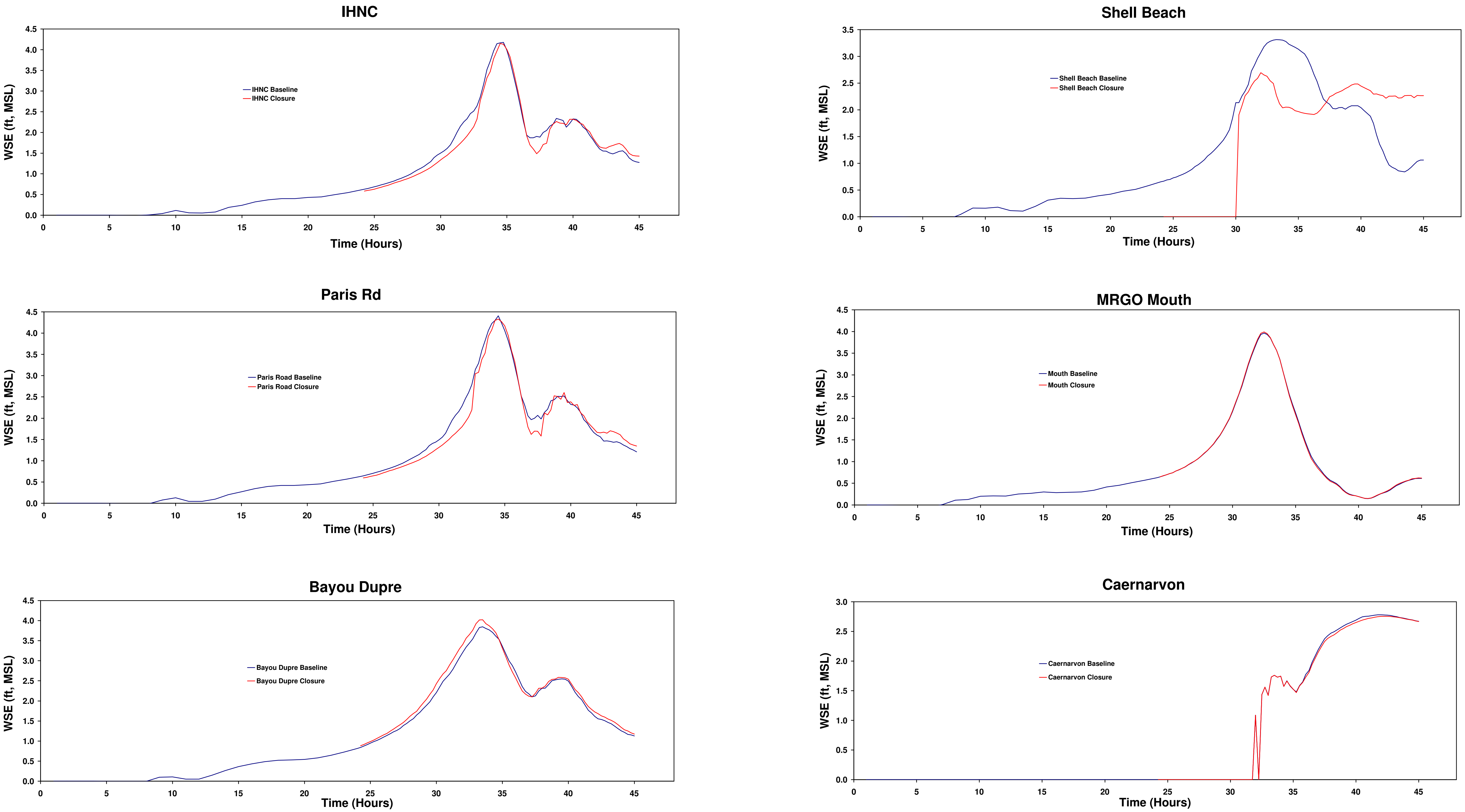

Figure 14
Storm Surge Stage Hydrographs, 124-Knot-Fast Storm, Baseline versus Closed MRGO

