The Dynamics of Storm Surge in the Pontchartrain and Maurepas Region

New Orleans' lakefront seawall during Hurricane Isaac: Image Source – European Press Agency

Lake Pontchartrain Basin Foundation

Pontchartrain-Maurepas Surge Consortium (PMSC) Steering Committee & Authors

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About the
Pontchartrain-Maurepas Surge Consortium

The Pontchartrain-Maurepas Surge Consortium (PMSC) was founded in 2015 through the Lake Pontchartrain Basin Foundation's (LPBF) Coastal Sustainability Program to facilitate a regional approach to storm surge risk management for the coastal communities along Lakes Pontchartrain and Maurepas.

The PMSC mission is to leverage local expertise and additional technical resources into a regional collaboration that will promote:
• broader understanding of storm surge dynamics in the lakes,
• better-informed storm surge risk-reduction strategies for all communities around the Lakes, and
• environmental sustainability, community resilience, and safety of residents through enhanced storm surge risk management.

During its first year, the PMSC held a series of workshops discussing various aspects of storm surge risk management, including storm surge dynamics within the study region, storm surge modelling, and historic storm surges observations. This report originated from the materials, science presented and technical discussions at these workshops.

The PMSC builds off of LPBF's role in pioneering the Multiple Lines of Defense Strategy for protecting coastal Louisiana, which has been endorsed by the US Army Corp of Engineers, the Louisiana State Master Plan, and numerous local governments along the coast. We've identified and advocated for sustaining key coastal lines of defense for the Lake Pontchartrain region and we recently completed a major system engineering assessment of the current surge defenses for the east bank of Greater New Orleans.

The PMSC is led by a steering committee composed of Dr. John Lopez, Dr. Ezra Boyd, Dr. Joe Suhayda, Dr. Hal Needham, and Kort Hutchison. Funding for this project is provided by the Kresge Foundation.

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Executive Summary

Analysis of time-lapse dynamics of recently simulated major storm surges and historical storm surge maximum observations shed new light on spatial and temporal patterns of storm surge within the Lakes Pontchartrain and Maurepas region (PMSC region, see **Figure 1**). While the terms tilting or sloshing have been previously used to describe key dynamic processes of storm surge movement in Lake Pontchartrain, these terms can be misleading because the peak surge generally rotates around the lake perimeter (**"surge rotation")** rather than directly transferring (tilting/sloshing) from one end of the lake to the other.

In this analysis, two recent storms are examined as archetypical events that exemplify a new conceptual model that we introduce. Hurricanes Katrina (2005) and Isaac (2012) had fundamentally different tracks which seem to illustrate well the contrasting patterns of storm surge rotation introduced here. However, while these exemplify a generalized surge rotation model, it is important to keep in mind that our conceptual model is built around local forcing on storm surge and not the larger coastal processes. Every storm is different and the resulting surge is always a result of regional and local forcing. The limitation of this study is that we only discuss the movement of surge within the PMSC region and not the dynamics of surge entering into the PMSC region by more regional meteorological or coastal processes. In spite of this limitation, much can be said about the generalized relative movement of maximum surge in the PMSC region.

The primary driver for the surge movement in the PMSC region is the changing local wind field over the PMSC region during a storm's coastal approach, landfall and movement inland. Wind set-up and wave set-up, due to the storm's cyclonic wind field, dominate the time-varying surge maximums around the PMSC region during a storm passage. At any given time during a storm's passage, the highest surge tends to occur at the Lake Pontchartrain's shoreline which is directly downwind at that time. In this regard, Lake Pontchartrain is far more significant influencing surge movement of the PMSC region than Lake Maurepas. During a storm's passage, the wind field changes both intensity and direction across the PMSC region due to the rotation of winds around the storm's eye as it moves inland. This local wind forcing and associated wave set-up push water downwind until it encounters the far shoreline where surge height increases. Because the cyclonic rotation of any hurricane creates a rotation of the wind field at any specific location as the storm moves inland, as the wind rotates, so does the surge maximum rotate, around Lake Pontchartrain.

Analysis of time lapse surge maps shows that the direction of surge rotation depends on the storm track relative to the PMSC region. For example, during a west passing storm, such as Hurricane Isaac, the peak surge rotates clockwise from the southwest quadrant of Lake Pontchartrain toward Madisonville and then east toward Slidell. If the storm passes east, such as Hurricane Katrina, the surge rotates counter-clockwise from the southwest quadrant of Lake Pontchartrain and towards New Orleans and then Slidell. However, this simple rotation model by itself does not explain why the highest surge tends to occur when the storm is inland and the wind is at less than the maximum that occurs during a typical storm event.

The asymmetries of shoreline type, bathymetry, and related landscape characteristics are important secondary influences to the actual surge heights during the for typical surge rotation, and may explain why highest surge can occur after the storm has moved inland. The western end of the PMSC region has expansive storage due to low-lying swamps and marsh which attenuate surge height and momentum of surge. Therefore, the western boundary of the PMSC region is described as equidistant and non-deflecting. In contrast, the eastern boundary of the PMSC Region can be described as converging boundaries with hard, deflecting shorelines due to both the natural topography and the hardened shoreline. The boundaries of the eastern end of the PMSC region constricts, deflects storm surge, which is referred to as "**surge focusing**". During recession of surge from the PMSC region, the combined effect of focusing and surge rotation is a heightened surge event referred to as "**outflow surge**", because at this time the storm is inland and surge is moving seaward. For storms that pass east of the PMSC region, the outflow surge near Slidell is likely to be the highest within the PMSC region, despite the presence of the weaker wind field of the southwest quadrant of the storm and despite that storm's eye having moved inland. That is, the greatest threat to Slidell occurs when the storm is inland and the lake is encountering the weaker quadrants of the storm. The consequences of any outflow surge threat is heightened by human behavior because it is likely to be assumed by the public that greatest threat is over because the storm is inland, when in fact the highest surge is about to occur.

Tertiary influences on surge in the PMSC region include astronomical tides, a true seiche oscillation, and direct rainfall. These modest influences could possibly have a cumulative effect of adding up to 3 ft. to the surge heights, depending on their individual timings relative each other and relative to the peak surge. Since the timing is independent, the tidal component is often treated as a random variable in storm surge forecasts, though some forecast systems explicitly account for tides. Generally speaking, because the "peak surge" at a location is really a 6 – 12 hr. plateau in the hydrograph, there are good odds that a high tide will occur during peak surge. Because the flood hydrographs in the north shore rivers generally peak two to five days after a rain event, the contribution of north shore drainage to storm surge is generally toward exacerbating backwater riverine flooding and prolonging the surge event, but not contributing significantly to peak surge conditions in the PMSC region. Finally, seiching is a natural harmonic oscillation that can occur when any enclosed or semi-enclosed water body is perturbed, for example Lake Pontchartrain if there is a drastic change in winds.

Based on this analysis, we propose a general a **surge rotation model** for the PMSC region. From this model, a map is presented in the "Discussion" section (see **Figure 37**) which demarcates the areas that are most at risk in the PMSC region based on the location of the eye of the storm and the surge rotation model. This map illustrates that initial storm set-up in the PMSC region is created early as a storm approaches, and therefore, has a large influence on the overall volume of surge to be subsequently rotated as the storm moves inland. Once inland, the storm's east or west passage determines which areas of the PMSC are most likely to have the greatest surge heights during that time of the storm's passage.

Introduction

The Pontchartrain-Maurepas Surge Consortium (PMSC) was established in February 2015 by the Lake Pontchartrain Basin Foundation (LPBF) to address storm surge risk around Lakes Pontchartrain and Maurepas. In this region, surge water moves freely across the jurisdictions of multiple levee boards and local municipalities that are at risk of flooding (**Figure 1**). The PMSC region includes the east bank of greater New Orleans, which was devastated in 2005 by Hurricane Katrina. It also includes many communities and industries outside of levee systems in southeast Louisiana. Although Baton Rouge is not considered a coastal city, during the past few decades Greater Baton Rouge has sprawled eastward into bedroom communities, while hurricane surge inundation seems to be incrementally moving further westward toward Baton Rouge. These trends suggest that the outlying communities of our state capital are no longer insulated from the crisis in our coastal zone. The PMSC is drawing together professionals to work on solutions for the region, including the prodigious economic corridor of the Mississippi River parishes between New Orleans and Baton Rouge. With sea-level rise, subsidence, and loss of wetlands, the surge risk is increasing, both in terms of deeper flood waters and a larger area subject to inundation. The PMSC hopes to assist in mitigating against the threat of surge to this region, building upon former work using the Multiple Lines of Defense Strategy (Lopez and Snider 2008, Lopez 2009).

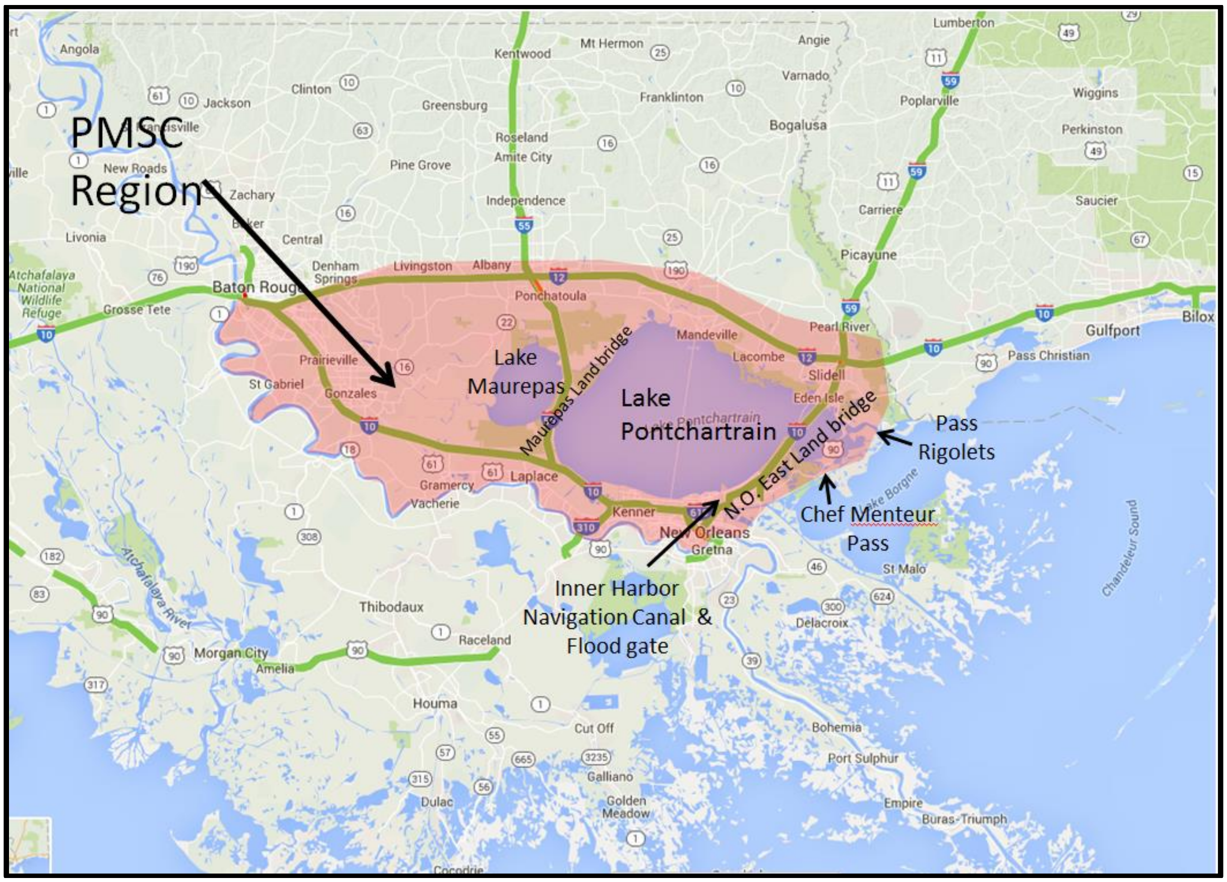


Figure 1: Pontchartrain-Maurepas Surge Consortium (PMSC) region and major hydrologic features

In 2014, LPBF completed a systems engineering based analysis of the New Orleans Hurricane Surge Defense System (Boyd, Lopez, and Storesund 2013) which includes levees, pump stations, and floodgates along with our coastal buffer and community resilience measures. The report is titled "*A Systems Engineering Based Assessment of the Greater New Orleans Hurricane Surge Defense System using the Multiple Lines of Defense Framework*" and it is available for download here. This report identified many "factors of concern," such as inadequate funding for long-term maintenance, weak links in evacuation routes, and the system's operational complexity. One example, that is explained in detail in the report, is the simultaneous evacuation of ships and people in the vicinity of the Inner Harbor Navigation Canal and Lake Borgne Surge Barrier, with contrasting needs for the position of the drawbridges (ships need them up and cars need them down) . Foremost, the report concluded that these risk reduction components must be ***managed as a system that integrates various elements across multiple geographic jurisdictions and legal authorities***.

To encourage a systems-based approach that reaches across jurisdictional boundaries, LPBF initiated the PMSC. The PMSC has invited professional representatives from levee boards, regional planning commissions, parishes, and municipalities from the areas around Lakes Pontchartrain and Maurepas. Because storm surge solutions may cross political boundaries, we hope to pool our knowledge, expertise and resources within this consortium to better understand surge behavior in this region as well as develop complementary solutions and sustainable risk reduction projects.

The PMSC has been holding topically focused workshops every 6-8 weeks since February 2015. Topics have included: surge dynamics, surge modeling, geodetic and hydrographic surveying, relative sea level rise, risk analysis, evacuation, demographics, and the New Orleans East Landbridge. Funding for this project is provided by the Kresge Foundation.

This report is the first of a series of reports expected to be produced through the PMSC. This report describes the dynamics of strong surge around the PMSC region and builds off of our workshops on this topic. This report utilizes pre-existing storm information of real storms for analysis, but future modeling may be pursued to confirm or refine concepts presented in this report.

The PMSC region is a mostly enclosed, oval shaped basin with the longer dimension along the east-west axis (**Figure 1**) that is composed of two major tidal waterbodies, Lakes Pontchartrain and Maurepas. A number of key features make this coastal landscape unique (**Figure 2**). Lake Pontchartrain is connected to the Gulf of Mexico through two natural passes (Chef and Rigolets), and one artificial channel (Industrial Canal). While floodgates block off the artificial channel during a hurricane, the two passes remain open and convey a large volume into the Lakes.