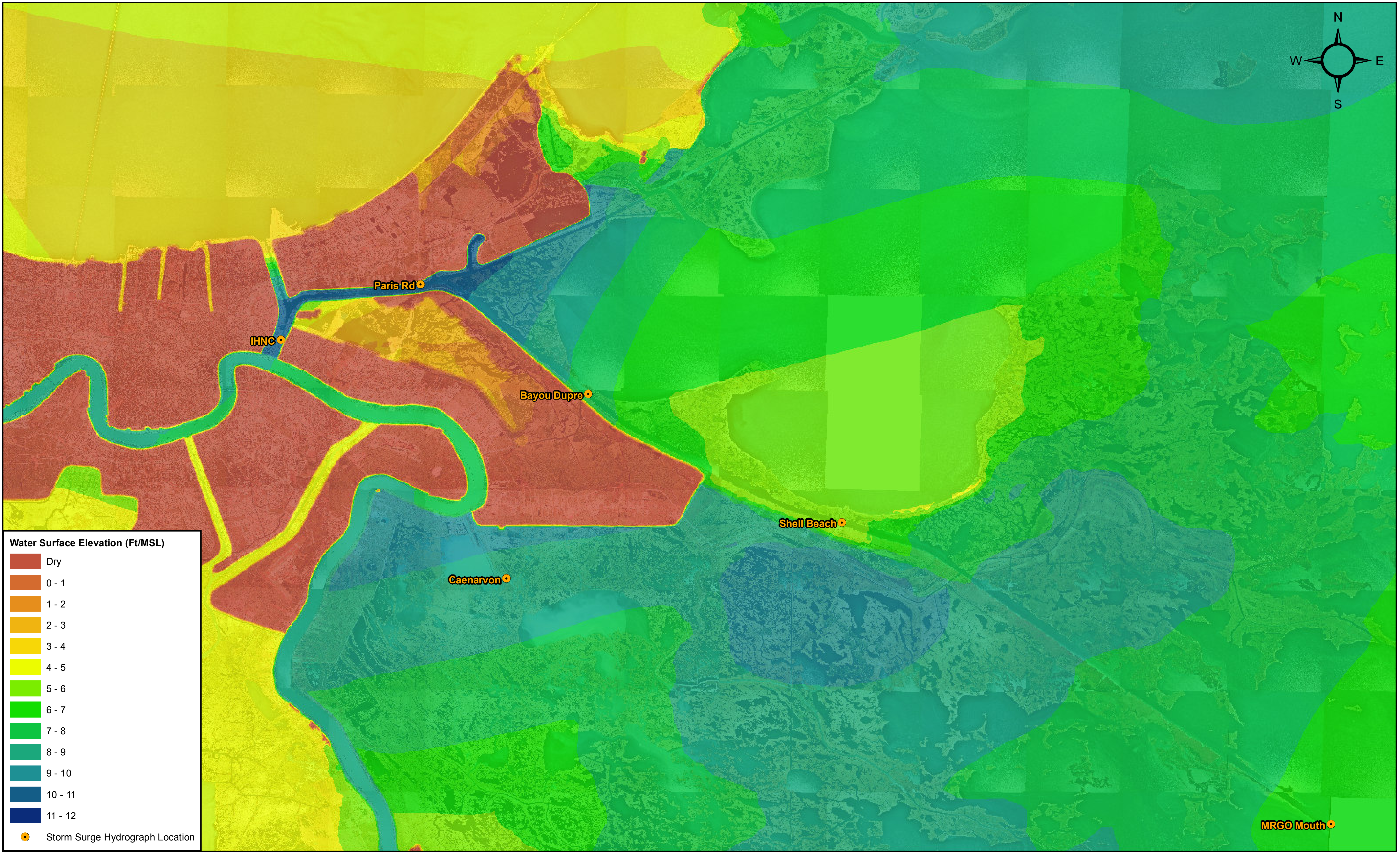

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Figure 15

Maximum Water Surface Elevation for Hurricane Betsy, Baseline MRGO

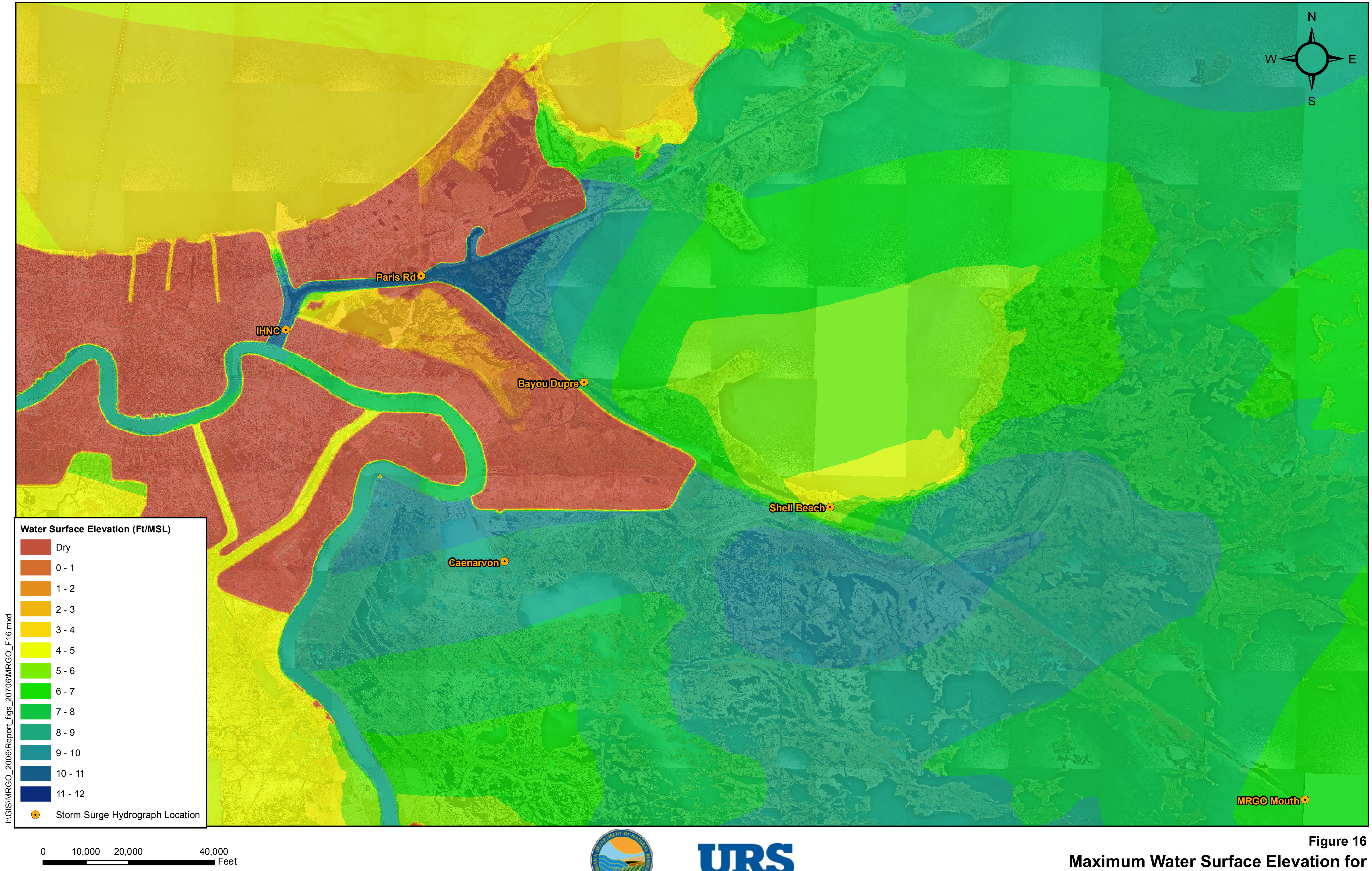
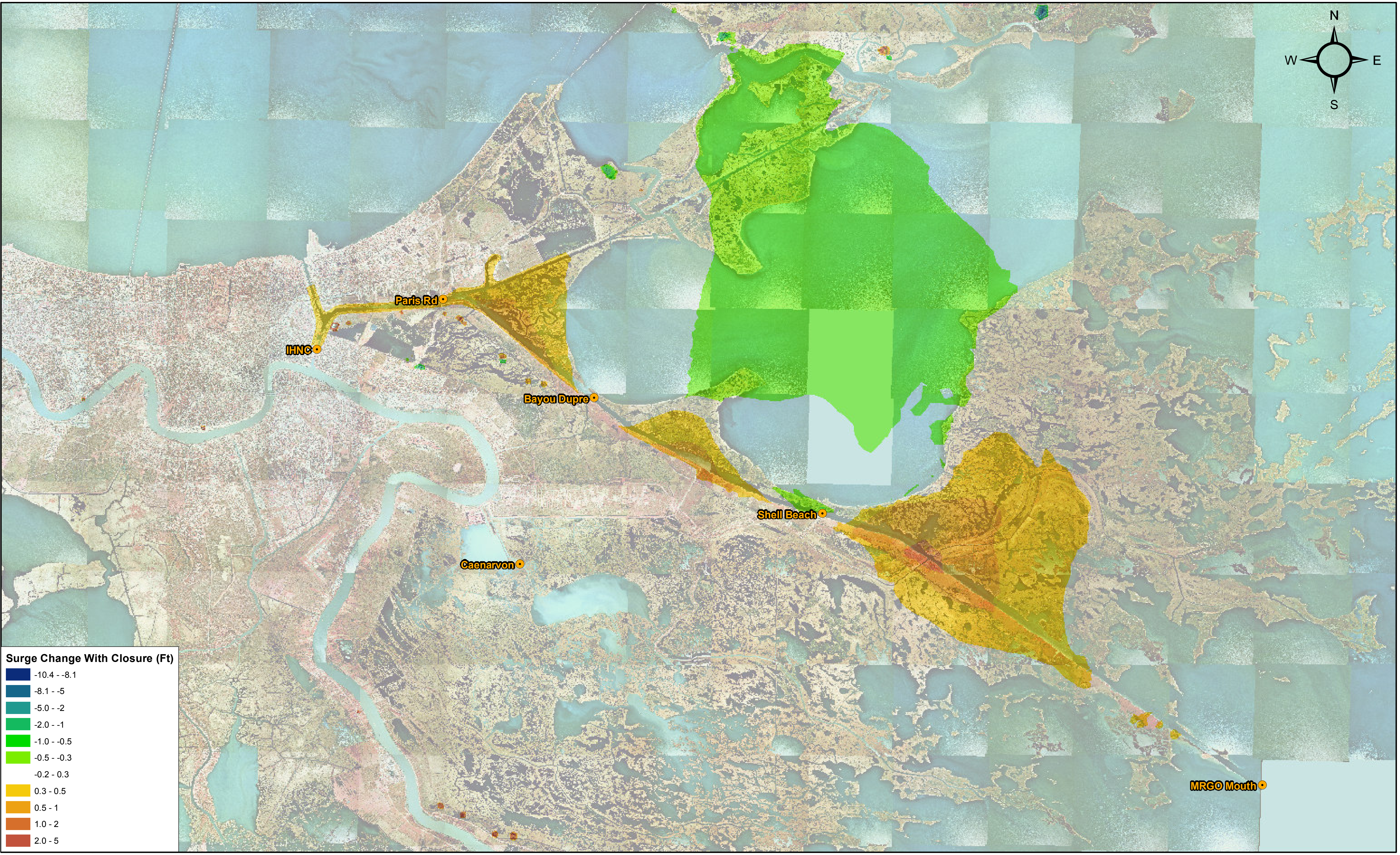


Figure 16

Maximum Water Surface Elevation for Hurricane Betsy, Closed MRGO



NOTE: Surge Reduction with Closure is Negative (Green).
Surge Increase with Closure is Positive (Red).

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Figure 17
Difference in Maximum Water Surface Elevation for
Hurricane Betsy, Baseline vs. Closed MRGO

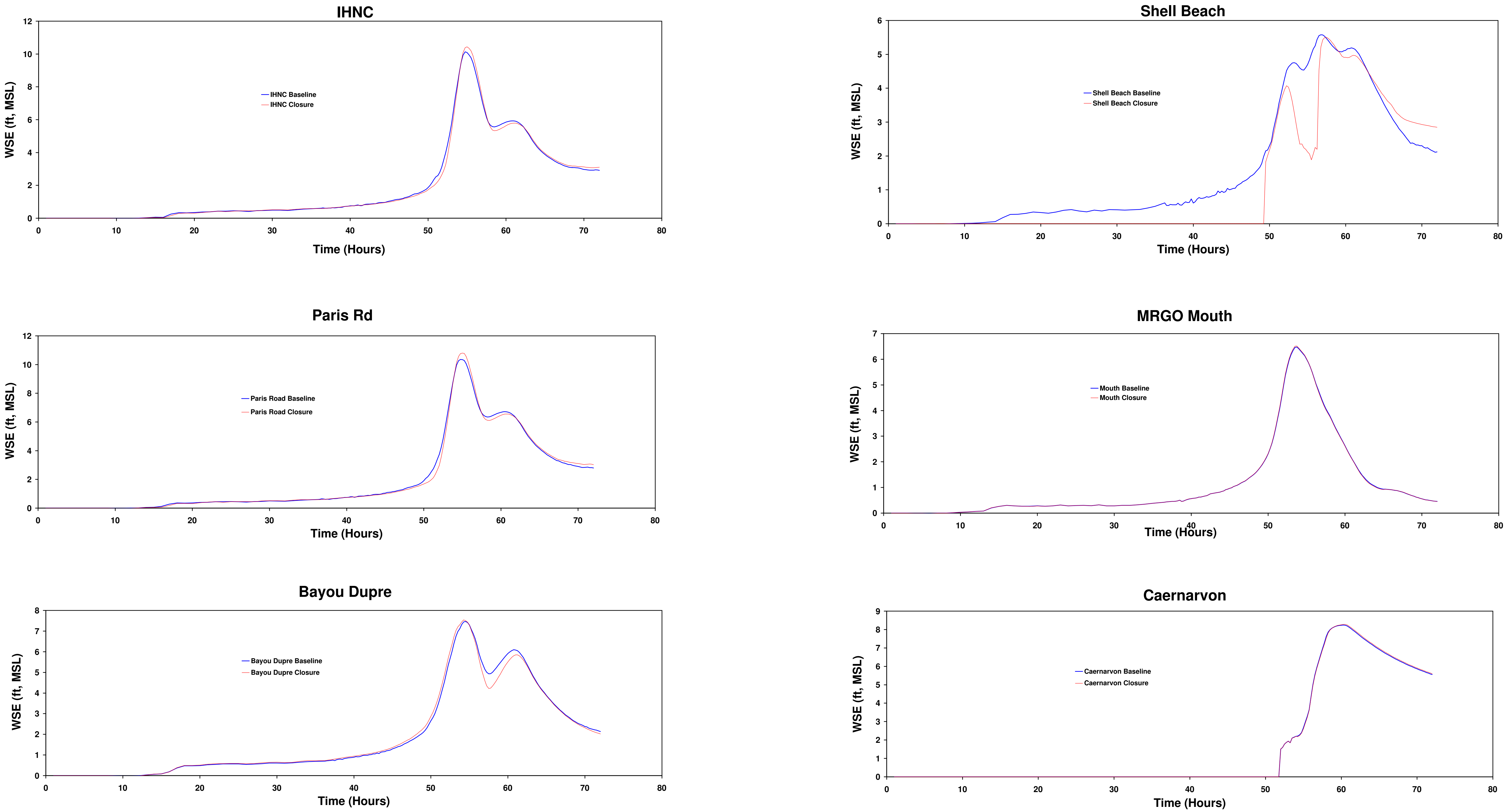

Figure 18
Storm Surge Stage Hydrographs, Betsy (WOT), Baseline versus Closed MRGO

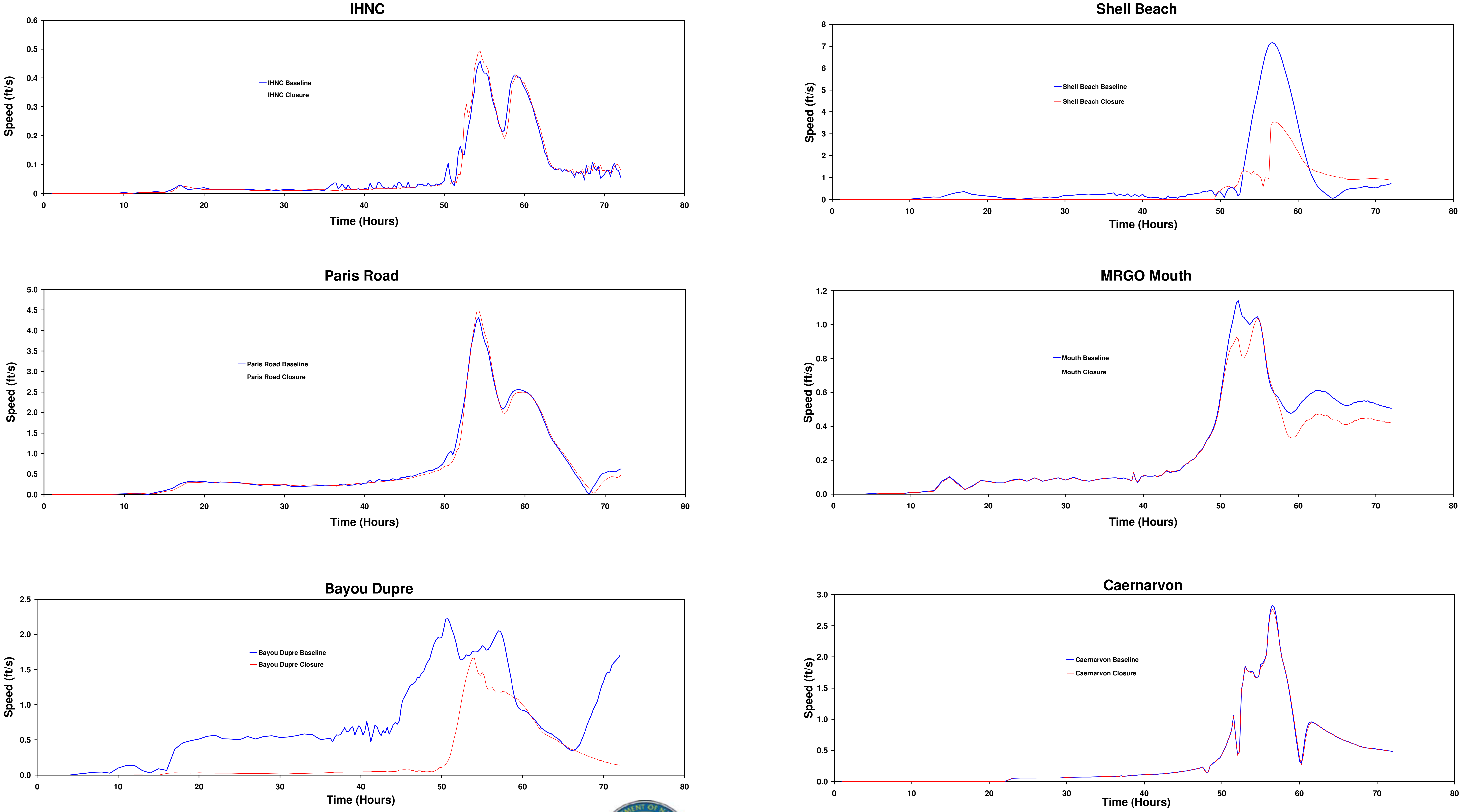

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Figure 19
Storm Surge Current Speed Hydrographs, Betsy (WOT), Baseline versus Closed MRGO

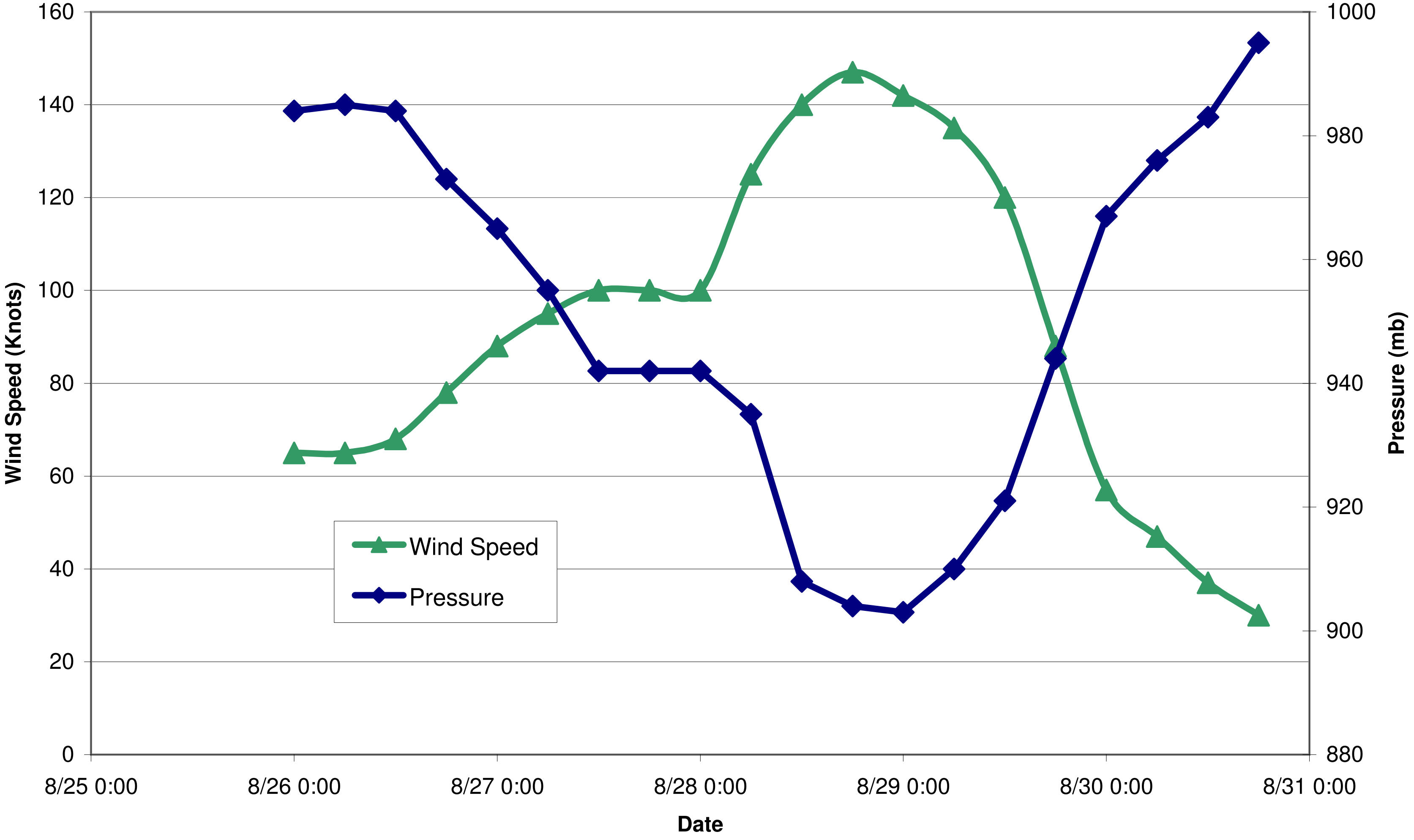

Figure 20
Hurricane Katrina Simulation

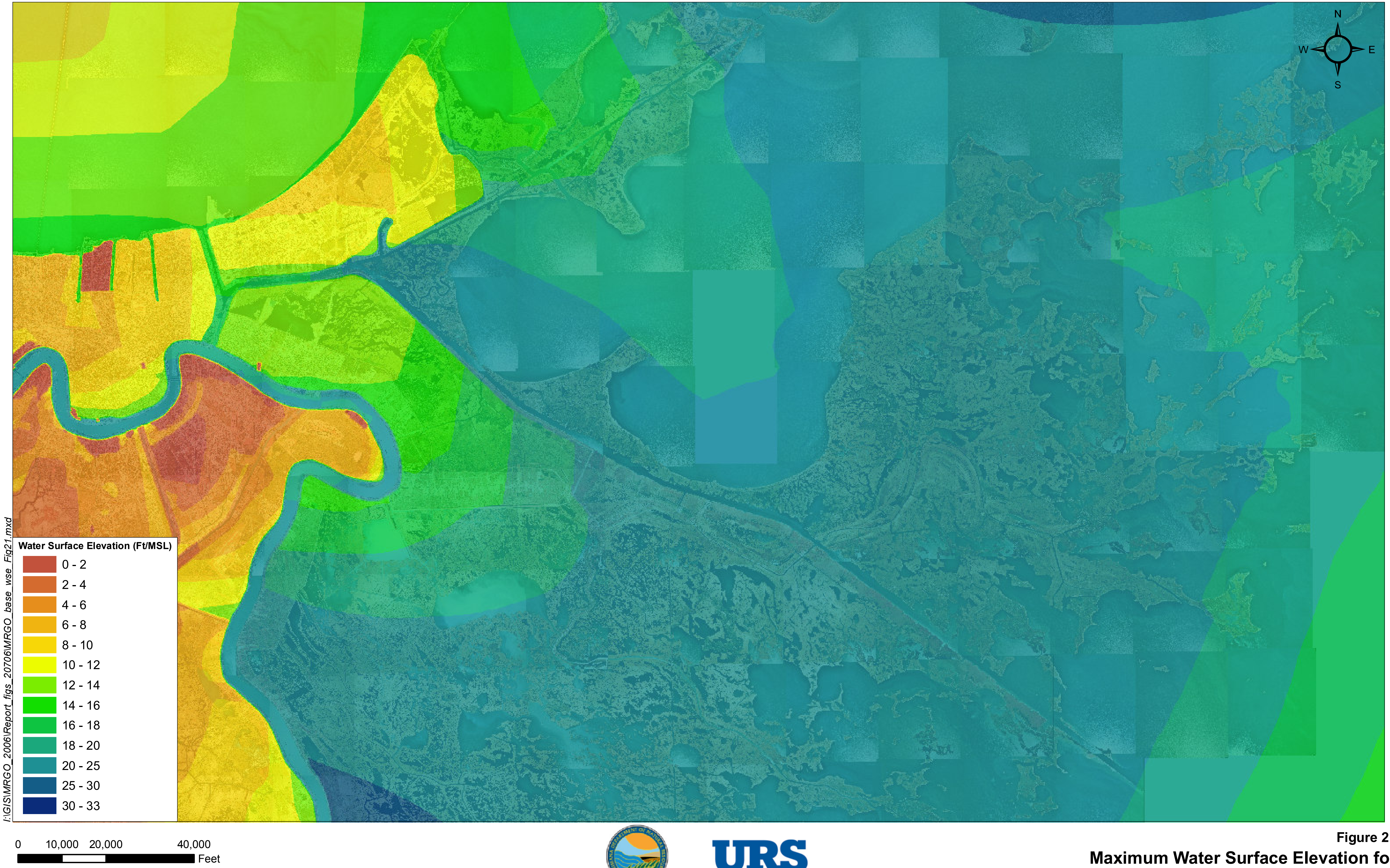

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Figure 21
Maximum Water Surface Elevation for
Hurricane Katrina, Baseline MRGO