In the early phases of a storm surge, the storm is still offshore, and remote forcing in the Gulf of Mexico via its outer windfield causes waters to rise across the coast, including Lake Borgne, the outermost of the three main lakes in the Pontchartrain Basin. Surge waters then flow through the Chef and Rigolets passes separating Lake Pontchartrain from Lake Borgne and then into Lake Maurepas via Pass Manchac connected into Lake Pontchartrain (**Table 1**). As rising waters reach around 5 ft. elevation, surge starts to flow over the low-lying NO East land bridge that separate

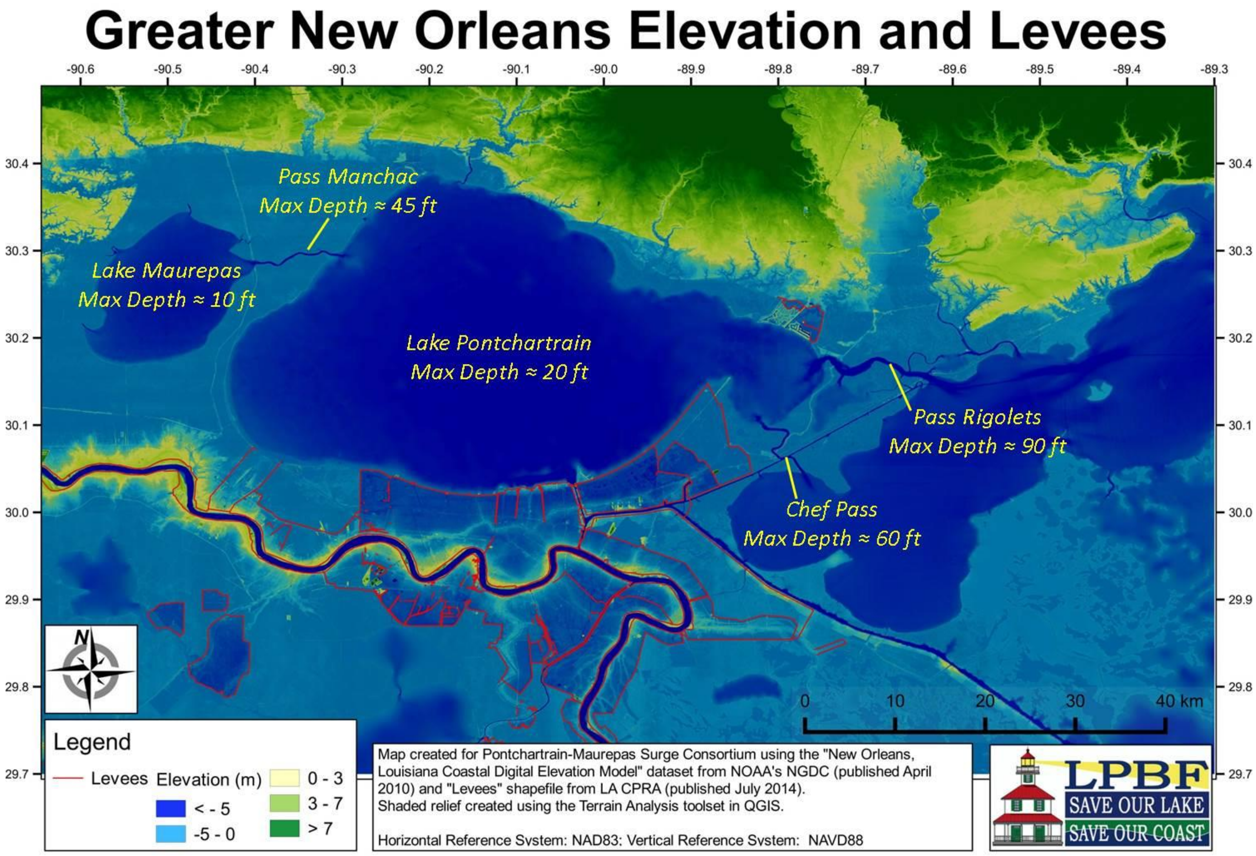


Figure 2: Elevation map of the PMSC region, which generally consists of low-lying marsh or swamp shoreline along the western half, either artificial or natural levees on the south shore, and the Pleistocene Terrace on the north shore. (Data Sources: NOAA 2010, CPRA 2014.)

the three lakes. Eventually the surge inundates both Lakes along with the adjacent wetlands, thus creating what is essentially a bay that stretches 75 miles in the east-west direction. Largely due to remote forcing while the storm is still offshore, this process is informally called "filling the lake."

Table 1: Characteristic dimensions and flow values for passes and lake cross-sectional transects

Tidal Passes	**Total Length (mi)**	**Average Depth (ft)**	**Average Cross-sectional Area (sq. ft)**	**Average Peak Tidal Discharge (cfs)**
Pass Rigolets	8.5	33.8	82,200	290,000
Cher Menteur Pass	6.4	41	39,400	85,000
Pass Manchac	9.3	26.2	31,500	
Lake Cross Sections	**Total Length (mi)**	**Average Depth (ft)**	**Average Cross-sectional Area (sq. ft)**	**Maximum Depth (ft)**
N.O. East-Slidell	8.4	6.4	781,388	24
Causeway	26.0	12.4	3,211,353	27
Maurepas Landbridge	26	NA	298,072	47
Lake Maurepas Midsection	26	9.5	1,983,623	11.7

Source: Lopez, Davis, and Cope (2011), NOAA (2010). See Appendix B for details on the lake cross-sectional calculations.

The term “tilting the lake” has been used to refer to the observed variable surge heights around Lake Pontchartrain during a single storm event. Once a storm makes landfall and the eye moves north, the windfield over the lakes shifts in a pattern dependent on the storms track relative to the lakes. These shifts in the local windfield create a more complicated dynamic process than the simple filling process. As opposed to a gradual, uniform surge rise, changes in water levels due to local forcing are uneven in timing and location within the PMSC region. While these effects are often called “tilting”, we suggest that the phrase “surge rotation” better describes the dynamics associated with changes in the local windfield.

In recent years, specifically since Hurricane Katrina, New Orleans has gained improved storm surge protection under the Hurricane Storm Damage Risk reduction system (HSDRRS) (USACE 2012). Other communities, like Slidell, were also devastated by Hurricane Katrina and have a partially built, local (non-Federal) perimeter levee. Hurricane Isaac occurred in 2012, precisely seven years after Katrina (both occurred on August 29). While it caused only minor impacts to New Orleans, this storm caused major impacts to other communities within the PMSC region, but outside of the HSDRRS, including Plaquemines, St. Tammany, St. John the Baptiste, St. James, Tangipahoa, and Livingston Parishes. The suburban communities of Laplace, Slidell, Mandeville, Lacombe, and Madisonville all experienced substantial storm surge flooding (Boyd 2012).

Hurricane Katrina was a large Category 3 storm whereas Isaac was a smaller, slower moving Category 1 storm. Both had a dominant northerly direction of movement, but Katrina passed just east of the PMSC region and Isaac passed just west of the PMSC region. Both storms have been well documented and have comprehensive hydrologic and meteorologic data, such as following Hurricane Isaac, the USACE completed a study to evaluate the impacts of the HSDRRS system on storm surge risk in nearby areas outside of the levee-protected areas. The study found that the newly built levees did not significantly increase the surge height in Lake Pontchartrain. Instead, the study found that the closure of Inner Harbor Navigational Canal via floodgates actually reduced surge by 0.1 ft. Only on the Westbank, in the vicinity of the West Closure Complex, did the study find a substantial increase (up to 0.8 ft.) in water levels (USACE 2013). However, this study only assessed the incremental changes in the levee and pump station system following Hurricane Katrina. It did not evaluate the total effects of current levee footprint around New Orleans (Thompson 2013, Exnicios 2013). The USACE is completing an additional study that is investigating changes in storm surge from a pre-Hurricane Betsy condition to a current condition. The report will be part of the HSDRRS Comprehensive Environmental Document and is expected to be released in early 2017. This report will be reviewed to determine if historical storm surge patterns in the PMSC region were fundamentally different from those observed in more recent storms.

General Storm Physics and Surge Analysis Methodology

NOAA defines a **storm surge** “as an abnormal rise of water generated by a storm, over and above the predicted astronomical tide.” **Figure 3** depicts a 15 ft. storm surge coinciding with a 2 ft. astronomical high tide to create a 17 ft. **storm tide**, which is defined as “the water level rise during a storm due to the combination of storm surge and the astronomical tide.” Therefore, the storm surge is the change in water level due to the storm passage, while the storm tide is the actual water level measured relative to an establish reference level (such as local mean sea level.) As noted, the abnormal rise in water reflects both remote forcing from offshore meteorological conditions and local forcing due to winds over the lake. This report deals almost exclusively with the local dynamics behind storm surge.

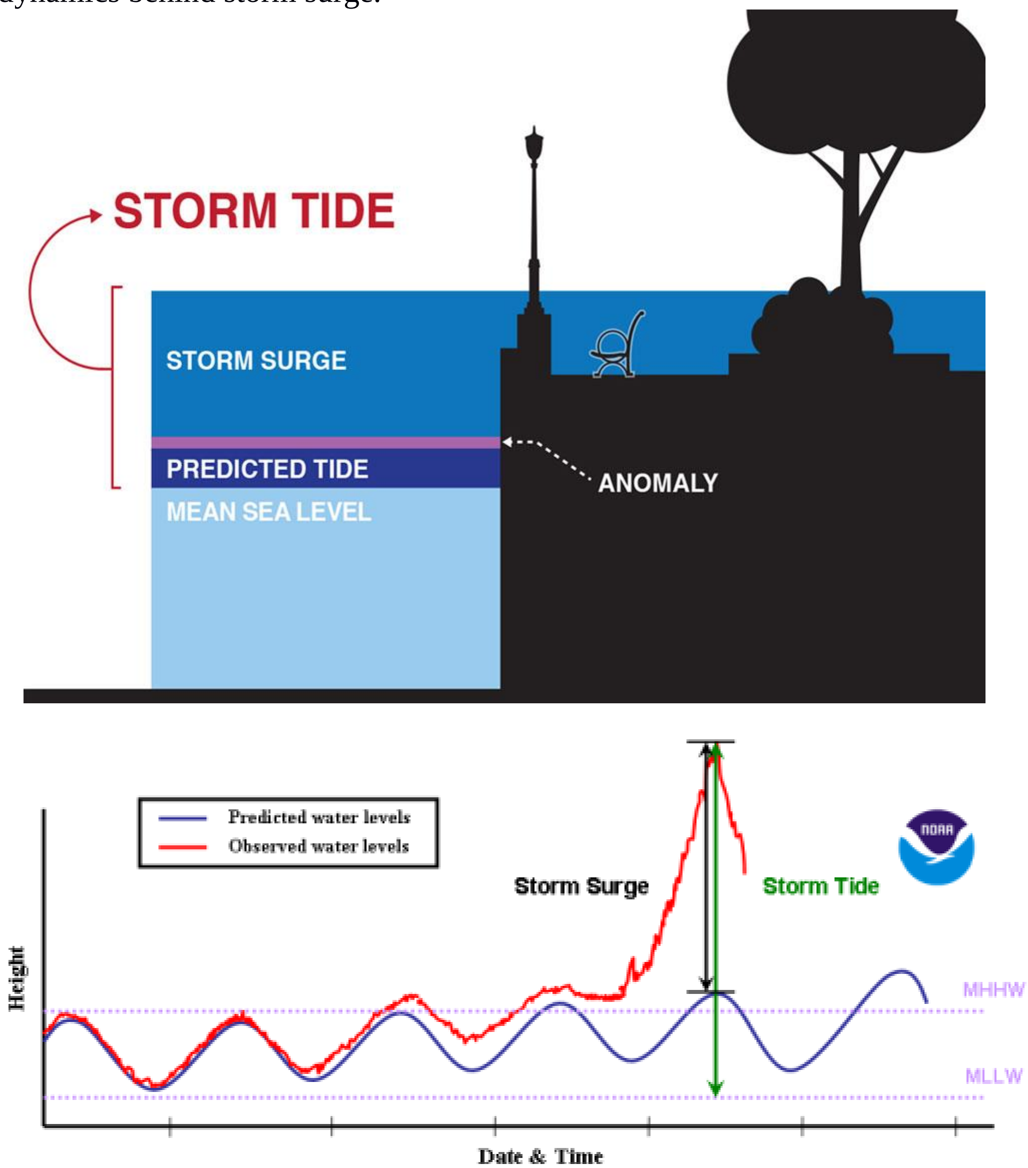


Figure 3: NOAA graphics describing a storm tide, which is the storm surge in addition to astronomical tide.

Our primary methodology of surge behavior in this study consists of examining time-lapse, ADCIRC (Advanced Circulation finite element, see http://adcirc.org/home/documentation/users-manual-v50/introduction/) model outputs in the PMSC region of recent storms, and examining historical surge heights. In particular, Hurricanes Katrina and Isaac are used as recent characteristic storms with accurate ADCIRC hindcasts (post-storm surge models)through CERA (LSU's Coastal Emergency Risks Assessment Interactive Website System). These models had a sufficient digital elevation model (DEM) for recent storms such as Hurricane Katrina and Isaac, and sufficient robustness to hindcast these storms to inform details of the interaction and movement of surge in the PMSC area. However, as described below, there are limitations to this approach, so empirical datasets are also used to corroborate and further illustrate dynamical processes not apparent in the ADCIRC results.

In this report, we introduce a few terms to describe a conceptual model of a surge dynamical processes that occur within the PMSC region. The term "**surge rotation**" describes the phenomenon that has traditionally been called surge tilting or sloshing. As we describe in the next section, the unique geometry of Lake Pontchartrain results in a surge peak that rotates around the shoreline as the wind changes directions with the storm's passage over the region. We also introduce the term "**surge focusing**" to describe the observed tendency of higher surge heights to occur in the northeast and southwest corners of the lake. Finally, "**outflow surge"** refers to the phenomenon of a late stage surge peak on the eastern (Gulf of Mexico) side of the lake due to the westerly wind patterns after the eye of the storm is north of the PMSC region.

There are four principle physical processes that drive storm surges (Fitzpatrick 2014):

1. **Pressure setup** refers to the decreased atmospheric pressure near the center of circulation which causes water levels to increase.
2. **Wind setup** is the increase in water levels due to the force of winds on the water surface. Specifically, the wind shear along the water surface creates vertical circulation patterns. As the storm moves inland, the shallow coastline interferes with the vertical circulation and pushes the water up.
3. The **geostrophic adjustment** is the rise of water levels attributed to longshore currents.
4. **Wave setup** occurs when the rate of breaking waves is greater than the time for waves to recede, thus causing water to pile up along the shoreline.

In addition, **astronomical tides** can contribute to the severity of the storm surge, with Rego and Li (2009) finding a direct correlation between inundation depth and the timing of the tides. Long -term, **relative sea level rise** (RSLR) will add to the severity of the storm surge, with recent numerical results finding that a 1 ft. rise in RSLR can cause up to a 3 ft. rise in surge heights (Smith and Atkison 2007). This occurs because RSLR increases the water depth during surge events, which results in faster surge propagation and increase wave setup. Finally, Jacobsen (2015) lists three types of landscape features that also impact the movement of water during a surge event. They are confinement, conveyance, and friction.

In a region such as the PMSC region, these forces interact with a complex terrain, resulting in a number of unique surge processes. Generally speaking, these can be divided between the remote forcing and the local forcing. Remote forcing refers to the effects of offshore winds, which cause water to rise along the coast and penetrate into the lakes. Local forcing refers to the effects of the windfield directly over the lake.

Table 2 summarizes the forces, processes, and controls that influence the surge dynamics in the PMSC region. The table also indicates what data may be utilized to assess these processes, including ADCIRC, models, empirical surge hydrographs, and maximum storm surge elevations.

Table 2: Major influences on storm surge dynamics in PMSC region.

Factors Affecting Surge movement in PMSC region	ADCIRC/STWave treatment	Empirical surge hydrograph
Atmospheric Pressure set up	Yes	Yes
Wind set up	Yes	Yes
Geostrophic Adjustment	Yes	Yes
Wave set up	Yes	Yes
Astronomical tides	No	Yes
Seiche Oscillation	in theory, but marginally	Yes
Lakes geometry (fixed DEM)	yes	Yes
Tidal passes (fixed DEM)	Yes	Yes
Direct Local rainfall	No	Yes
Local rainfall runoff	No	Yes
Spatially Variable Landscape resistance	Yes, but possibly not sufficiently	yes
Outflow Surge	yes	yes

Numerous models are available for storm surge studies, including ADCIRC (Luettich and Westerink 2004), SLOSH (Jelsnianski, Chen and Shaffer 1992), and Delft 3D (Deltares 2014a, Deltares 2014b). There have also been numerous major modeling efforts applied to our study region, including two coastal master plans, the IPET investigation (Interagency Performance Evaluation Taskforce) following Hurricane Katrina, the MOMs/MEOWs (Maximum of Maximums/Maximum Envelopes of High Water) produced by the National Hurricane Center, and the Coastal Emergency Response Assessment (CERA). Many of these efforts simulate surges from a large suite of storms for long-term planning and engineering design purposes. CERA, a joint initiative involving Louisiana State University and University of North Carolina, Chapel Hill, provides storm surge forecasts and hindcasts for some recent storms. The ADCIRC model simulates the surge movement based on the physical processes driven by a meteorologically defined storm interacting with a digital landscape model. When coupled with the STWAVE wave model (STeady State spectral WAVE), it can also model the contribution of open water waves to the storm surge. These models and the elevation/bathymetry grids, on which the models rely, have improved significantly in the past 20 years and particularly since Hurricane Katrina in 2005.

Since astronomical tides in coastal Louisiana are relatively small, their contribution to the storm tide is modest compared to the storm surge. Still, this modest change can nevertheless add significantly to flood damages. In most applications, the astronomical tide is treated as a random variable, since the timing of the surge and tide are completely independent. However, some implementations of ADCIRC, specifically the CERA website, do explicitly include tides in the simulation. In this regard, we will note that water levels in the lakes tend to average 0.5 ft. above zero elevation NAVD88 (due to local currents, wind setup, and runoff effects), and the typical astronomical tide ranges about 1 ft. above and below this elevation. Rainfall also contributes to the volume of water in the lakes, and this aspect is covered later in this report. It also worth noting that the region is subject to high rates of local relative sea level rise, and that storm surge modelers have observed a non-linear response between relative sea level rise and increase in storm surge height (Smith and Atkinson, 2007)

True **seiching** is a natural oscillation of a perturbed water body and it can also add or detract from the height of the water surface at any given time. As described in more detail below, a seiche is a standing wave oscillation in an enclosed water body. Compared to the tidal cycle, seiches have a shorter period which is determined by the lake dimensions. They are investigated through their signal in the surge hydrograph.