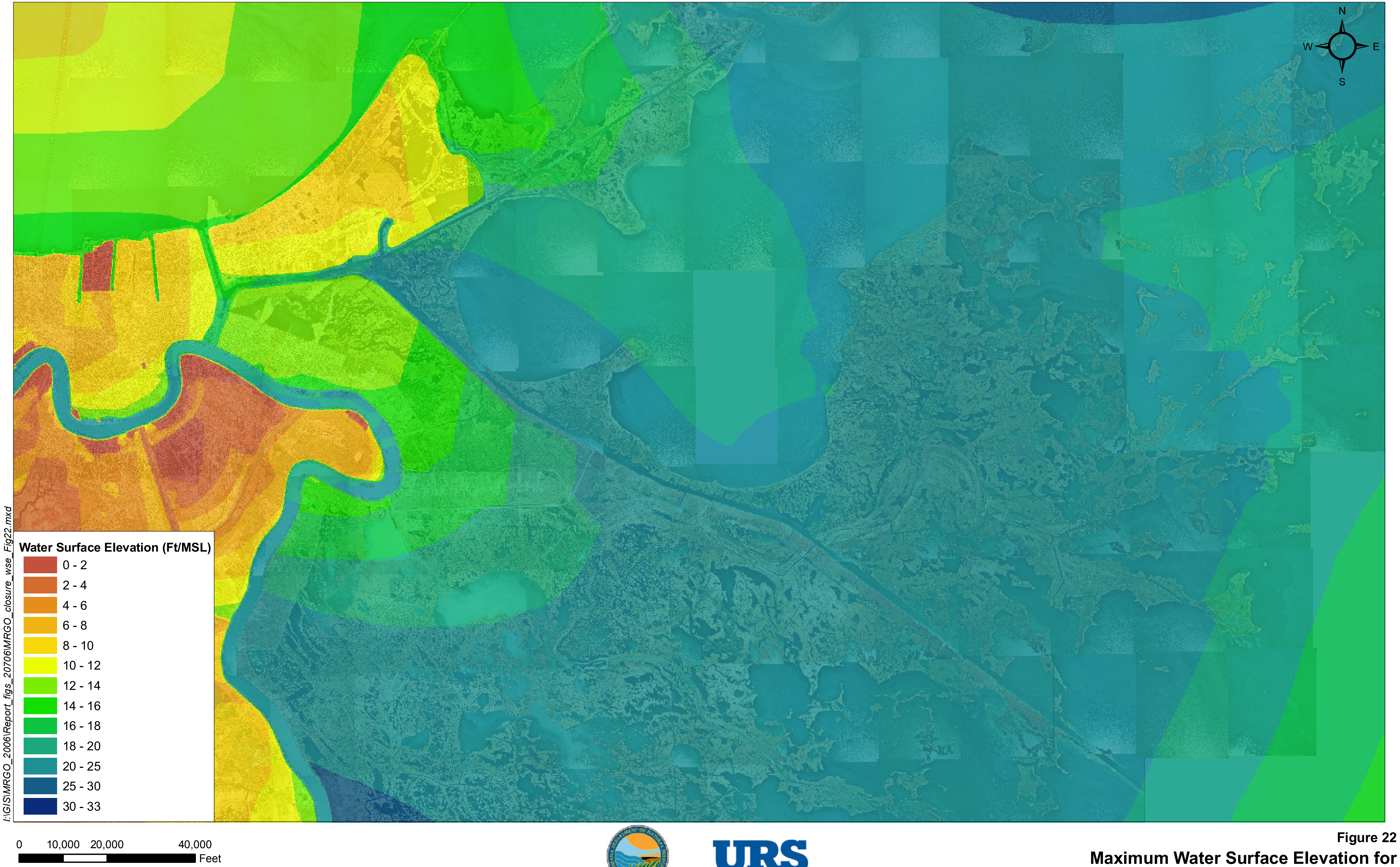

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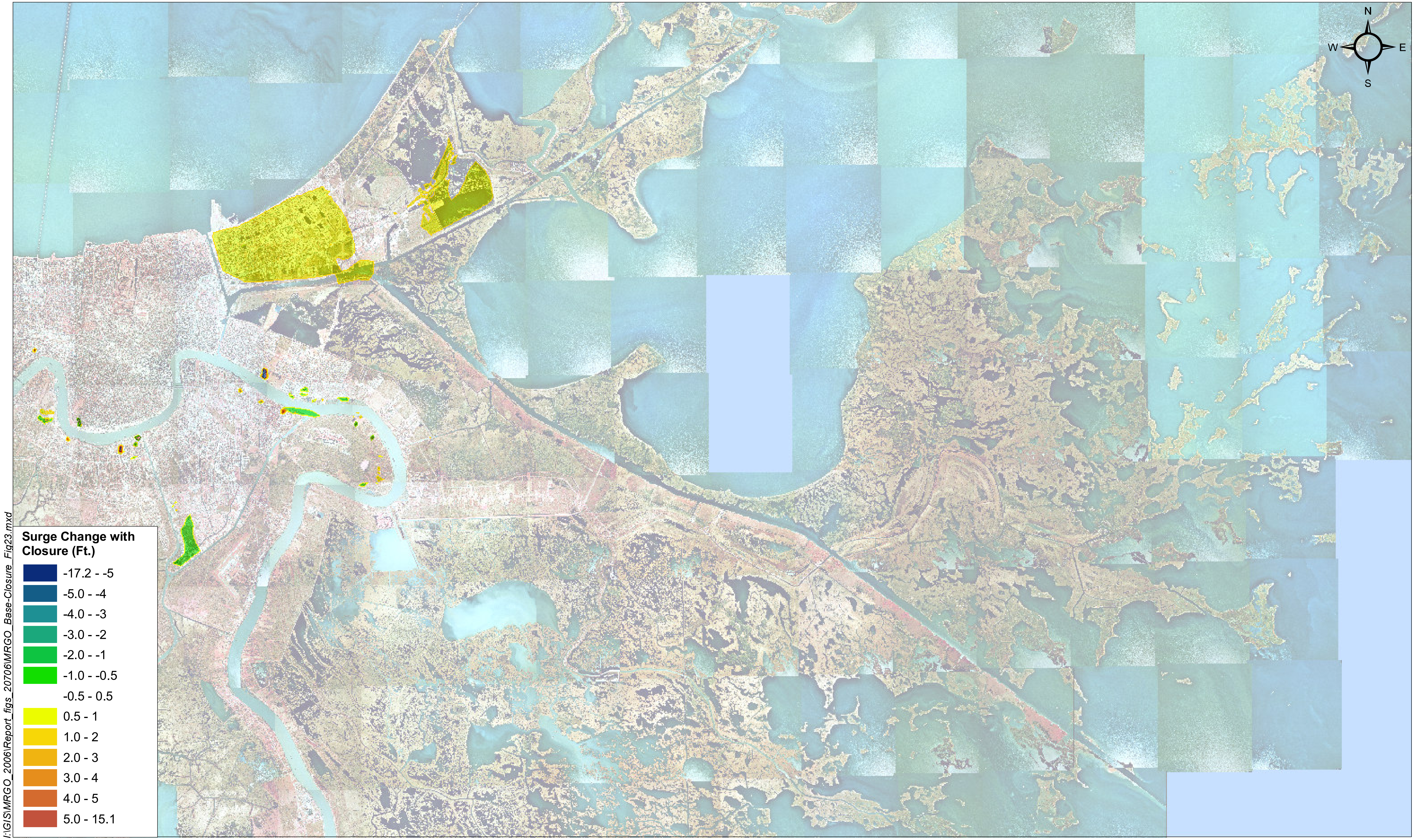
Figure 22

Maximum Water Surface Elevation for Hurricane Katrina, Closed MRGO



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NOTE: Surge Reduction with Closure is Negative (Green).
Surge Increase with Closure is Positive (Red).

0 10,000 20,000 40,000
Feet

URS

Figure 23

Difference in Maximum Water Surface Elevation for Hurricane Katrina, Baseline vs. Closed MRGO

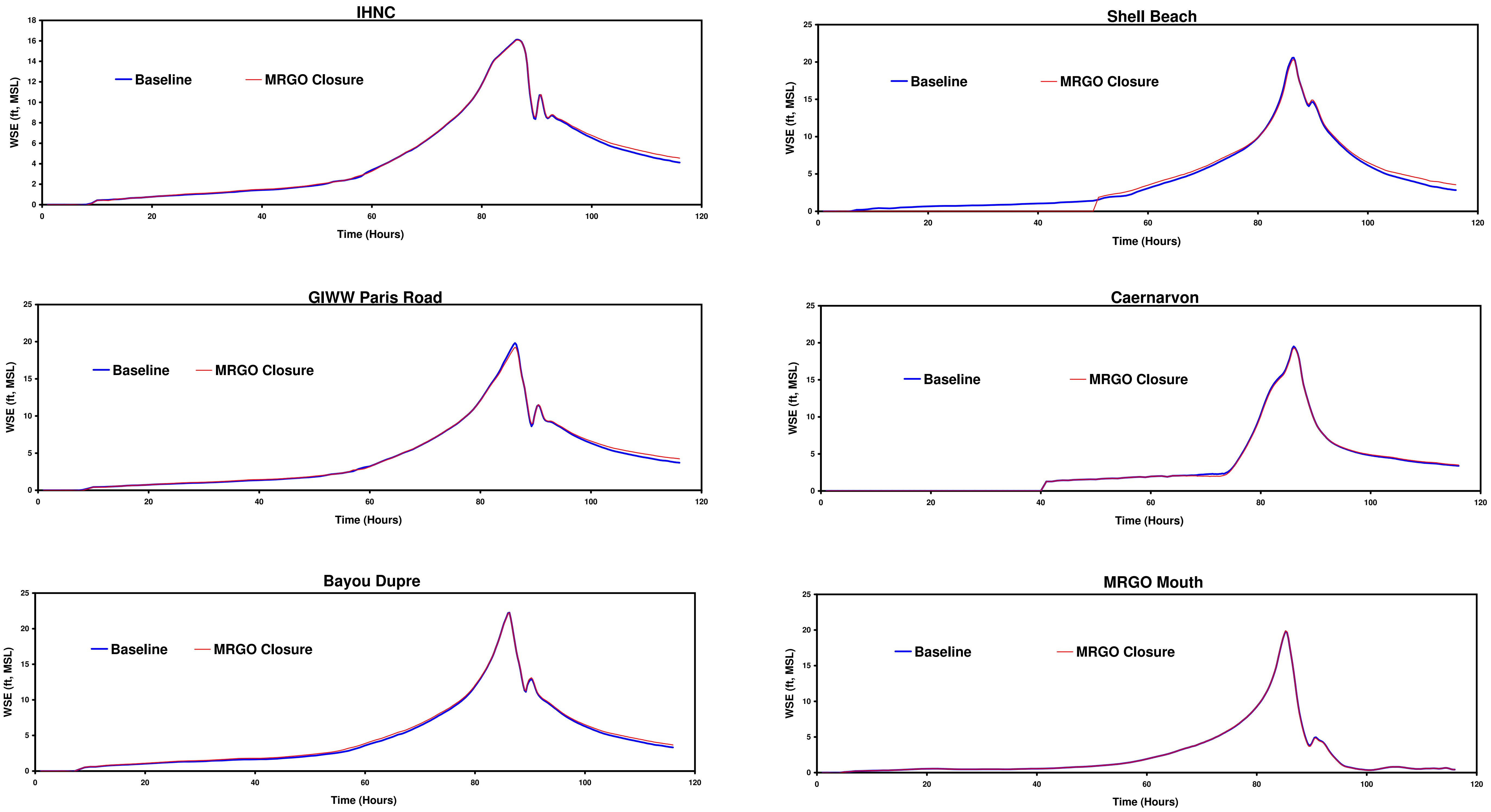

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Figure 24
Storm Surge Hydrographs, Hurricane Katrina, Baseline versus Closed MRGO

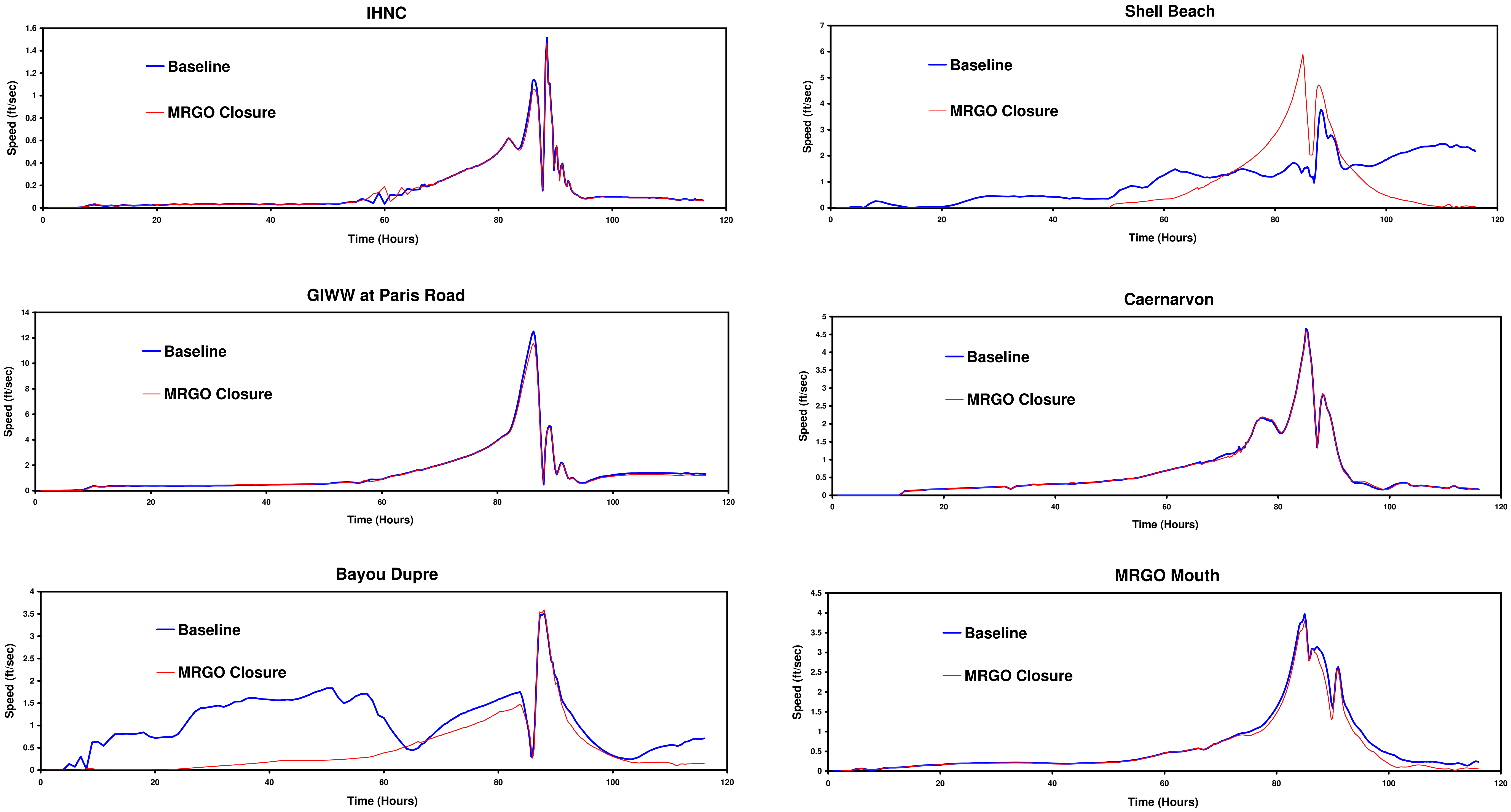

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Figure 25
Storm Surge Current Speed Hydrographs, Hurricane Katrina, Baseline versus Closed MRGO