Lake Pontchartrain's surge rotation is sometimes confused with seiching. Because a seiche is a natural oscillation of any water body at a certain frequency which is based on the water body's dimensions, it is a fundamentally different driver of water movement than the storm surge physics (described previously). Seiching occurs when the surface of the water is perturbed, such as can happen from storm surge, but once perturbed the physical oscillation is theoretically independent of other storm surge drivers. A storm surge event is primarily driven by wind, and as a result the storm surge shifts as the wind shifts. This shift of wind and surge has no temporal connection to the natural oscillation of the water body. A seiche can be triggered by winds responsible for the surge movement. Once initiated, the seiche follows its own oscillation determined by the lake dimensions, and its pattern is largely independent of the subsequent wind field. In other words, once there is an initial perturbation, the seiche oscillation evolves independently of the wind and surge patterns that follow. This will simultaneously increase and decrease surge elevations on alternate sides of the lake. The seiche effect is investigated in this report.

ADCIRC model runs typically do not include direct rainfall or local drainage. Obviously, rainfall and storm water are often an important component of a storm event. This will be discussed qualitatively in the analysis, but it is a shortcoming of this report to not fully evaluate rainfall influence on the surge dynamics of PMSC region. Hsu and Blanchard (2000) looked at the storm surge-rainfall discharge interaction within the coastal portion of the Amite River Basin, and found that peak in the hydrograph (largely wind driven) preceded the peak in the stream discharge. Future surge models for the lakes should incorporate the rainfall in surge modeling within the PMSC region because of the nature of restricted drainage through the tidal passes.

Following Hurricane Katrina, the terrain models for the PMSC region were improved and continue to be improved. The terrain models are sufficient to understand regional patterns of surge movement within the PMSC region. However, this may not be adequate for localized surge dynamics within the PMSC region, particularly in areas of high turbulence and/or erosion during the surge event. This report does not seek this level of analysis, but future work may require finer terrain models and the inclusion of fine scale physics to better refine our understanding of surge movement around the PMSC region. **Figure 4** below shows a recent version of the ADCIRC terrain grid.

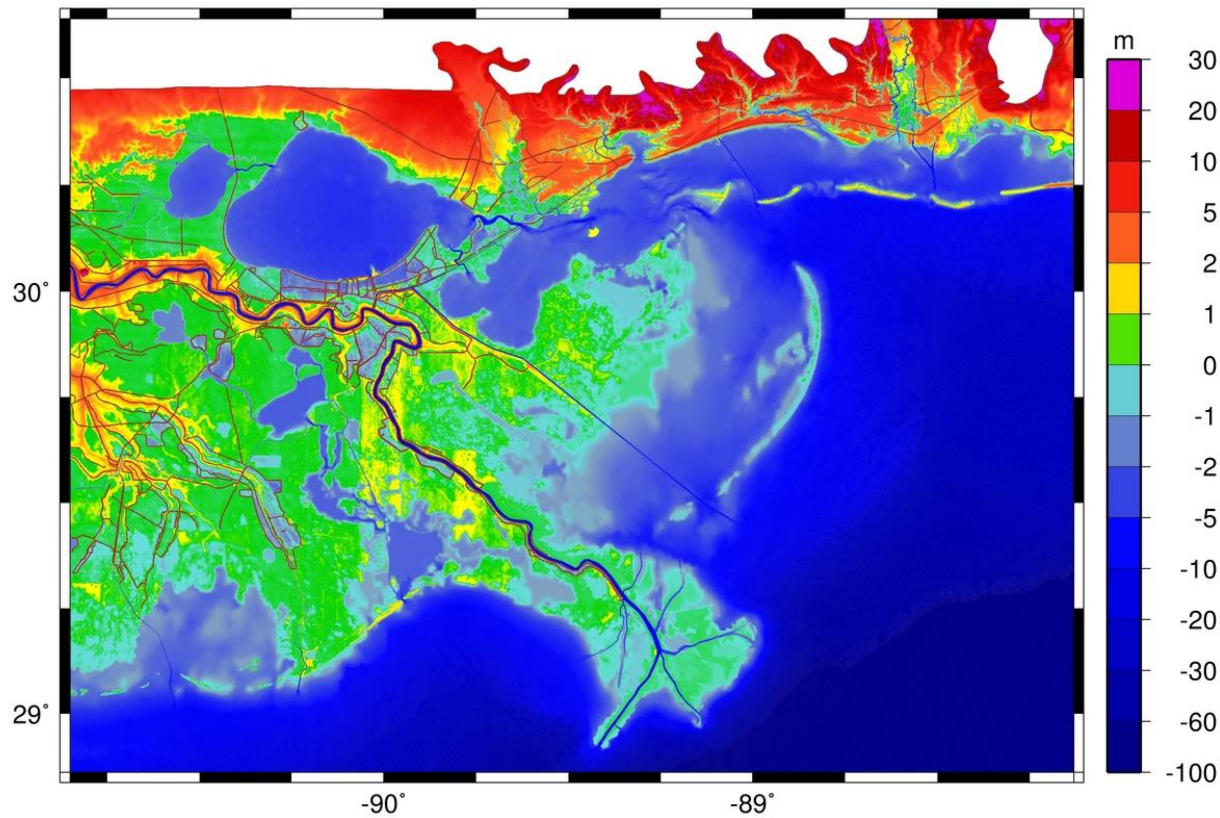


Figure 4: The ADCIRC elevation grid for the southeast Louisiana coastline. (Source: https://www3.nd.edu/~coast/images/SL15-Bath_SL15v7l_large.jpg)

In most storm surge models, including ADCIRC, a Manning's N grid is used to incorporate the resistance at the water bottom. In the equations of motion of a fluid in an open flow channel, the Manning's N parameter characterizes roughness of the surface, and the frictional force acting on the fluid is proportional to N. In a flood modelling context, different landcover types are associated with different Manning's N values. As seen in **Figure 5**, the Manning's N grid is similar to the elevation/bathymetry grid except that cell values characterize the roughness of the landcover for the node's location. In the ADCIRC Manning's N grid below, distinct values for areas such as open water, saltwater marsh, fresh water marsh, urban areas, and forested swamp are visible. Keep in mind, that once the surge inundates otherwise dry areas, that surface then becomes the water bottom. Of note, the model calibration process involves tweaking the values of Manning's N until the simulation matches observations for a particular event or set of events.

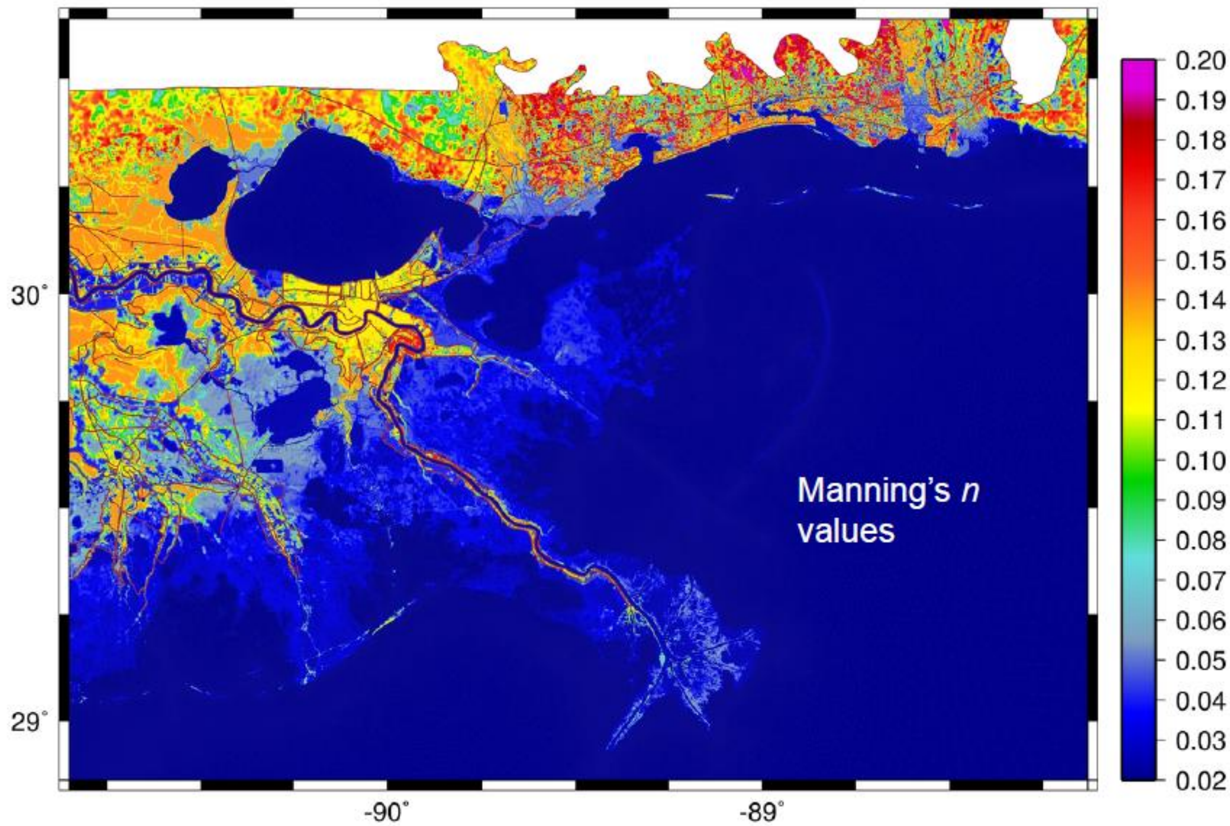


Figure 5: ADCIRC grid of Manning's n coefficient. (Source: Massey 2015.)

Outflow surge is a term introduced in this report to describe the phenomenon often observed in Lake Pontchartrain as a late (seaward) surge event on the eastern side of the lake. It refers to the late-stage process of surge attempting to recede to the open sea, but restricted to only flow through the tidal passes or over the landbridges. Westerly winds on the lower quadrants of the storm (which has moved on land by this stage) cause a late buildup of storm surge along the landbridge and the associated landscape features. The outflow surge is an essential part of the common perception of lake "sloshing", and this process will be elaborated on in the analyses and discussion sections in fuller context of the surge dynamics.

An important caution regarding the use of the ADCIRC models is that we utilize only recent storm events which we feel have been well vetted, and that have the benefit of refinements incorporated since Hurricane Katrina. The two primary storms that we examine are Hurricanes Katrina (2005) and Isaac (2012) (**Figure 6**). Both storms had major impacts in the PMSC region, and both have ADCIRC model outputs available through CERA. Fortuitously, one storm passed east of the lakes and the other west, which as we will describe, has significance to the surge behavior. Regardless, though, these two storm events represent a very small sample of the number of variable meteorological conditions, and tracks of storms.

To help address this limitation, we have also examined an empirical data set of reported high water surge heights from historic storms as far back as 1880. This data set includes 735 observations in the PMSC region, and so may add some robustness to a fuller range of surge scenarios. However, data for nearly all of these empirical storm events are limited to the maximum heights for a given storm and at only a few observation points. This means that we have limited information related to the temporal and spatial patterns in the storm surge events. Nevertheless, we examine the empirical record to find consistency with the surge processes suggested by the ADCIRC models.

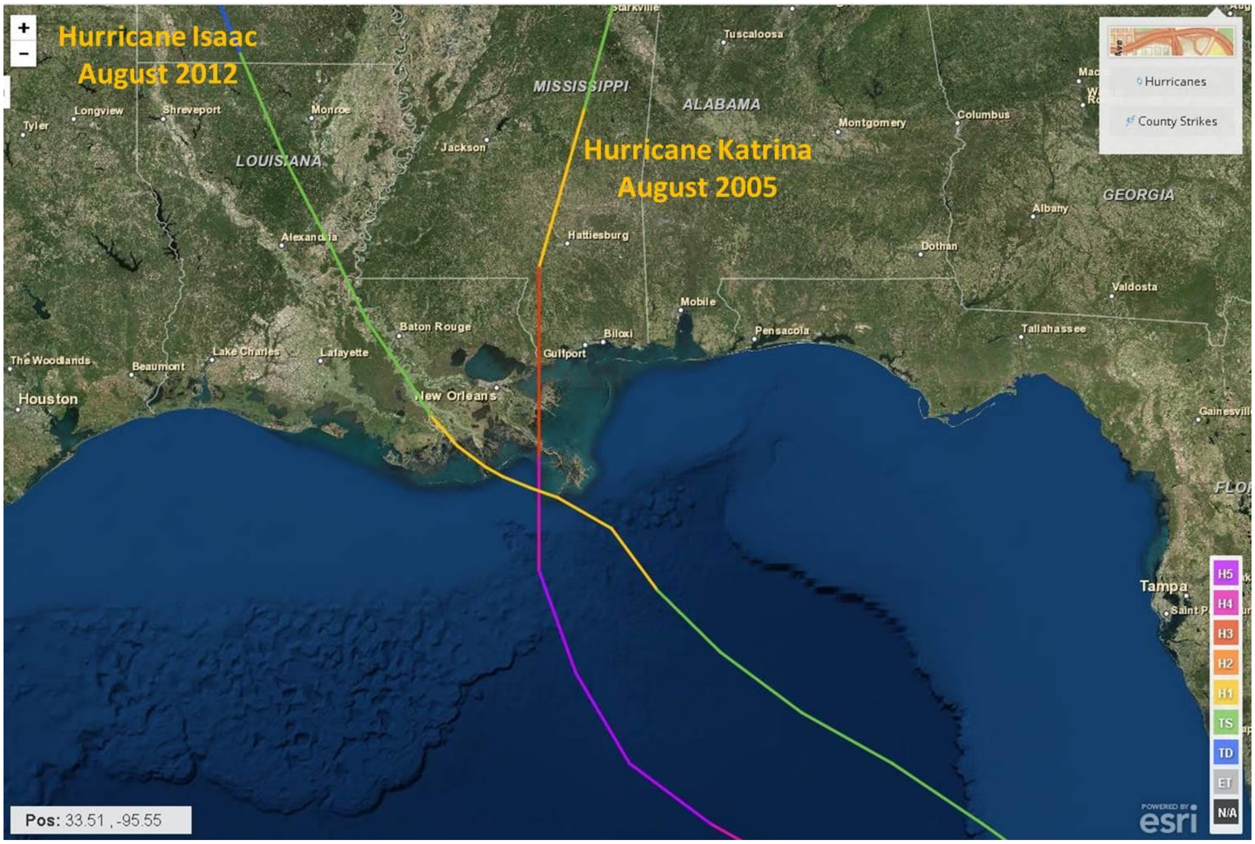


Figure 6: Tracks of Hurricanes Katrina and Isaac whose ADCIRC models were primarily used in this study (NOAA 2016).

Surge hydrographs for specific storm events have also been examined. A gage provides a temporally explicit and a complete observational record of surge height (hydrograph) through the duration of the event (assuming the gage functioned throughout the event). Unfortunately, there are few gages, and even fewer that typically survive a storm, and so the data set is not spatially complete. The hydrograph only indicates what water level was present at that exact location, and almost nothing of where the water came from. Nevertheless, these data are useful to look for consistency with other data sets and patterns of storm surge. **Figure 7** below presents Hurricane Isaac hydrographs for four different locations, and illustrates many of the processes described here.