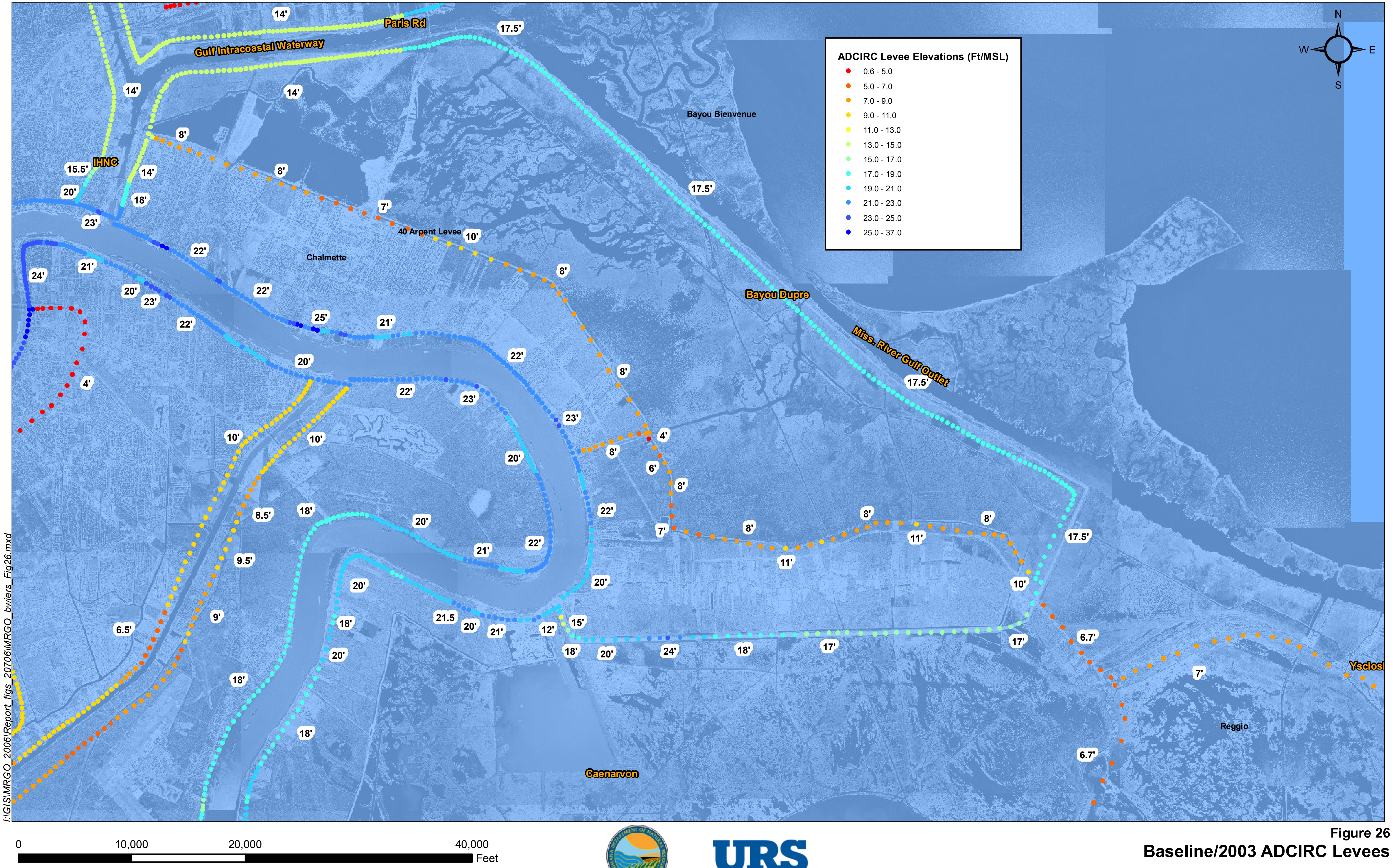

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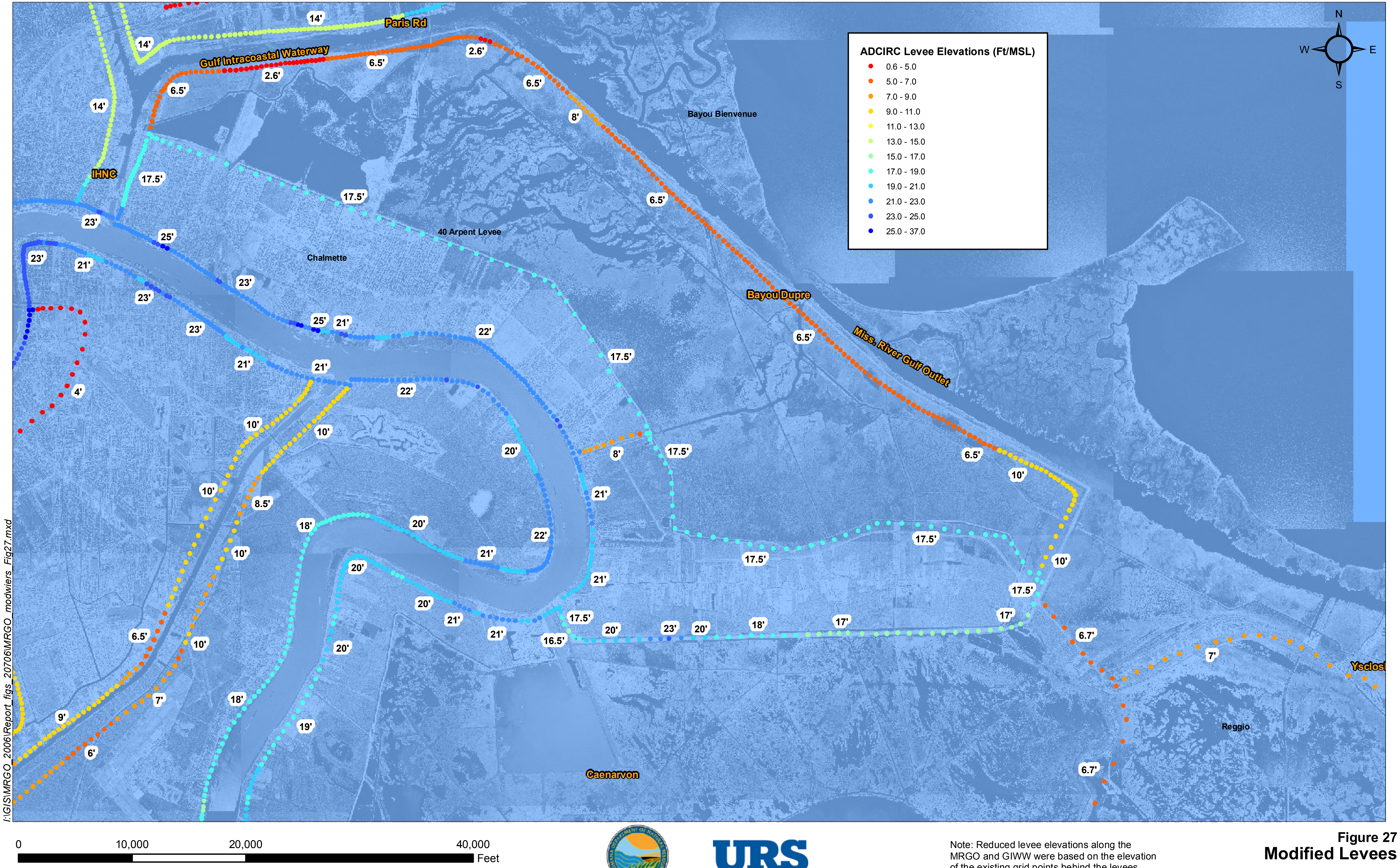
Figure 26

Baseline/2003 ADCIRC Levees

ADCIRC Grid



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Note: Reduced levee elevations along the MRGO and GIWW were based on the elevation of the existing grid points behind the levees.

Figure 27
Modified Levees

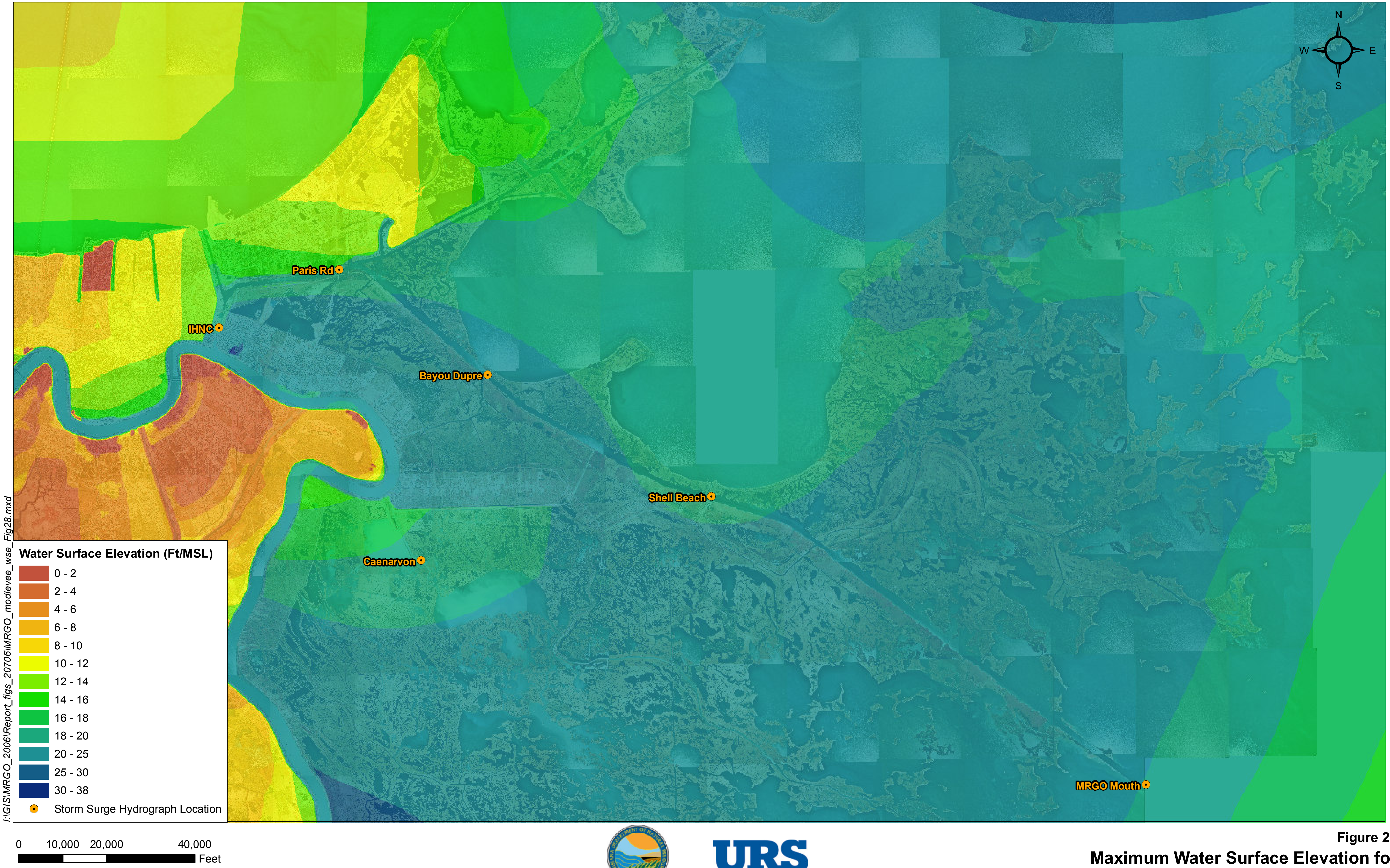

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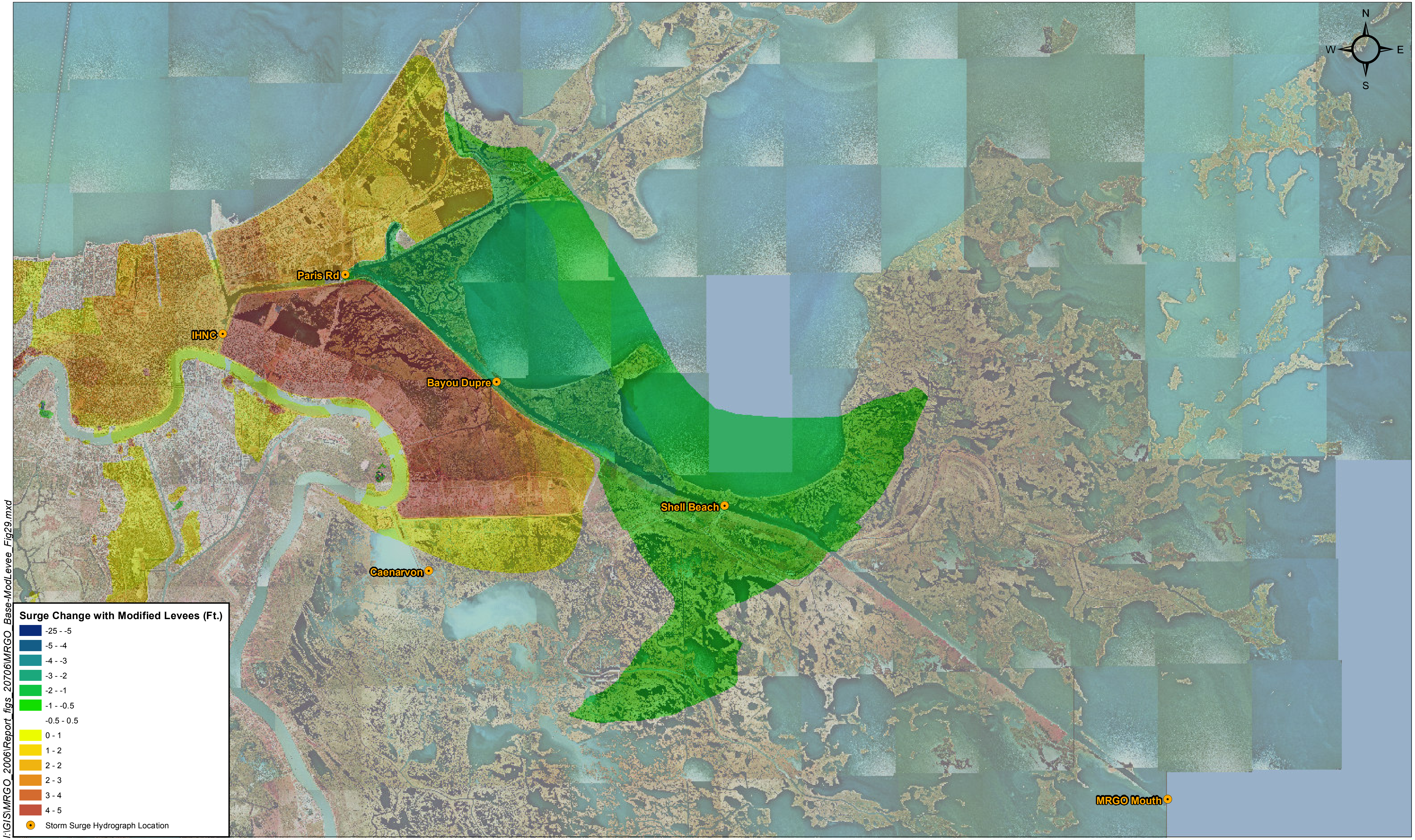
Figure 28

Maximum Water Surface Elevation for Hurricane Katrina, Modified Levee MRGO



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NOTE: Surge Reduction with Modification is Negative (Green).
Surge Increase with Modification is Positive (Red).

0 10,000 20,000 40,000
Feet

URS

Figure 29

Difference in Maximum Water Surface Elevation for Hurricane Katrina, Baseline vs. Modified Levees MRGO

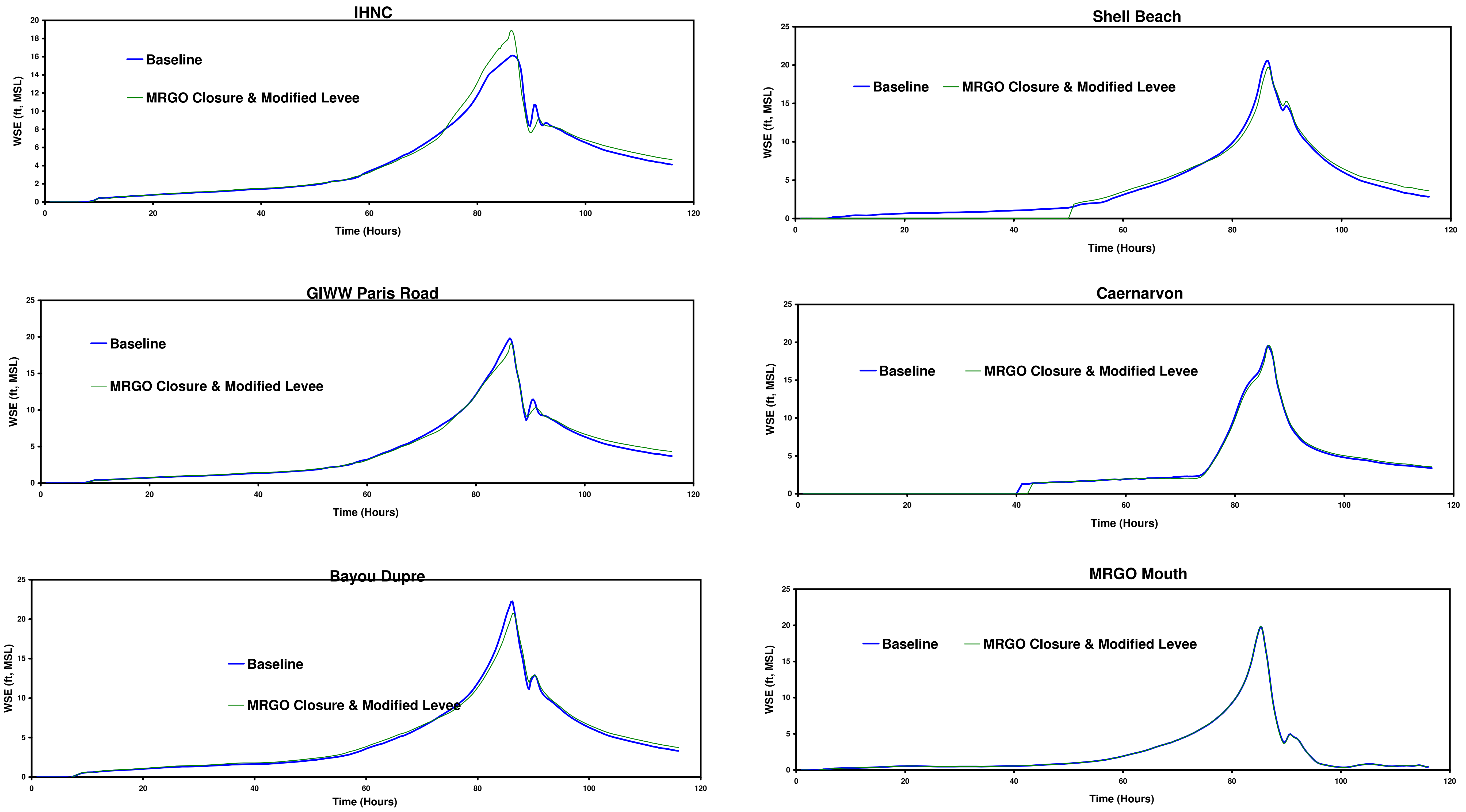

Figure 30
Storm Surge Hydrographs, Hurricane Katrina, Baseline versus Modified Levees

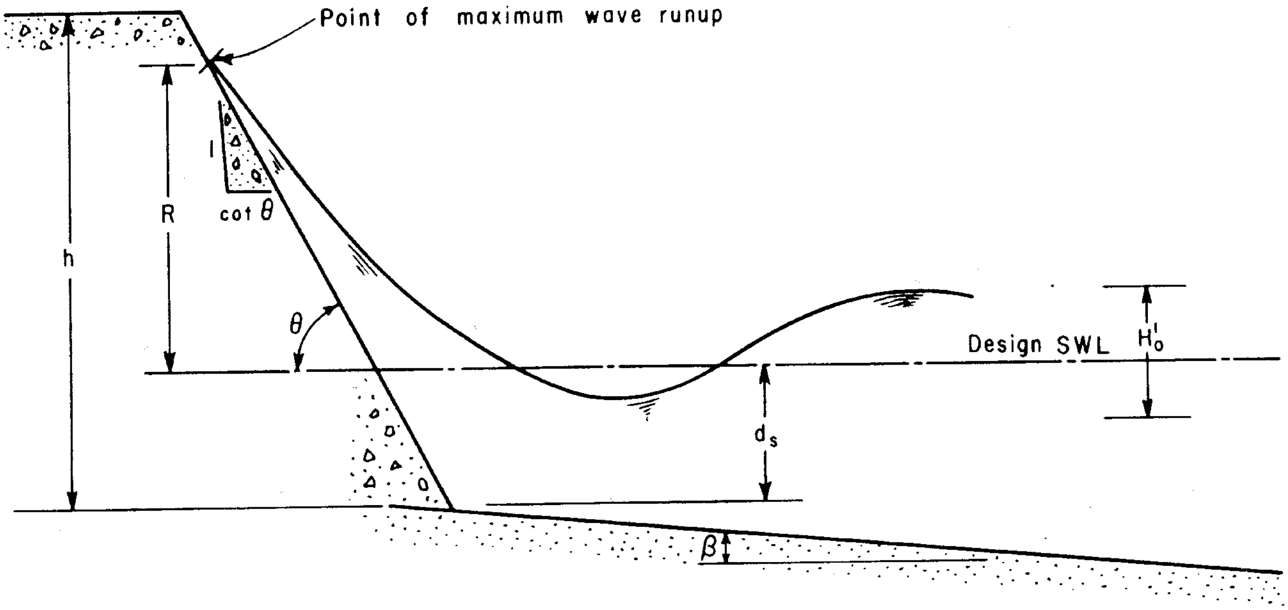

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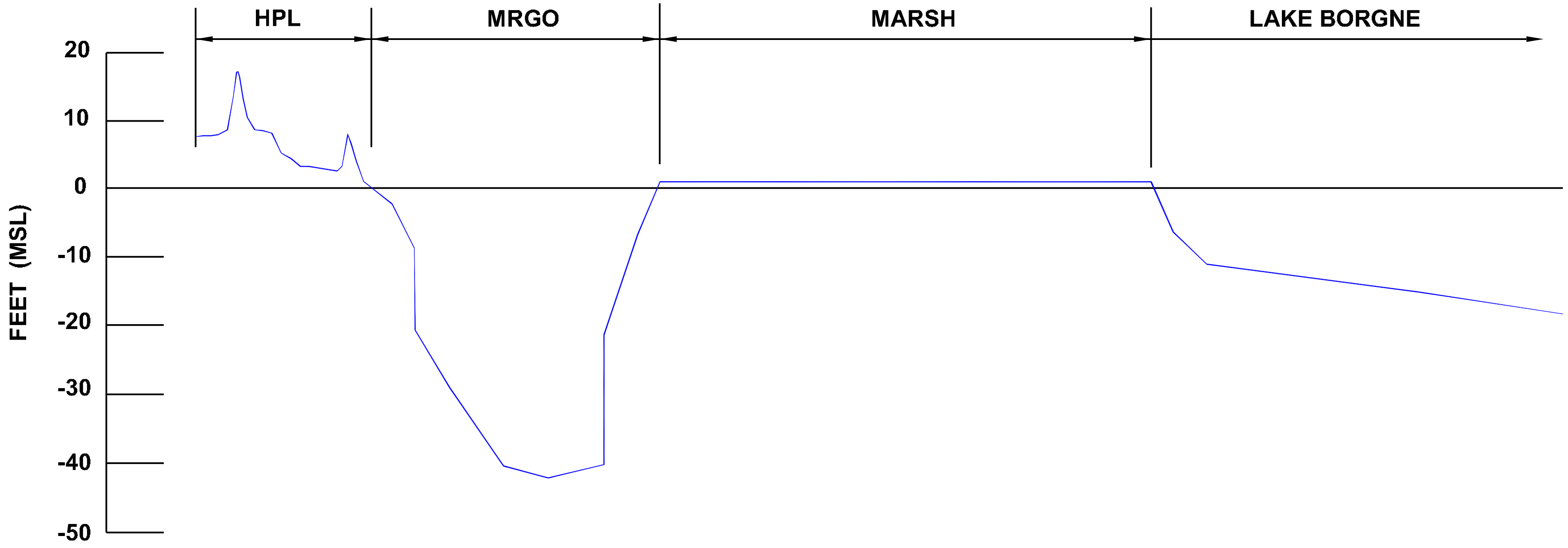
Figure 31

Schematic of Wave Set-up and Run-up



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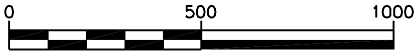