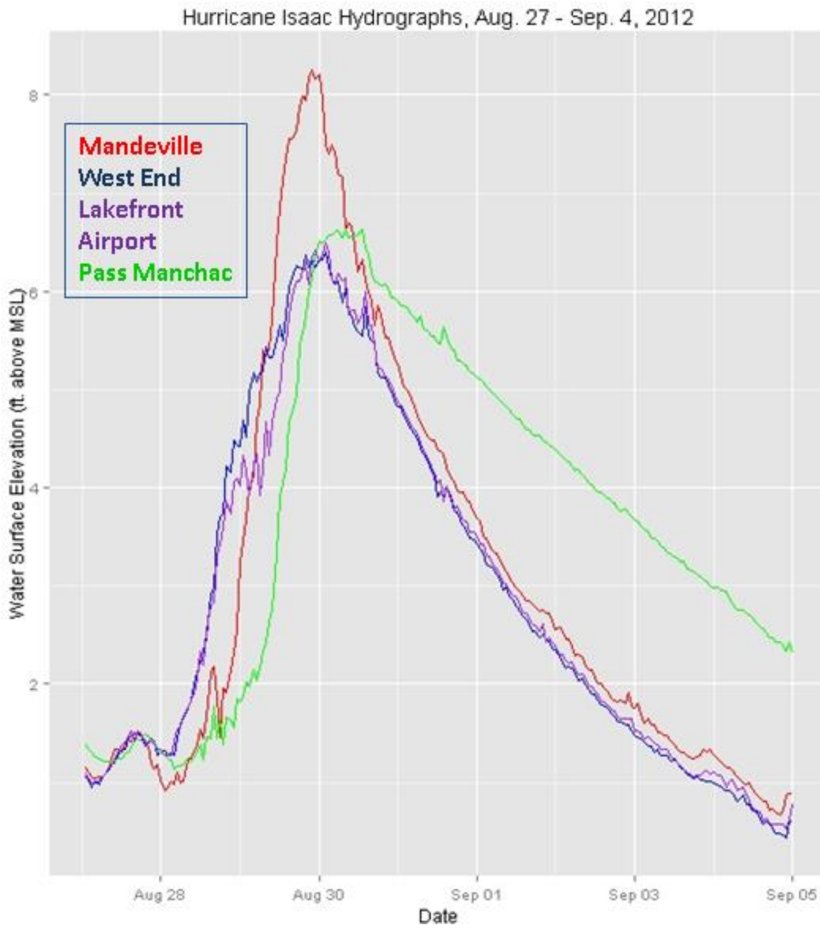


Figure 7: Hurricane Isaac surge hydrographs for Lakes Pontchartrain and Maurepas. Mandeville is located on Lake Pontchartrain's Northshore, West End and Lakefront Airport are both located on the Lake's south shore, and the Pass Manchac gauge is located on the eastern shore of Lake Maurepas. It can be seen that the different locations peaked at different times, due to the surge rotation. Additionally, the Pass Manchac gauge shows an extended tail, due to rainfall draining into the lake and delay drainage from the lake due to the Maurepas Landbridge. Finally, early in the surge rise, the Mandeville gauge drops about 4 inches, possibly due to a seiche. (Gauge Data provided by USACE.)

Maps of maximum surge from a hurricane are the most commonly available data. These maps may be derived from direct observation and from model outputs. They are instructive to understand the maximum destructive threat from a storm, but can be misleading in that at any moment in time the storm surge never actually reaches to full extent of inundation shown on these maps. Because the maximum surge maps show maximum surge spatially regardless of when it occurred during the storm event, surge movement over-time cannot be inferred. Obviously, interpreting temporal movement of surge from a map of maximum surge is undesirable since time is not depicted in map.

Analysis/Results

The previous section introduced new terms to describe patterns we have observed while studying the dynamics of storm surge in Lakes Pontchartrain and Maurepas. In this section, these phenomena are further elaborated and illustrated using the available tools. These tools include time lapse snapshots from the ADCIRC surge model, surge hydrographs from tidal gauges, and a database of historic peak surge observations.

Surge Rotation during Hurricanes Katrina and Isaac

The surge rotation, surge focusing, and outflow surge can all be seen and explained in time lapse graphics obtained from the ADCIRC model. Further, as seen in **Figures 8 and 12**, these images from Hurricanes Katrina and Isaac illustrate that terms such as sloshing or tilting are misleading, as they do not fully capture the dynamic processes in play. While these terms suggest that storm surge simply alternates between one end of the lake to the other, the more nuanced examination of the simulations shows that the surge actually hugs the far shoreline downwind during the storm, and thus rotates around the lake edge as the windfield moves across the region. The tilting or sloshing terminology suggests that only two opposite ends of the lake are affected by the surge dynamic, but in fact the surge sweeps from west to east in a clockwise or counter clockwise rotation (based on the trajectory and windfield of the storm). In doing so, the peak surge sweeps across either the north or south shore between the west and east peaks. The two storms surge patterns also reveal the distinct surge rotations from storms passing either east or west of the PMSC region. While these two storms provide recent archetypical examples of the dynamic for which ADCIRC simulations are available, it is important to keep in mind that there are exceptions to the this generalization, which indicates that our conceptual model is not a complete physical explanation of all the processes at play.

Hurricane Katrina, an east-passage example, produced a counter-clockwise rotation of peak surge (**Figures 8, 9, 10)** that swept across the south shore as the storm moves inland**.** The peak surge initially forms near the southwest corner of Lake Pontchartrain, in the Frenier area, and then shifts toward the south shore, followed by a progression toward the southeast, and finally fully eastward near Slidell before draining through the tidal passes. This pattern is what the surge rotation model predicts given the changes in wind direction from an east passing storm. A useful way to describe this wind/surge progression is by referring to the aviation “o’clock position” with the clock centered in south Lake Pontchartrain (**Figure 9**).

For an east-passage storm in the following locations relative to the center of Lake Pontchartrain:

<u>5 o’clock position</u>

The PMSC region is within the northwest quadrant of the storm and sustains northeast or easterly winds. Due to the wind field, the east-west elongation of the PMSC region, and curvature of the shoreline, the surge builds in the southwestern quadrant of Lake Pontchartrain (**See Figures 8 and 9**).

<u>3 o’clock position</u>

The PMSC region is roughly the same latitude of the eye of the storm and the wind field is roughly northerly, rotating the surge toward the south shore.

2 o'clock position
The PMSC region is within the southwest quadrant of the storm and winds are becoming northwesterly to westerly. Due to the east-west elongation of the PMSC region, surge is concentrated toward the southeast side of the lake near New Orleans' Lakefront. However, the hard boundary there deflects much of the surge toward the northeast.

The temporal pattern of Katrina's surge is shown in **Figure 10**, which shows the time at which the maximum surge occurred for each location. The arrows show counter-clockwise rotation on both the north shore and south shore, but it is the south shore which develops the greatest surge. This pattern observed in the surge modeling is consistent with the prior descriptions. **Figure 11** summarizes the movement of the greatest surge from Hurricane Katrina, which sweeps the south shore and peaks near Slidell after the storm has moved northeast of Lake Pontchartrain.

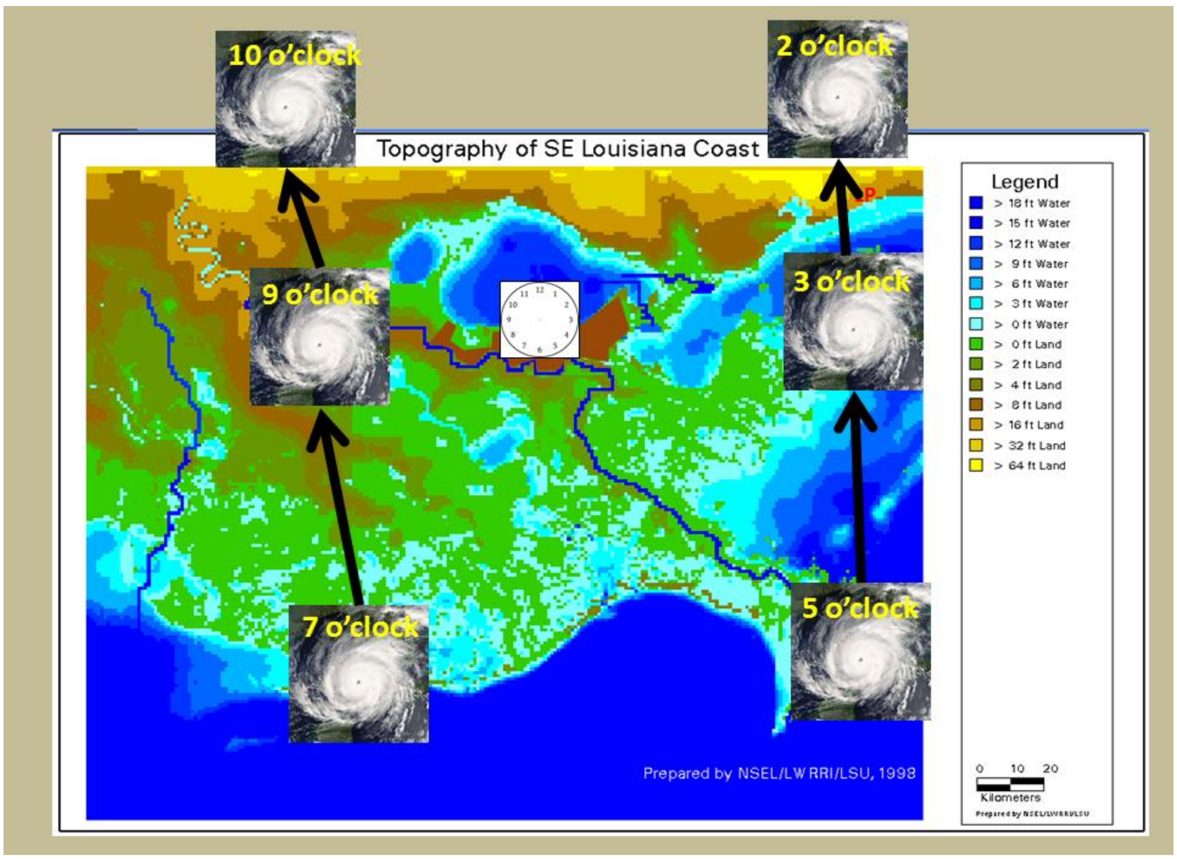


Figure 8: Schematic diagram depicting the two different archetypical hurricane trajectories relative to the PMSC study region. (Source: Modified from Suhayda 2015.)

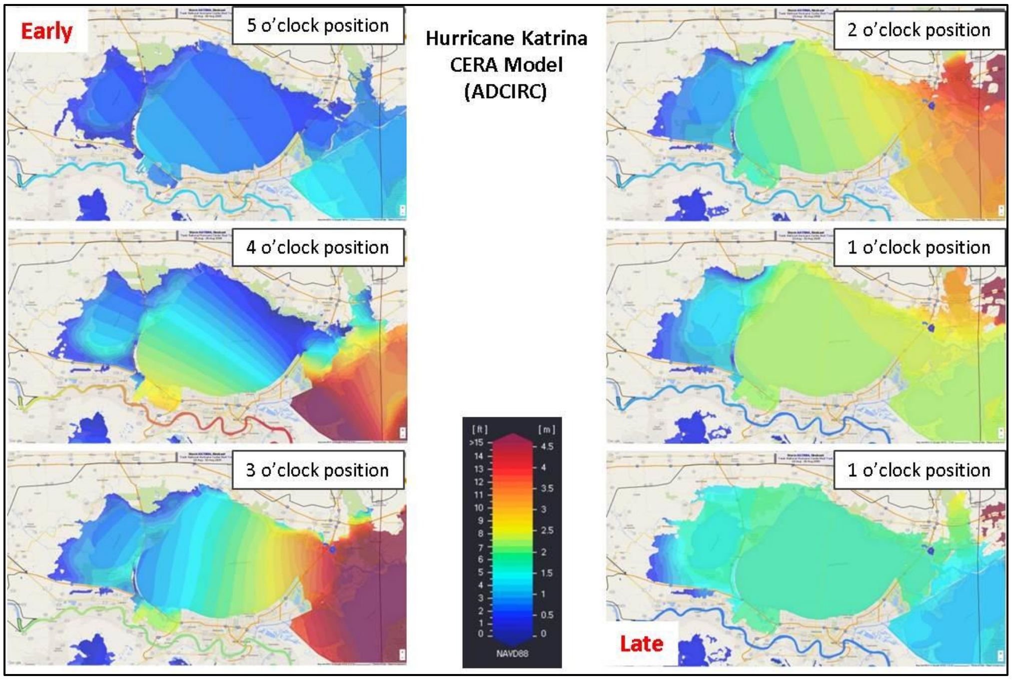


Figure 9: Snapshots from the ADCIRC surge model for Hurricane Katrina showing the peak surge rotating along the shoreline from the southwest banks toward the eastern banks in a counter clockwise direction. (orange-yellow=high surge; blue=low surge) (Source: CERA.)

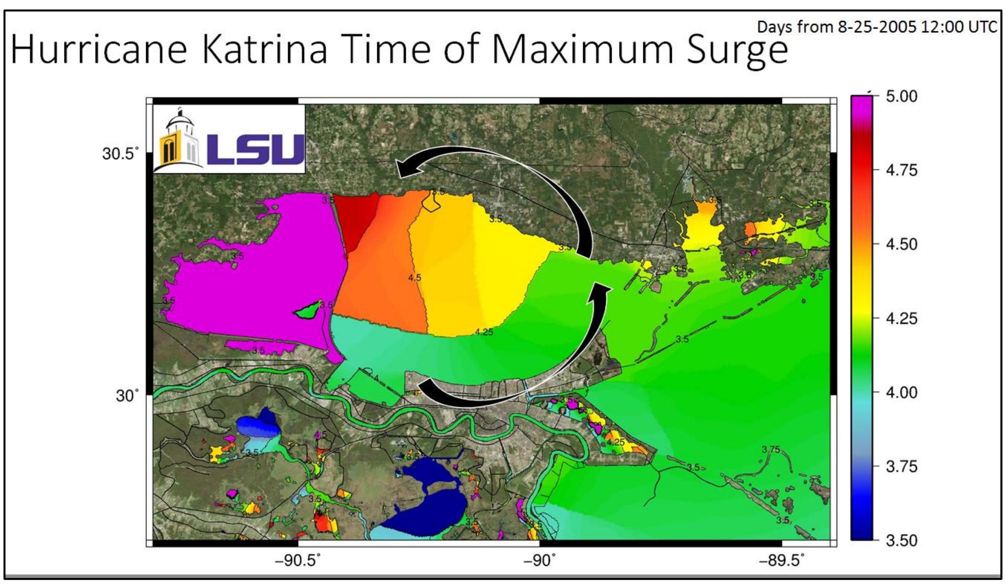


Figure 10: Time of maximum (peak) surge across Lakes Pontchartrain and Maurepas for Hurricane Katrina in 2005. The color scale depicts hours from August 25 12:00 UTC. The earliest peak (light green) occurred in the southwest corner of Lake Pontchartrain. The peak surge then rotated counter clockwise toward the east (darker green) then west along the northshore (yellow to orange) and then peaking in Lake Maurepas (purple), a pattern expected for an east passing storm. (Source: Scott Hagen and Matt Bilskie, LSU)

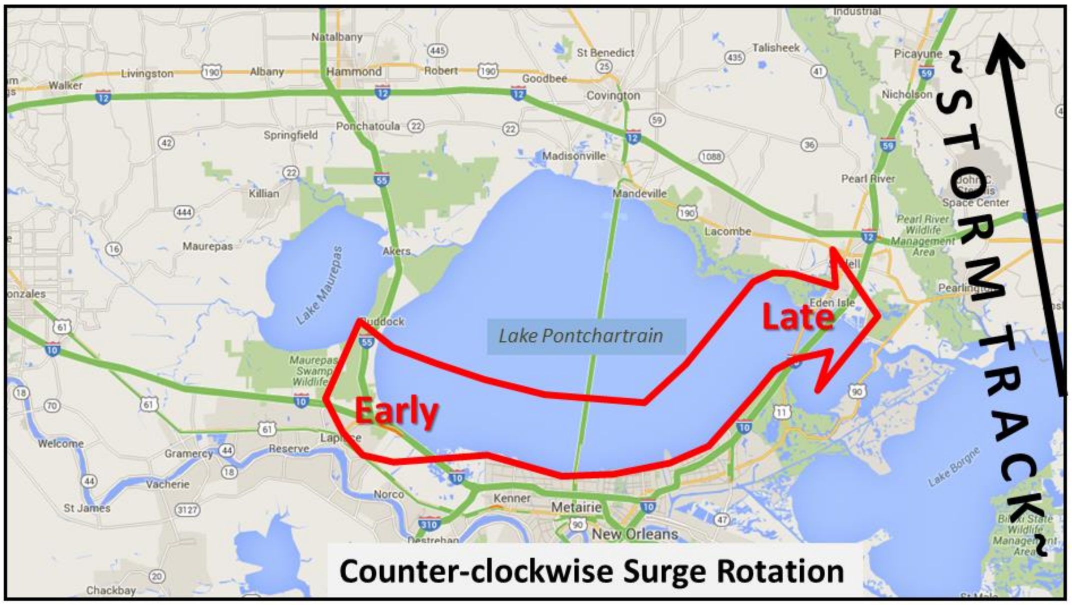


Figure 11: General pattern of maximum surge in the PMSC region during an east passage of a hurricane.

Hurricane Isaac is an example of a west-passage storm, which produces a clockwise rotation of peak surge (**Figure 12, 13, and 14**). With this type of wind pattern, the highest surge also initially forms near the southwest corner of Lake Pontchartrain (approximately the Frenier area), but then shifts toward the north shore with the southerly winds, then progressively northeast toward Mandeville before shifting east due to westerly winds. This pattern is precisely the pattern that should be expected given the changes in wind direction from a west passing storm.

For a west-passage storm, consider the following storm positions relative to the center of Lake Pontchartrain (**Figure 14**):

<u>7 o'clock position</u>
The PMSC region is within the northeast quadrant of the storm and sustains southeasterly or easterly winds. Due to the wind field and the east-west elongation of the PMSC region, the surge builds in the western or southwestern quadrant of the Lake (See **Figure 12**).

<u>9 o'clock position</u>
The PMSC region is roughly the same latitude of the eye of the storm and the wind field is roughly southerly forcing surge to concentrate along the north shore.

<u>10 o'clock position</u>
The PMSC region is within the southeast quadrant of the storm and winds become southwesterly to westerly. Because the lake is now within a weaker quadrant of the storm the surge exit from the lake is slower. Surge build-up occurs along the eastern shoreline because it cannot exit from the lake fast enough due to marsh landbridges. At this point, it is expected that drainage of the typical heavy rainfall throughout the Pontchartrain watershed contributes to water levels in the lakes.

The temporal pattern of Isaac surge is shown in **Figure 13**, which depicts the time of maximum surge. The arrow shows clockwise rotation on the western shore, consistent with the prior descriptions. **Figure 14** summarizes the movement of the peak surge from Hurricane Isaac, which sweeps the western shore and peaks near Madisonville and Mandeville.

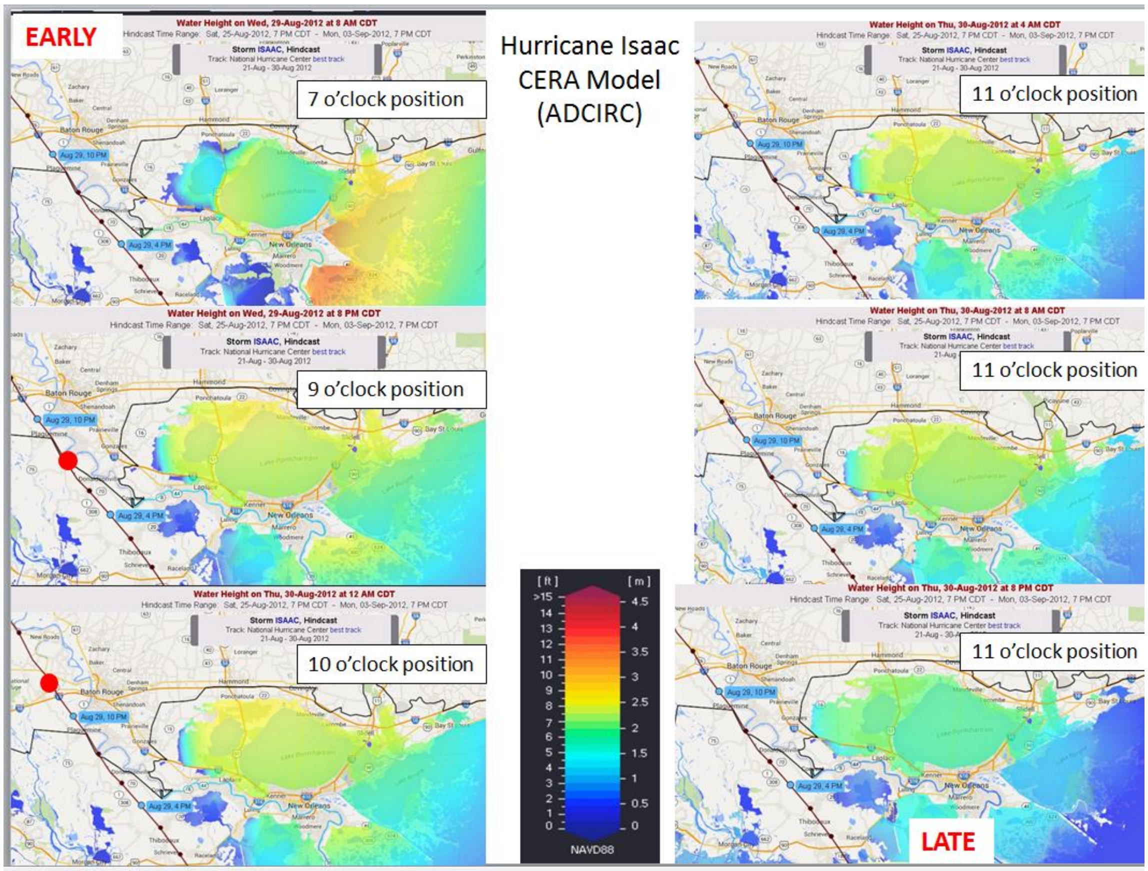


Figure 12: Snapshots from the ADCIRC surge model for Hurricane Isaac showing the peak surge rotating along the shoreline from the southwest banks toward the eastern banks in a counter clockwise direction. (orange-yellow=high surge; blue=low surge; red dot is eye of the hurricane) (Source: CERA.)

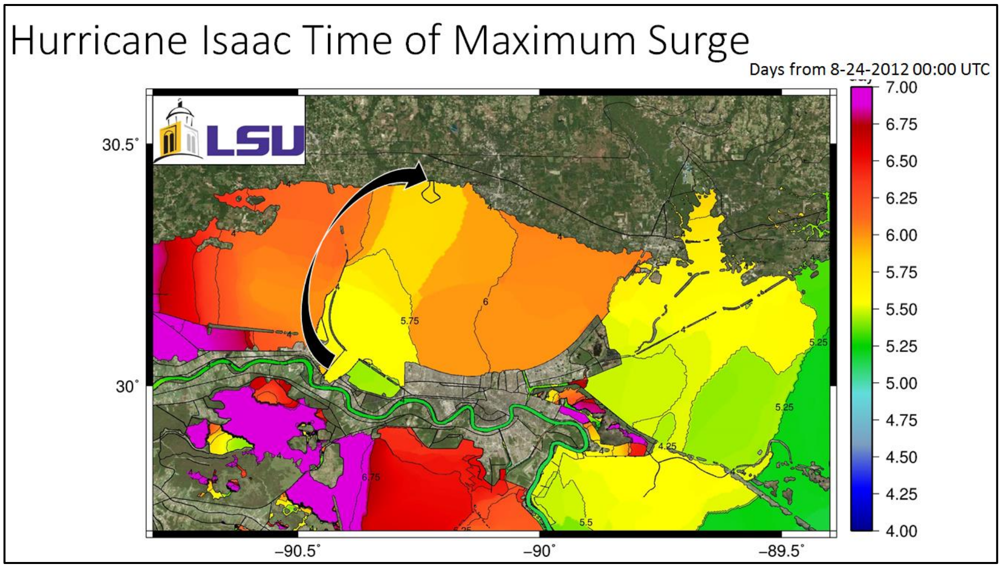


Figure 13: Time of maximum (peak) surge across Lakes Pontchartrain and Maurepas for Hurricane Isaac in 2012. The color scale depicts hours from August 24 10:00 UTC. The earliest peak (yellow) occurred in the southwest corner of Lake Pontchartrain. The peak surge then rotated clockwise toward north and then the east (orange), a pattern expected for a west passing storm. (Source: Scott Hagen and Matt Bilskie, LSU)

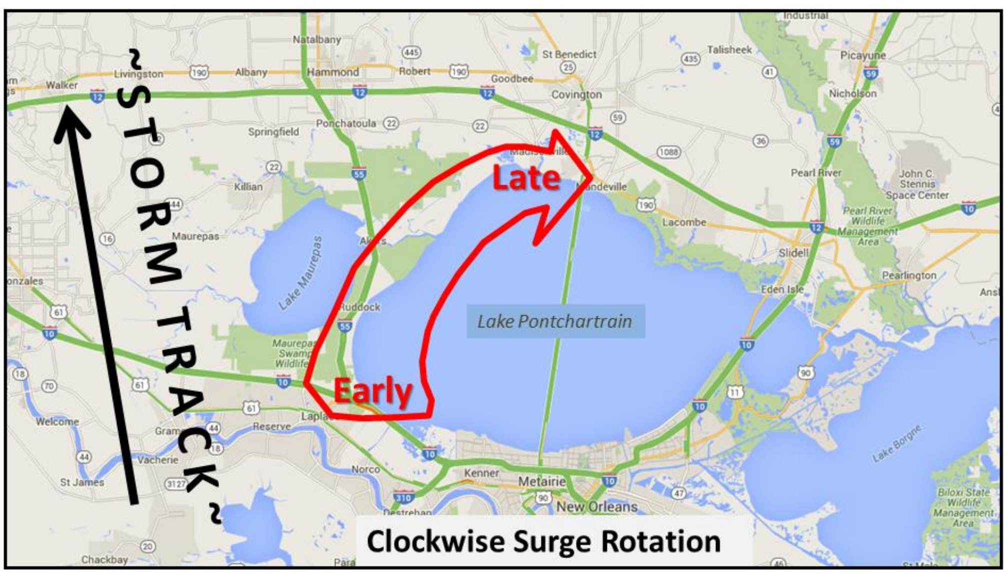


Figure 14: General pattern of maximum surge in the PMSC region during a west passage of a hurricane.

Surge Focusing

Some manifestations of the surge rotation, particularly the focusing of the peak surge toward the southwest and northeast shorelines of Lake Pontchartrain, can be seen in spatial trends of historic surge observations. As described below, the historic data show that the highest surges have been observed in the northeast and southwest corners of Lake Pontchartrain. In the surge rotation model, these opposite corners are the start and end of the surge rotation. As such, storm water has more time to pile up at these locations, as opposed to the intervening sections of shoreline that experience a transitory event that sweeps around the shoreline with the changing winds. This focusing, due to the wind patterns, is also exacerbated by landscape features, including ridges and levees, which focus surge momentum toward specific shoreline sections.

The surge focusing effect can be examined using SURGEDAT, a database of observed peak surge observations compiled from historical records (Needham et al. 2015). This database archives the location and measured height of more than 700 tropical surge events around the world since 1880. While built mostly from scientific and technical sources, including government reports, historical maps, academic papers and books, the database supplements these with additional sources, such as newspaper articles and historic documents. This approach allows for the inclusion of smaller-magnitude storm surges in the earlier time period when official records are not available. Using SURGEDAT, various spatial trends can be explored.

Table 3 shows the record storm surge values for various locations around Lake Pontchartrain. The highest surges were observed in Slidell (the northeast corner) and in Frenier (the southwest corner.) SURGEDAT further reveals that these two quadrants have the highest mean and maximum surges, and that the expected surge values for a given return period are highest at these locations. **Table 4** shows the 50-yr, 100-yr, 200-yr, and 500-yr expected surge heights obtained using extreme value statistics with the historic record of observations in SURGEDAT. Across the board, the highest values are expected in northeast corner, near Slidell, and the opposite southwest corner, near Frenier. Note that these return periods are calculated using historic data located within circular areas drawn around each location. They do not necessarily represent observations drawn from a single point location, nor do they reflect a statistically representative sample of the long term (over 100 years) record. **Figure 15** shows that the ends of the Lake experience the highest surges.

Table 3: Record water levels in feet at various locations around Lake Pontchartrain, based on a SURGEDAT dataset covering 1900 - 2013. The highest water levels in the lake are expected in Slidell (northeast shoreline) and Frenier (southwest shoreline.)

Location	Storm	Year	Water Level (ft)	Calculated Recurrance Interval (yr)	Datum
Slidell	Katrina	2005	15.7	114	NAVD88
Frenier	Betsy	1965	13.1	115	Unknown
New Orleans Lakefront	Katrina	2005	11.9	98	NAVD88
Mandeville	Katrina	2005	10	78	NAVD88

Table 4: Expected water levels in feet for selected return periods at various locations around Lake Pontchartrain, based on extreme value methods with SURGEDAT data from 1900 - 2013. The highest water levels in the lake are expected in Slidell (northeast shoreline) and Frenier (southwest shoreline.)

Location	50-yr	100-yr	200-yr	500-yr
Slidell	12.3	15.2	18.1	21.9
Frenier	10.3	12.6	14.9	18
New Orleans Lakefront	10.2	12	13.7	16.1
Mandeville	9.2	10.6	12	13.8

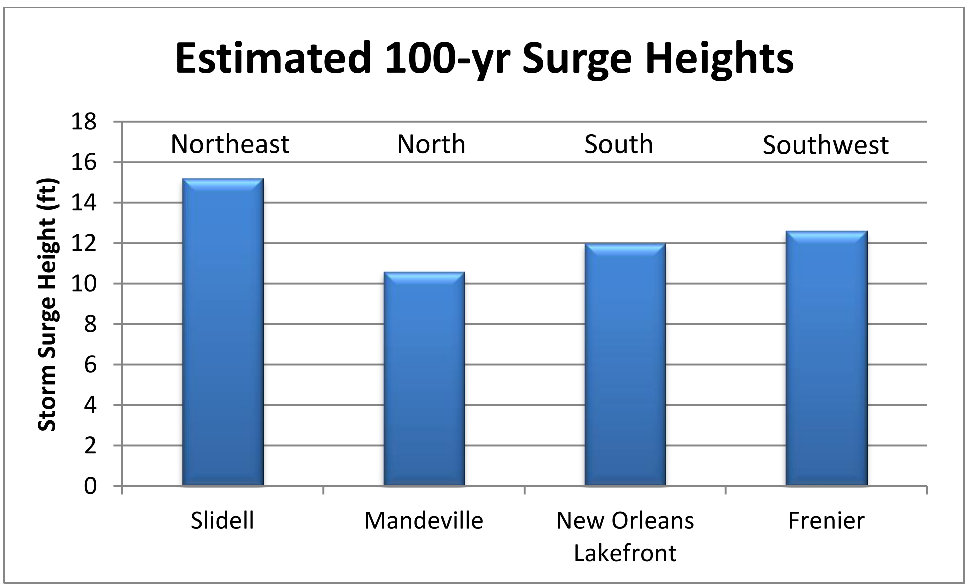


Figure 15: Comparison of the expected 100-yr surge height at various locations around Lake Pontchartrain based on extreme value methods with SURGEDAT data from 1900 - 2013. The highest water levels in the Lake are expected along the northeastern shoreline (Slidell) and southwestern shoreline (Frenier.)

Finally, **Figures 16 to 19** summarize the SURGEDAT data points from the Lake Pontchartrain and Maurepas shoreline. These figures were created by first identifying SURGEDAT observations inside the PMSC study area. To isolate just surge effects along the shoreline (as opposed to riverine discharge or levee effects), the points were manually classified as “Shoreline”, “Levee Protected”, “Open Water”, “Interior Riverine”, and “Outside Lakes.” In addition, points without a standard vertical reference were discarded, and the recorded storm tide for the remaining observations were converted to NAVD88 based on vertical reference recorded for each observation. Appendix A has details of this calculation. This left 392 points along the lake shorelines with a vertical reference. Finally, summary statistics of the storm tide values were calculated for different sections of the shoreline.

Figure 16 shows all of the resulting points, color coded by storm tide. **Figure 17** shows the points along with the mean value for each shoreline section, while **Figure 18** shows the maximum value for each shoreline section. Finally, the boxplots in **Figure 19** show the distribution of storm tide observations for each region. Again, the highest point values along with the highest mean and maximum values are seen in the northeast and southwest corners of Lake Pontchartrain.