HORIZONTAL SCALE IN FEET

VERTICAL EXAGGERATION 20X

Figure 32

Hurrican Protection Levee
Cross-Section Near
Bayou Dupre, Station 673+00

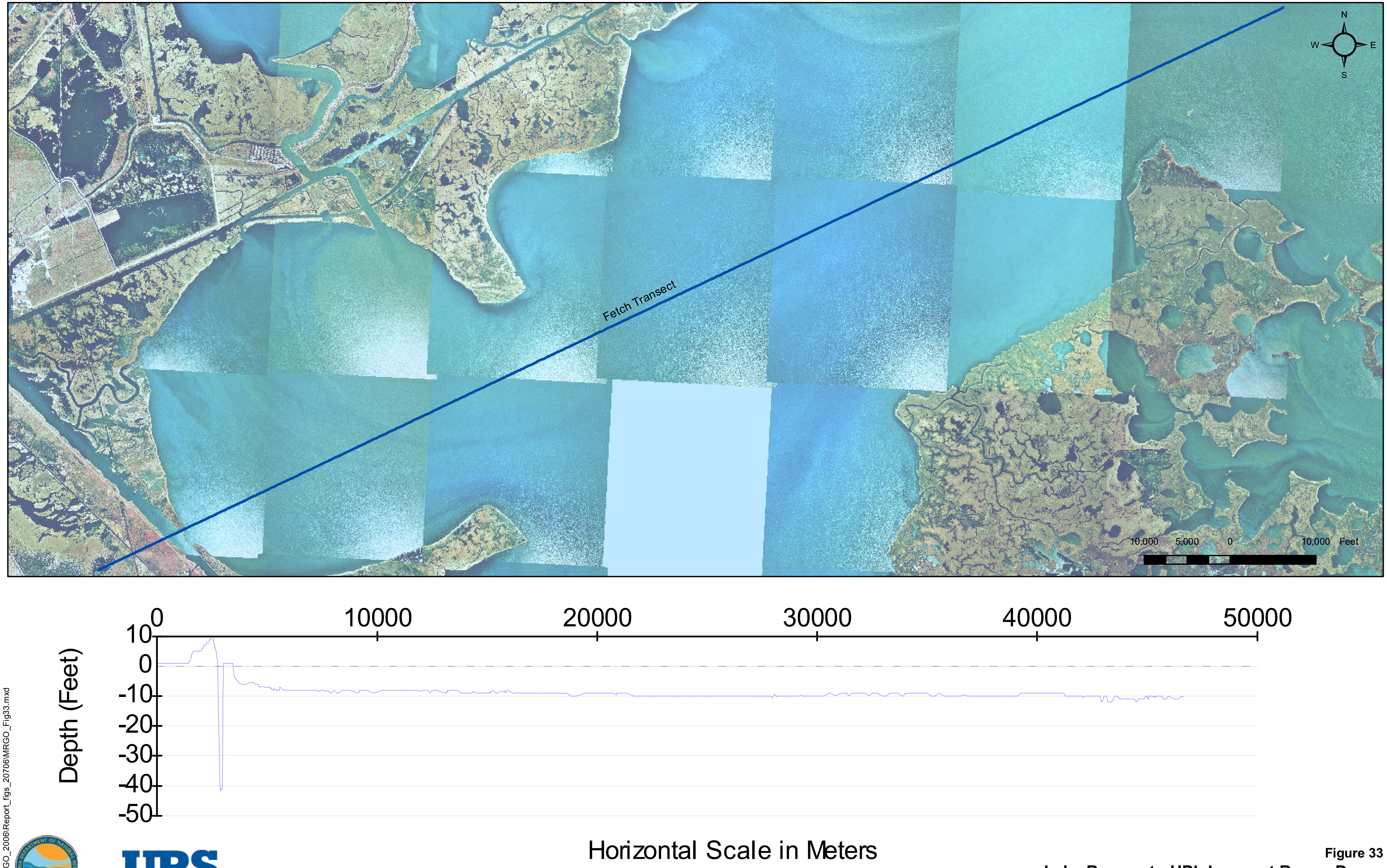

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Figure 33
Lake Borgne to HPL Levee at Bayou Dupre
Transect for Wave Run-up Analysis

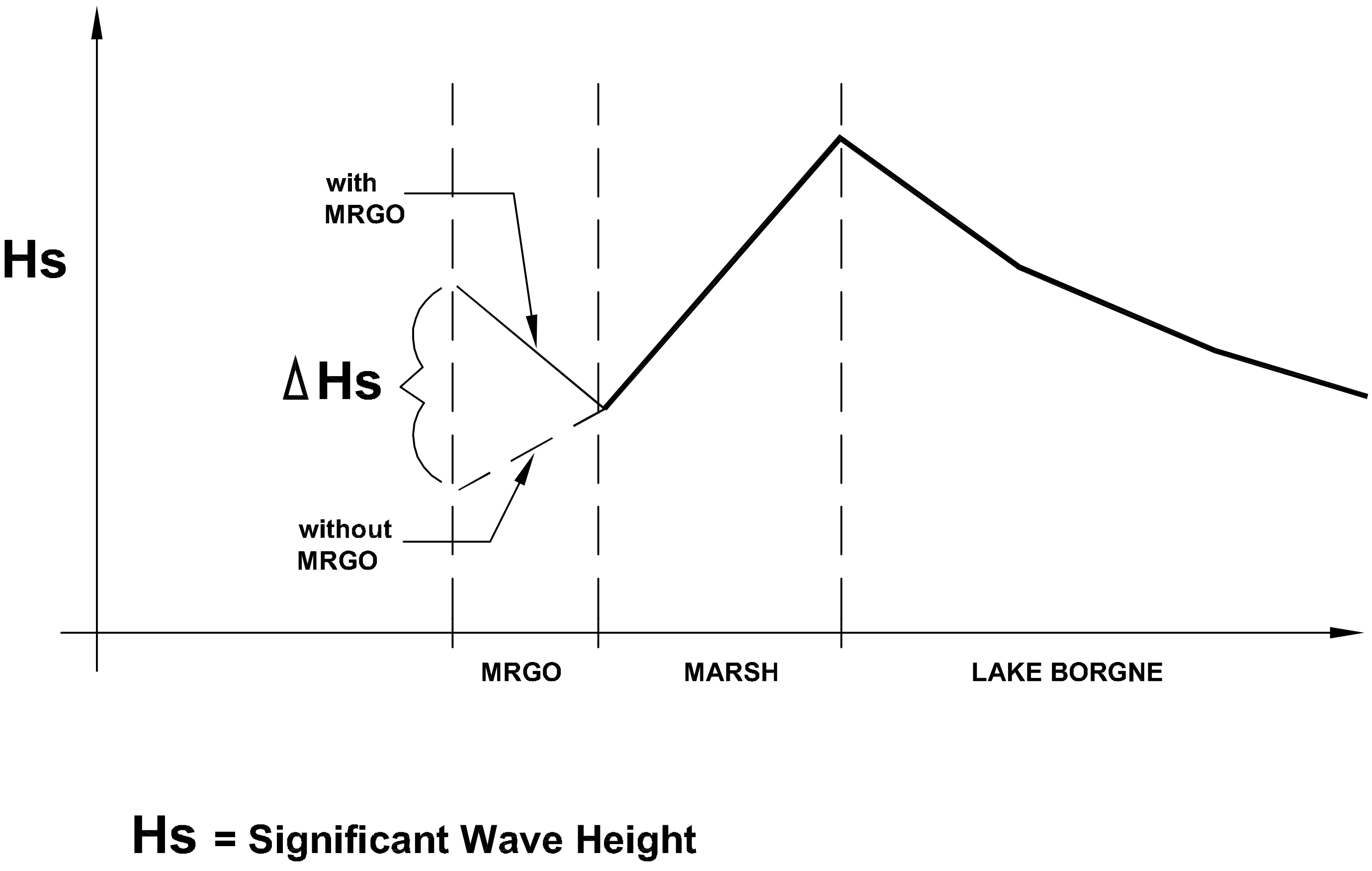
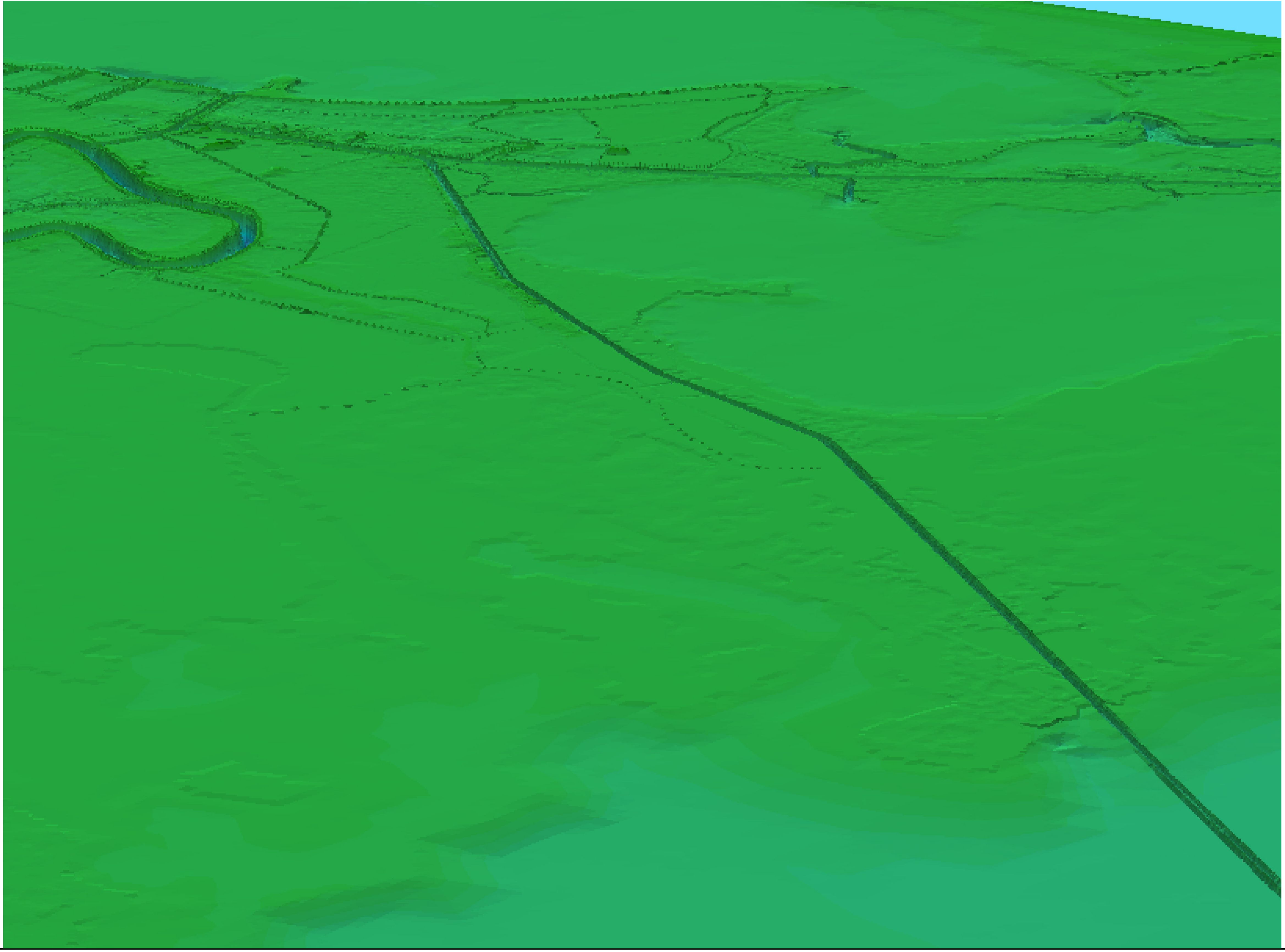


Figure 34

Schematic of Wave Generation and Attenuation for Lake Borgne to HPL Levee at Bayou Dupree



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Note: Image created in ArcScene. Vertical Exaggeration 25x.
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NOT TO SCALE

Figure 35
3D Depiction of High Resolution ADCIRC Terrain for MRGO and Surrounding Area