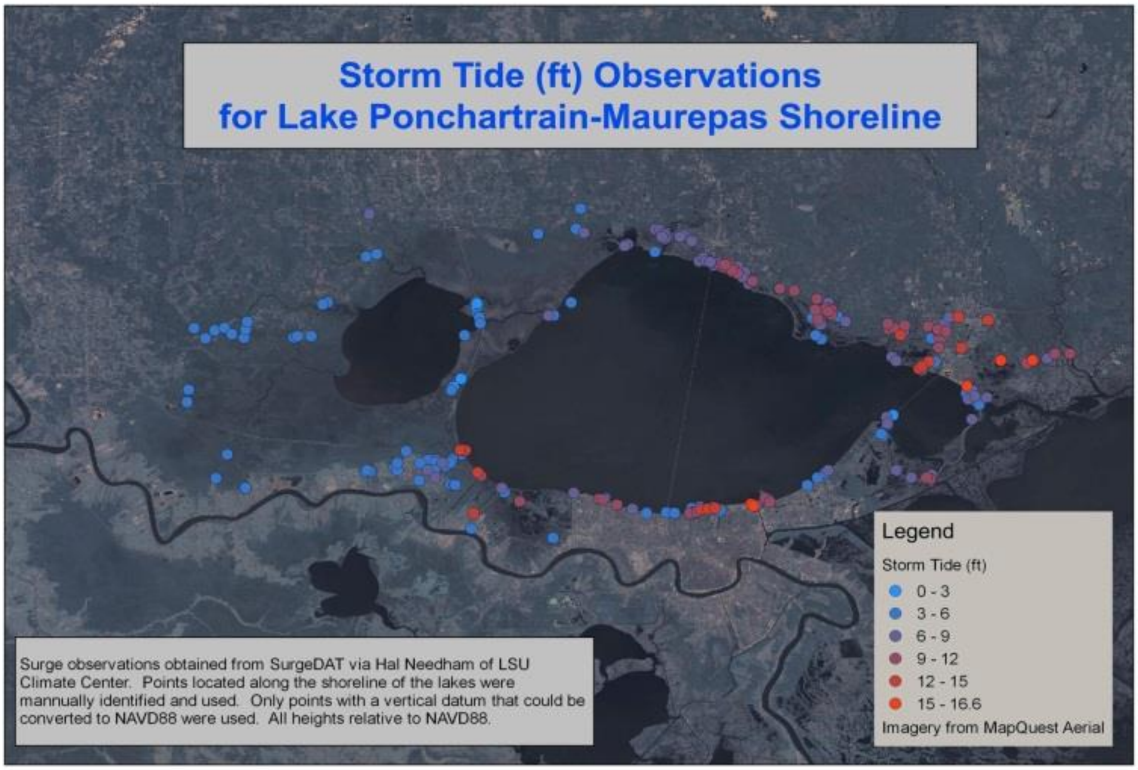


Figure 16: Color coded storm tide heights for the shoreline areas of the PMSC Region, based on SurgeDAT. Heights adjusted to NAVD88. Map shows 392 observations that included a datum that could be converted to NAVD88. (Data provided by SURGEDAT.)

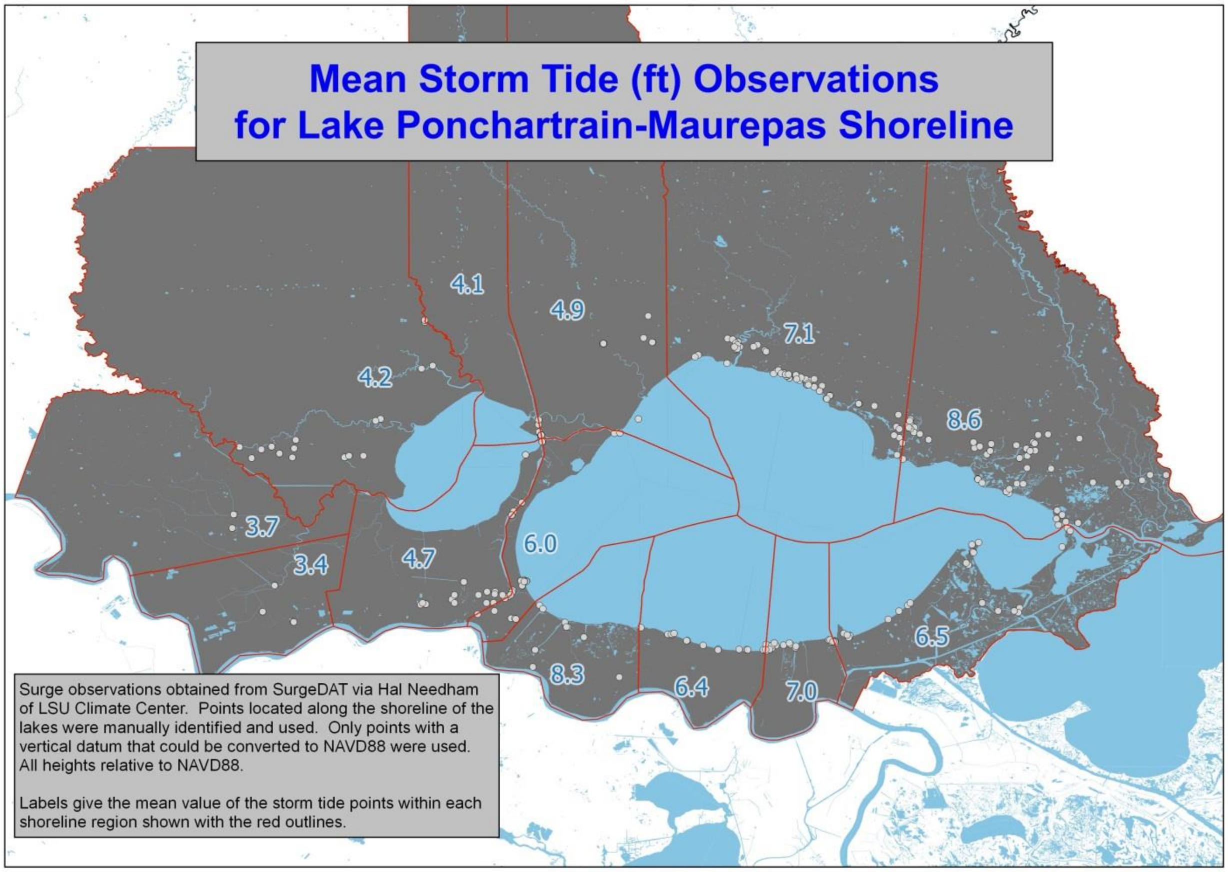


Figure 17: Mean of all storm tide observations for different shoreline sections of the Lake Pontchartrain shoreline, based on SURGEDAT (adjusted to NAVD88.) The highest mean surges are observed in eastern St. Tammany Parish and along the southwest corner in St. Charles Parish. (Data provided by SURGEDAT.)

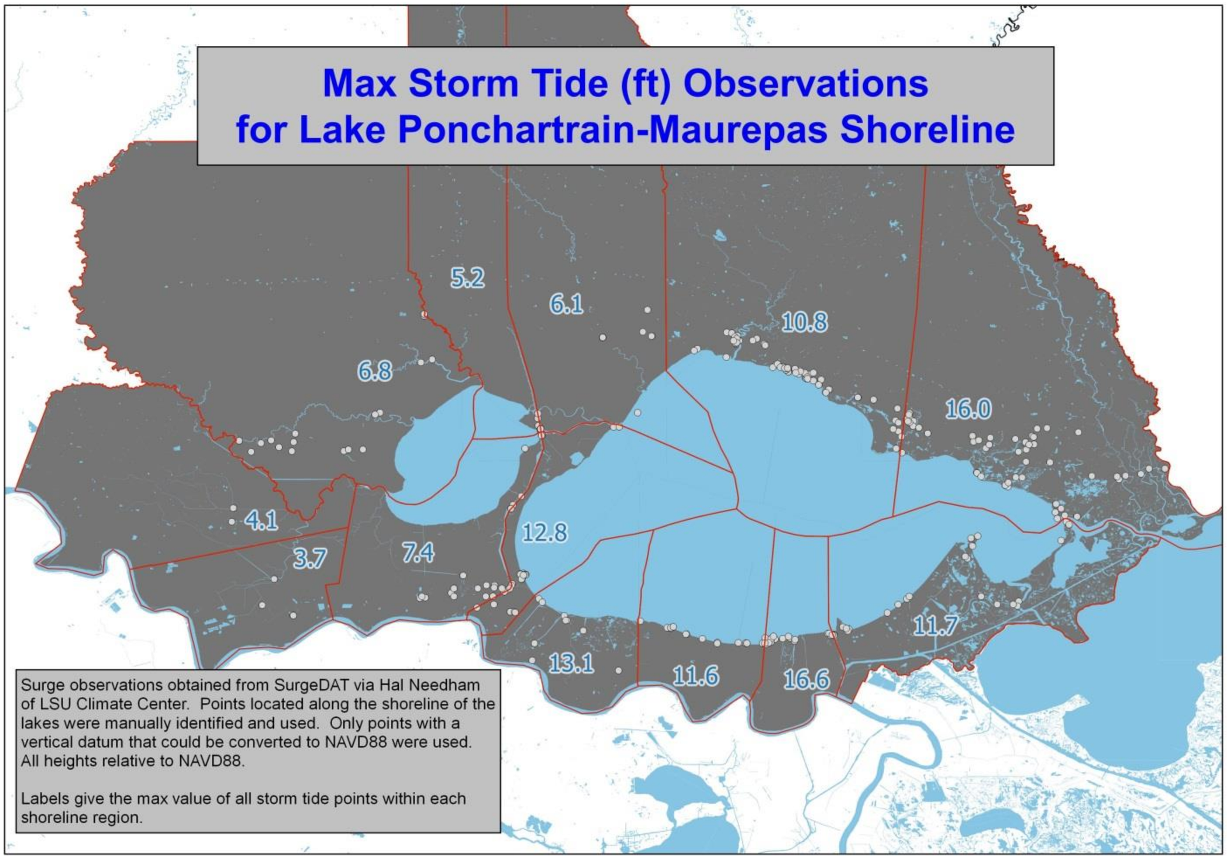


Figure 18: Maximum of all storm tide observations for different sections of the Lake Pontchartrain shoreline, based on SURGEDAT (adjusted to NAVD88.) The highest maximum surges are observed in eastern St. Tammany Parish, central Orleans parish, St. Charles, and St. James Parish east of the New Orleans landbridge. (Data provided by SURGEDAT.)

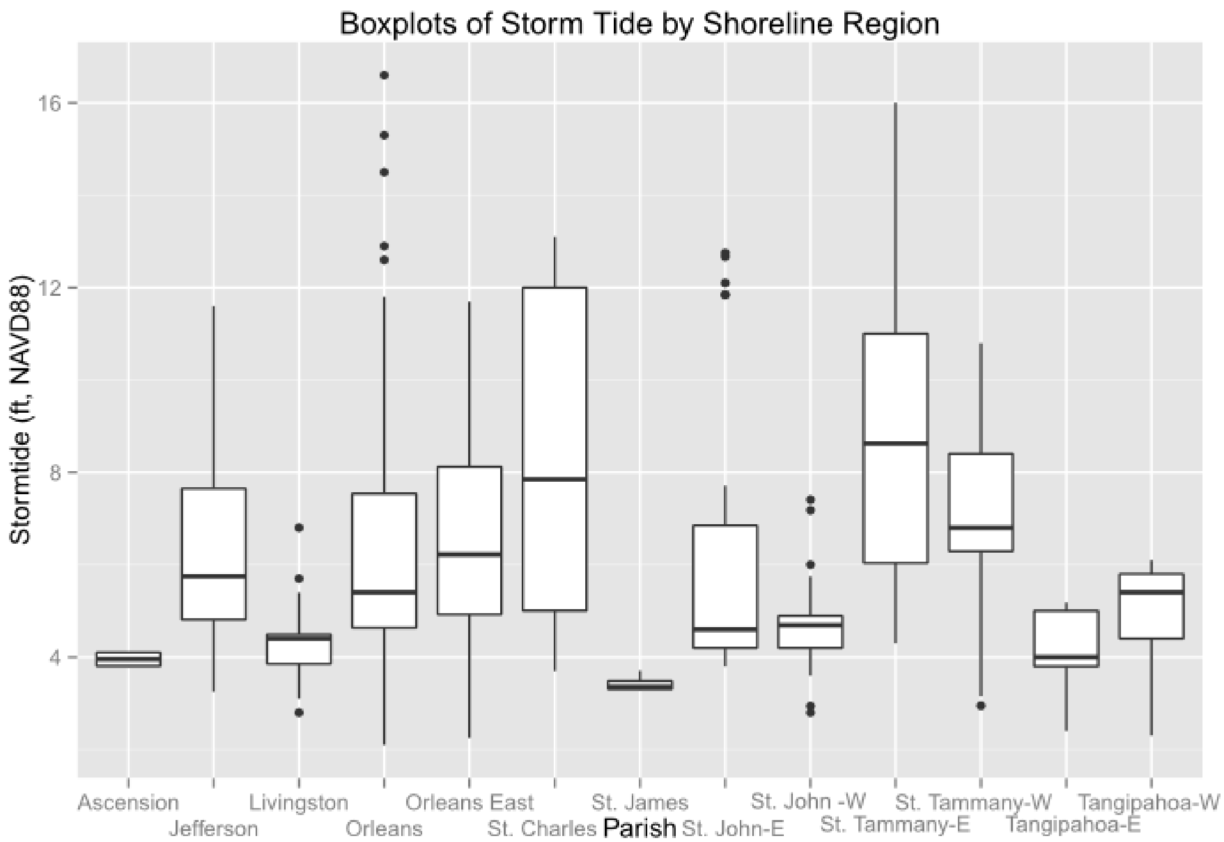


Figure 19: Boxplots of storm tide observations along the Lake Pontchartrain-Maurepas shoreline by shoreline region. "-E" and "-W" refer the eastern and western portions of the parishes. The boxplot is used to illustrate the distribution of a set of observations. The white box represents the interquartile ranges, which is the middle 50% of values, and the line across it is the median value. The vertical lines extended above and below the box represent the 5% and 95% ends of the distribution, while the dots depict observations that are considered outlier values. (Data provided by SURGEDAT.)

In sum, the empirical maximum surge data are consistent with the focusing aspect of the surge rotation model. The highest surges tend to occur where the surge rotation begins, the southwest corner, and ends, northeast corner. The data do suggest a wider spread over the two lake ends, but this should be expected considering this represents a suite of storms rather than the two spatially explicit storm models previously discussed. The empirical data illustrate the tendency of overall highest surges occurring at the east end of the lake (the St. Tammany-E boxplot). Because these empirical data consist of maximum surge heights, the temporal aspects cannot be examined.

The ADCIRC models and empirical maximum surge data both support the surge rotation model with opposite directions of rotation for the easterly or westerly passages. Additionally, they both indicate a focusing of storm surge at the opposite corners of the lake. However, both analyses show with an eaterly passage the highest surge peaks on the east side of the lake in a seaward direction storms. Storms of westerly passage do not show as consistent a maximum surge at the east side of the lake. With a westerly passage there is still an outflow surge effect, but the maximum surge may occur on the north shore near Mandeville or Madisonville for a westerly passage.

From a larger perspective, the tendency for significant outflow surge is rare because surge nearly always peaks in a landward direction. We suspect that the pattern of surge peaks occurring in a seaward direction is very unusual, and reflects additional dynamic factors beyond the surge rotation model. This result cannot be explained from the standpoint of the wind field or wind speed. When this peak surge occurs as an outflow surge the storm has moved inland, and probably diminished, but more importantly the wind field driving the outflow surge is being driven by the weakest quadrant of the storm. The rotation model explains the direction of movement, but not why surge peaks as an outflow surge as water is moving seaward and the storm is weakened. This suggests there are secondary factors which are influencing the primary surge pattern produced simply by the wind field and resulting surge rotation.

Outflow Surge and the Asymmetry of the PMSC Region

Two major terrain features create an asymmetry between the east and west sides of PMSC region, and explain additional patterns in storm surge dynamics. One factor is the shoreline type and geometry, while the other is Lake Pontchartrain's bathymetry. This asymmetry and particularly its position relative to the storm's track and windfield, are probably the most important secondary factors influencing hurricane surge dynamics. While the wind direction is the primary factor driving the overall surge rotation, these secondary factors help explain why the rotational windfield effect is not equal around the lake perimeter. The lake asymmetry is shown in **Figures 20 and 21.**

Foremost, the contiguous open water area during a storm event (**Figures 21 and 22)** is elongated 3 times east to west (longitudinal) than north to south (latitudinal). Lake Pontchartrain itself is asymmetric being 40 miles east to west but only 25 miles north to south. When a surge inundates the Maurepas landbridge and essentially joins Lake Maurepas and Lake Pontchartrain, the fetch is nearly 75 miles. The larger distance along the longitudinal direction creates a larger fetch along this axis. This then implies that east or west travelling progressive waves are not likely fetch-limited during the storm and may more fully developed to a depth limitation. In general, more wave energy likely develops longitudinal because of the fetch along the longer axis. This effect, along with the extended duration of winds in this direction, likely explains why surge tends to be highest at the eastern and western ends of Lake Pontchartrain. It does not explain why empirically derived surge height estimates for all return periods tend to be higher in the east compared to the west (Table 4 and Figure 15).

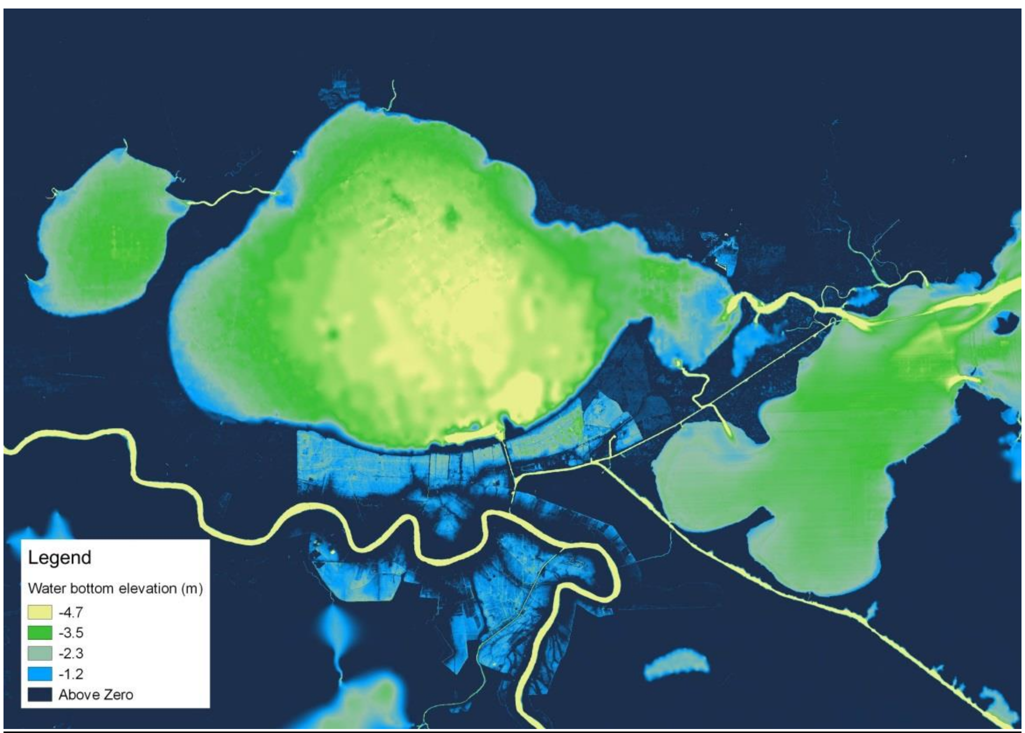


Figure 20: Lake Pontchartrain Bathymetry. Note that the deepest portions are located just south and east of the geometry center of the lake. (Blue=shallow; yellow=deeper)(Source: NOAA 2010.)

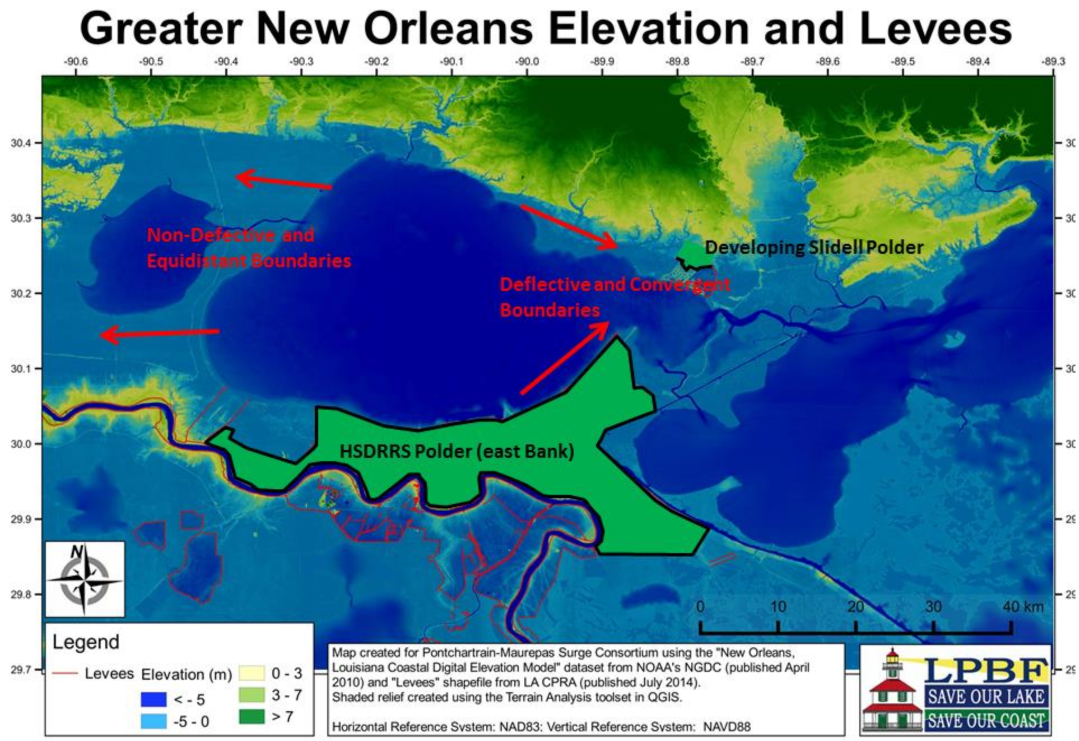


Figure 21: Terrain map for the PMSC region shows the east-west asymmetry in shoreline type and configuration. (Data Source: NOAA 2010.)

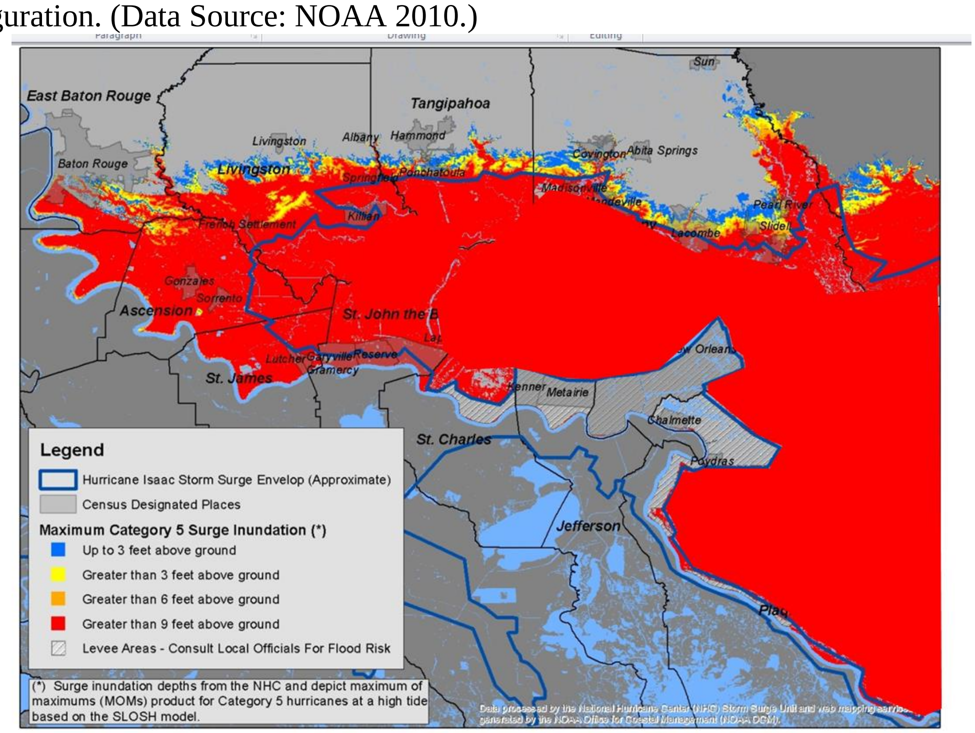


Figure 22: Lakes Pontchartrain and Maurepas when inundated by storm surge. With the natural ridges inundated, the "lakes" are temporarily transformed into an open "bay" that stretches more than 75 miles from the outskirts of Baton Route to Slidell (Source: NHC 2014).

Another significant secondary influence on surge is likely the result of the difference in cross sectional areas of the PMSC along north-south transects. Even during a surge event, the eastern side of the PMSC region narrower and has a smaller cross-sectional area than a mid-lake profile. For example with a surge of 12 ft., a profile at mid-lake, the cross-sectional area from the south shore levee 26 miles northward to the 12 ft. elevation contour in Mandeville is approximately 3.2 million sq. ft. Whereas, a 12-mile profile from the south shore NO East Levee (Pointe aux Herbes) to 12 ft. contour in Slidell is approximately) 0.8 million sq. ft. or just 25% of the area at mid-lake. In general, the surge at mid-lake (~Causeway Bridge) has 4 times as much cross-sectional area to move surge east or west than surge at the east end of the lake (~Interstate 10) where surge must exit the PMSC region. Therefore there is a constricting or funneling effect as surge is moving eastward in Lake Pontchartrain which occurs during outflow surge.

In addition, the hydrologic characteristics of the boundaries of the inundated areas are also very different. The west end of the lake is dominated by wetlands and swamps, which dissipate surge energy with much less deflective force. In contrast, the eastern side of the lake on the south shore includes an armored shoreline and HSDRRS earthen levee and floodwall. This boundary deflects water movement rather than absorbing it. Directly across the lake, the shoreline consists of wetlands that are dominantly marsh, which provides less resistance than swamp habitat. They also provide much less shoreline before reaching the relatively hard boundary of the Pleistocene terrace. **Figure 21** summarizes this contrast that may be described as non-deflective and equidistant on the west end versus deflective and convergent on the east side of the PMSC Region. The east side of the PMSC region is more likely to have faster surge movement and with focusing of surge and surge energy toward a nexus between South Point and the Slidell Levees. Finally, also contributing is the east bank HSDRRS polder, which reduces the total amount of storage available to accommodate surge within the PMSC region, and this further exacerbates surge build up on the east side of the PMSC region.

The bathymetry of Lake Pontchartrain is another element of the asymmetry in the PMSC Region that may contribute as a secondary factor in storm surge behavior. **Figure 20** shows that the deepest area (excluding channels) of Lake Pontchartrain is southeast of the center. If surge heights are exceeding six to eight feet, fetch is large if the wind is blowing longitudinal. Wave heights may be depth limited. However, the actual depth during a storm is not just normal bathymetric water depth **(Figure 23).** The additional surge elevation is added on top of the normal water level. Water depth varies around the lake, as surge elevations in the PMSC are never equal, due to the rotational and asymmetric effects. ADCIRC coupled with STWAVE does include these combined effects to produce the resultant surge, but the wave field should be examined more closely for the potential destructive energy of the waves. In Hurricane Katrina, the largest waves produced by the ADCIRC/STWAVE model were located in the southeast quadrant of the Lake with a northwest wind (**Figure 24**), and the storm at a 2 o'clock position, which is well after landfall, as the eye of the storm is north of Lake Pontchartrain. At this time, late in the storm event, waves exceeding eight feet were breaking and pounding the southeast shore of Lake Pontchartrain where the hurricane levee directly faces the lake. This levee reach has been redesigned and re-built post-Katrina as part of the HSDRRS program.

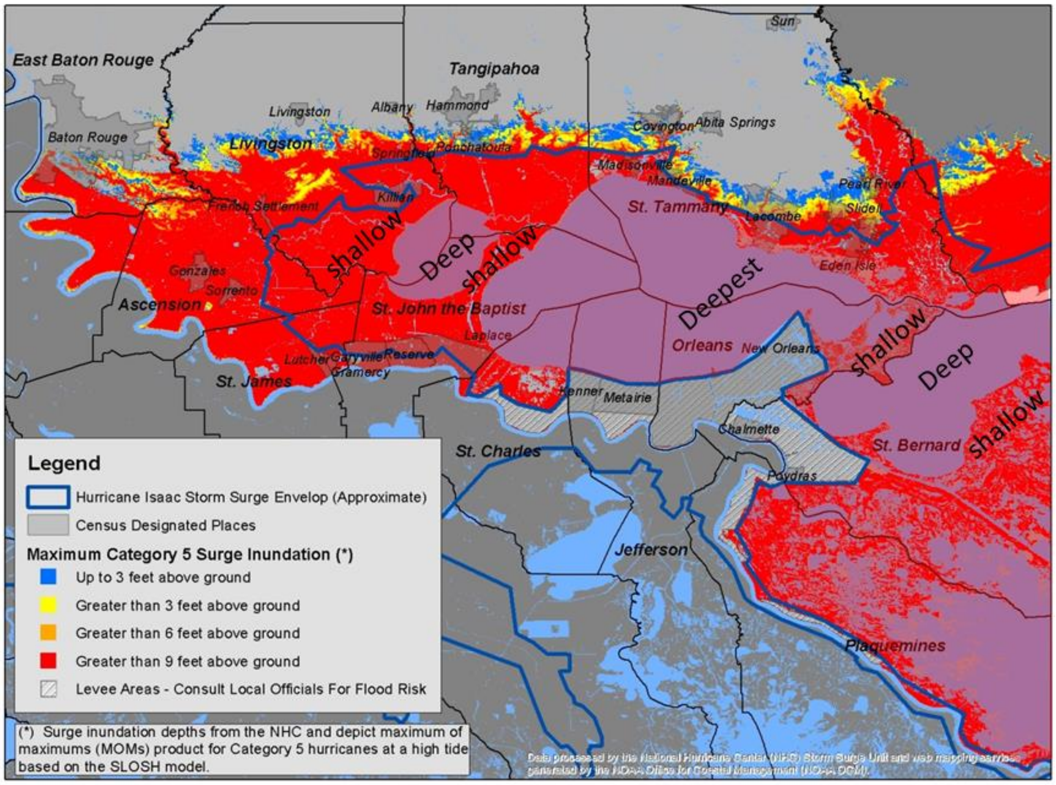


Figure 23: Mockup of terrain model when both Lakes Pontchartrain and Maurepas are inundated by surge (Surge Data Source: NWS 2014).

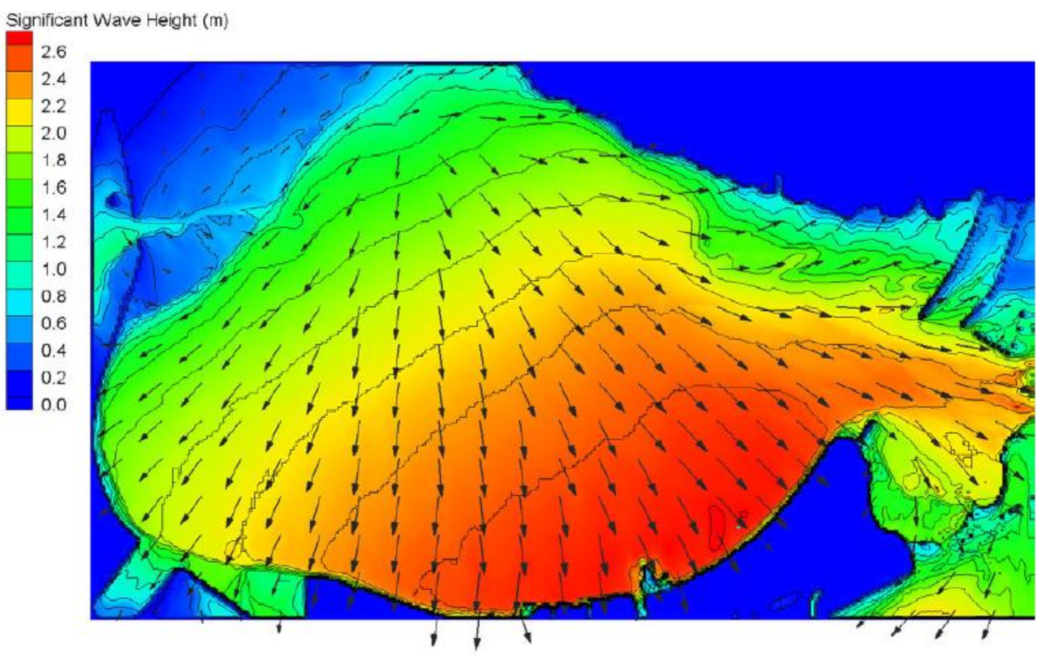


Figure 24: Modeled wave heights and direction for Hurricane Katrina that indicate the highest waves along the southeast shoreline of Lake Pontchartrain. The winds are northerly at this time, and the wave direction is southerly. The wave field along the southeast quadrant of the lake has the highest wave heights due to deeper areas of the lake being located nearer the shoreline (Smith 2006).

Examination of Storm Hydrographs & Seiche

Seiching is a well-known phenomenon that may also contribute to surge dynamics in Lake Pontchartrain. A seiche is a standing wave oscillation (see **Figure 25**) in an enclosed or partially enclosed body of water. According to NOAA:

> "Seiches are typically caused when strong winds and rapid changes in atmospheric pressure push water from one end of a body of water to the other. When the wind stops, the water rebounds to the other side of the enclosed area. The water then continues to oscillate back and forth for hours or even days." (NOAA 2015)

An apparent seiche can be seen in tidal gauge hydrographs from Hurricane Gustav. **Figure 26** shows surge hydrographs for Mandeville and West End along with wind direction for the New Canal Station. While water levels at these two locations are initially in sync, we see changes late on August 31 when the West End gauge starts to rapidly rise while the Mandeville gauge rapidly drops. On the morning of September 1, this changes as the West End drops and Mandeville rises. From the wind direction graph (top portion of the figure), the initial perturbation in water levels appears to coincide with a change in wind direction. For most of the day on August 31, the winds were consistently from a northeasterly direction. But later that night they fluctuated between northeasterlies and northerlies, likely initiating a seiche.

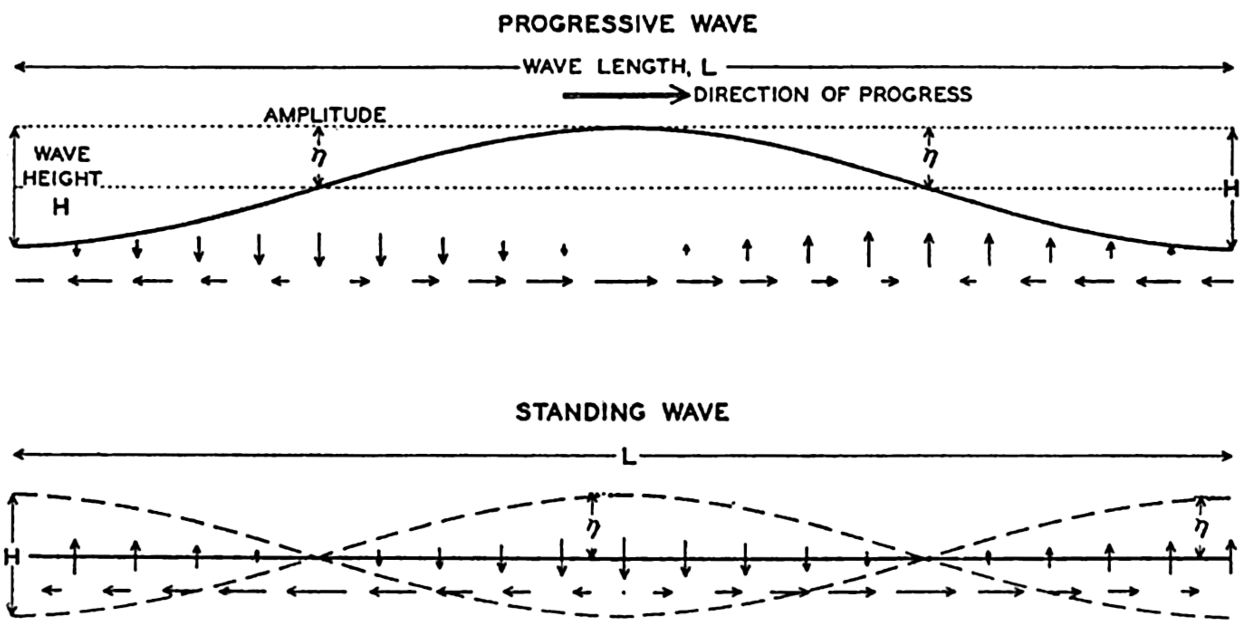


Figure 25: Progressive wave, such as open water waves that progress toward the shoreline, versus a standing wave, Source: http://publishing.cdlib.org/ucpressebooks/view?docId=kt167nb66r&chunk.id=ch14&toc.depth=1&brand=eschol)

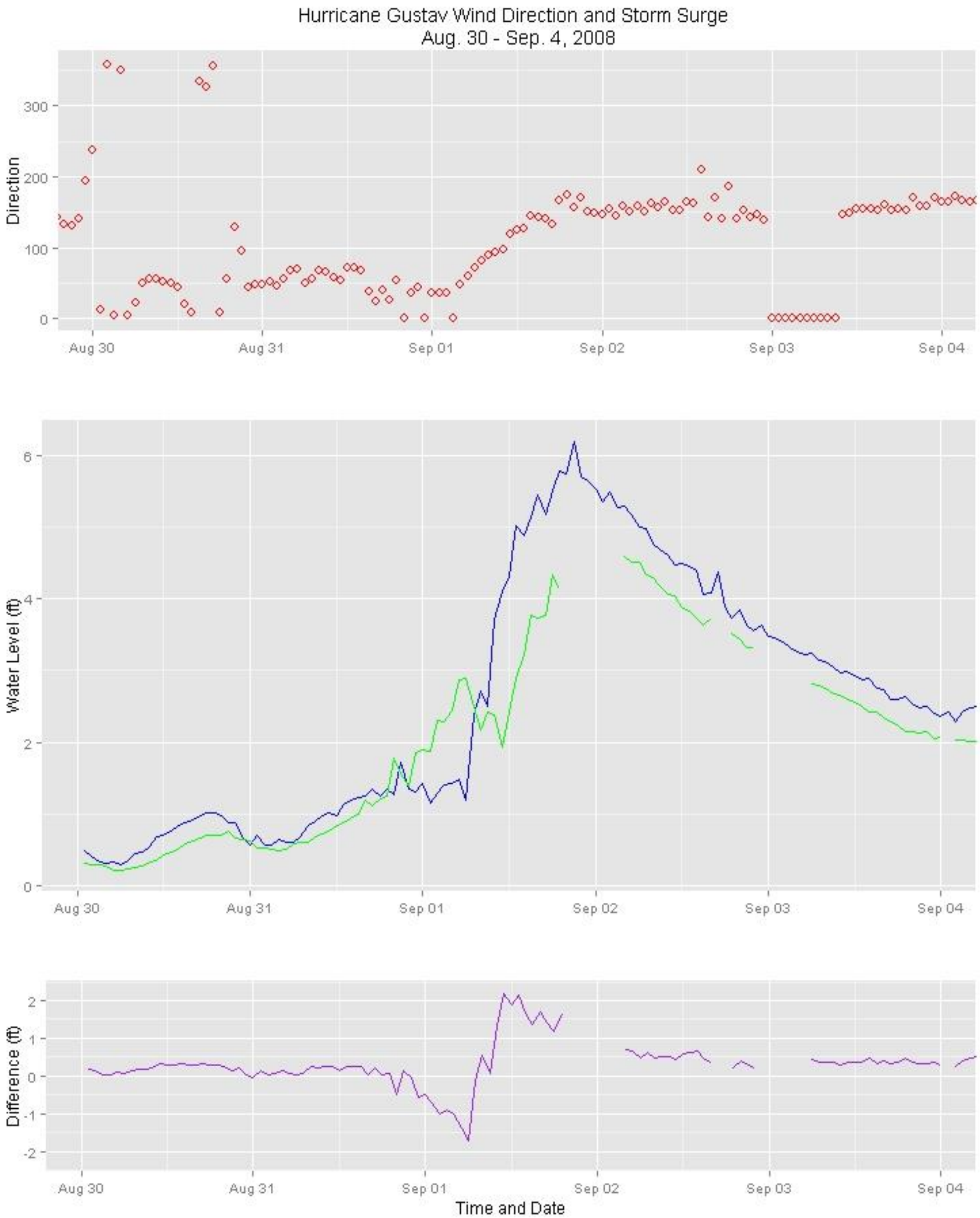


Figure 26: Hurricane Gustav surge hydrographs for Mandeville (blue) and West End (green) along with wind direction (red circles) for the New Canal Station. On late August 31, a possible standing wave oscillation (seiche) initiates due to fluctuations in wind direction. (Data Sources: USACE and NOAA.

In simple terms, a seiche is a standing wave with a wavelength of the fundamental node which is fixed ends of no movement or in this case assumed to be equal to the diameter of the lake. The Coastal Hydrodynamics part of the USACE's *Coastal Engineering Manual* (Seabergh 2002.) gives the formula for the period of a standing wave in a rectangular basin with uniform depth and closed boundaries:

$$T = \frac{2l}{n\sqrt{gh}}$$

where l is the length of the basin, h is water depth, n is node (1 for the fundamental node), and g is gravitational acceleration (32.2 ft/s^2). During a 6-ft surge, the water depth is approximately 20 ft. and the distance between the 6-ft contours on the gauge on the southshore and near the gauge on the northshore approximately 23.4 miles. Inserting these values into the equation above gives:

T = 2.7 hrs.

Entering at a range of plausible values for the north-south and east-west axes into the formula yielded a range of possible periods of 2.5 – 5 hrs.

The ratio of the lake diameter (20 miles) to its water depth (20 ft.) is about 5,000. This is roughly the ratio of a sheet of paper. So we should not expect a seiche to be robust and add significantly to surge heights. The Hurricane Gustav hydrograph (**Figure 26)** does seem to show indications of a frequent, low amplitude fluctuation in water levels. The spectral (frequency) decomposition shows a signal in the range that may correspond to a seiche **(Figure 27).** As shown in **Figure 28**, this dynamic was also captured in the ADCIRC simulation.

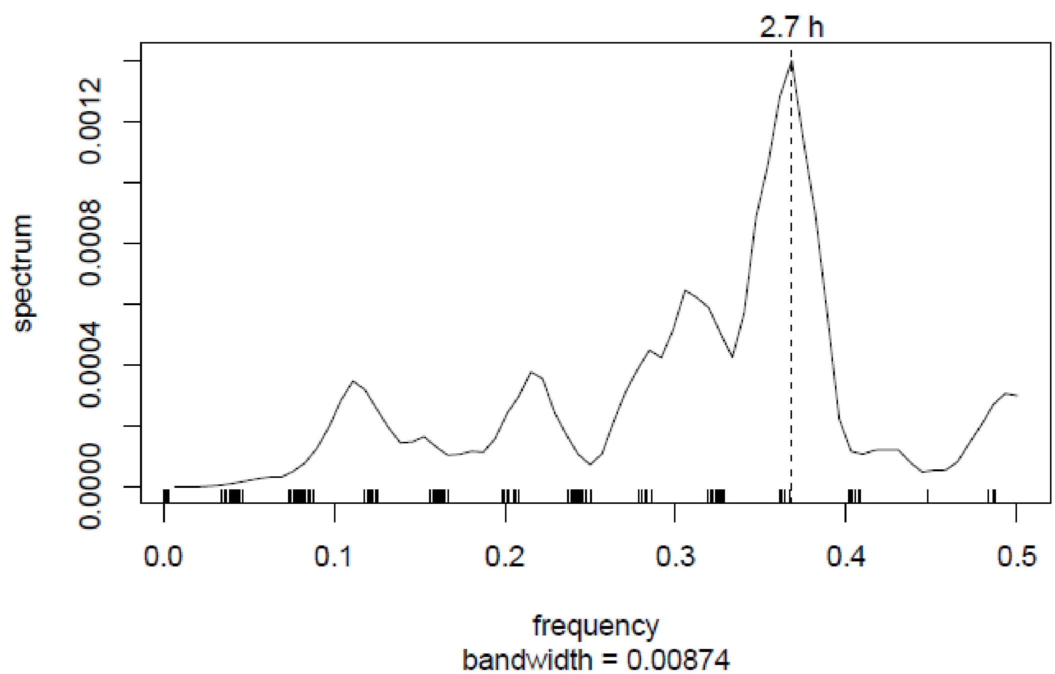


Figure 27: Spectral analysis of the Hurricane Gustav filtered surge hydrograph from Mandeville shows evidence of an oscillation at a 2.7 hour period along with other longer period harmonic oscillations. The tick marks along the bottom denote tidal constituents. (Figure provided by Dan Kelley using USACE dataset. See Appendix C for details.)

Figure 28: Simulated ADCIRC hydrographs from Hurricane Gustav from near the Mandeville gauge (A) and near the West End gauge (B). The fluctuation seen in the gauge hydrographs is also apparent in the ADCIRC results (Source: CERA.)

Taken together, these pieces of evidence suggest that early northerly winds caused a pileup of water on the southshore. When the wind direction changed, the water receded quickly with a progressive wave travelling toward the northshore. This perturbation then excited the natural harmonic oscillations of the lake, with the subsequent seiching lasting through the duration of the surge event.

Direct Rainfall, Runoff, and Delayed Drainage

As previously described, ADCIRC does not include direct rainfall or local stream runoff, though it does include gravity-driven drainage of the storm surge once winds have diminished. The PMSC region is hydrologically enclosed on three sides, and the fourth side at the Orleans land bridge is where water enters and exits the region during a hurricane in the PMSC region. Therefore, stream runoff and direct rainfall onto flooded areas directly add to the volume of surge water in the lakes. The direct rainfall onto flooded areas is an immediate contribution to the surge volume, but the stream runoff contribution to lake surge is delayed.

The peak of the north shore stream hydrographs often occur 2 to 7 days after a rainfall event on the north shore, and therefore, is delayed relative to a typical peak hydrograph of lake storm surge (**Figure 29**) assuming the rainfall is due to the storm event itself. However, it is common that surge is transmitted upriver during the hurricane event, and therefore the combined surge and riverine flood may be back-water flooding due to the reduced or reversed hydraulic gradient. Examining the two prototype storms of Hurricanes Isaac and Katrina, we see that Hurricane Isaac rainfall was very asymmetric (**Figure 30),** i.e. a typical pattern with the wettest portion of the storm was the northeast quadrant. Hurricane Katrina's rainfall was a little unusual in that it was more evenly distributed (**Figure 31).** In general, it should be expected that a west passage event will put more rainfall into the PMSC Region than an east passage. Hence, the hydrographs of lake surge show an extended tail due to the prolonged inflow from north shore rivers. There is also a risk that an unrelated rain event may occur as much as a week in advance of a storm in which the stream peak hydrographs could coincide with the peak surge event, in which case the peak lake surge would be increased.

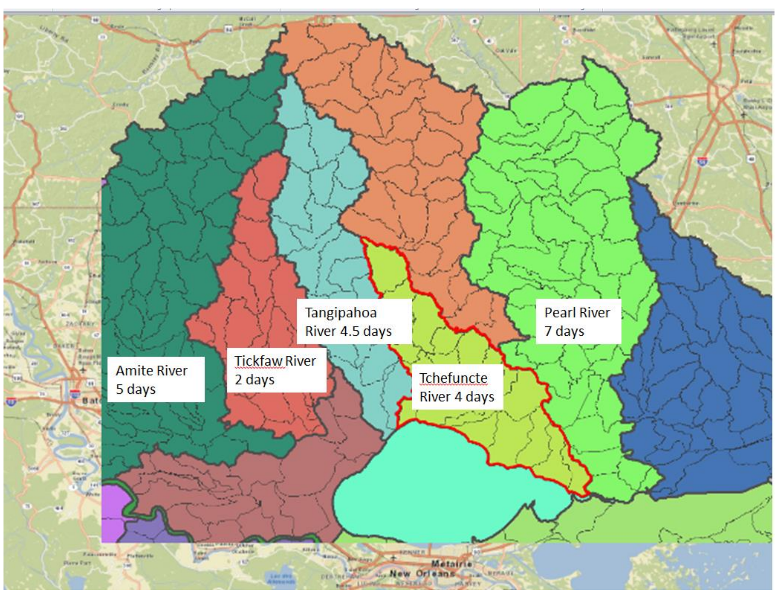


Figure 29: Major North Shore watershed HUC's (USGS), with approximate time required for peak stream flood from time to initial rainfall event source (Prof. Alex McCorquodale –Pers. Comm.).

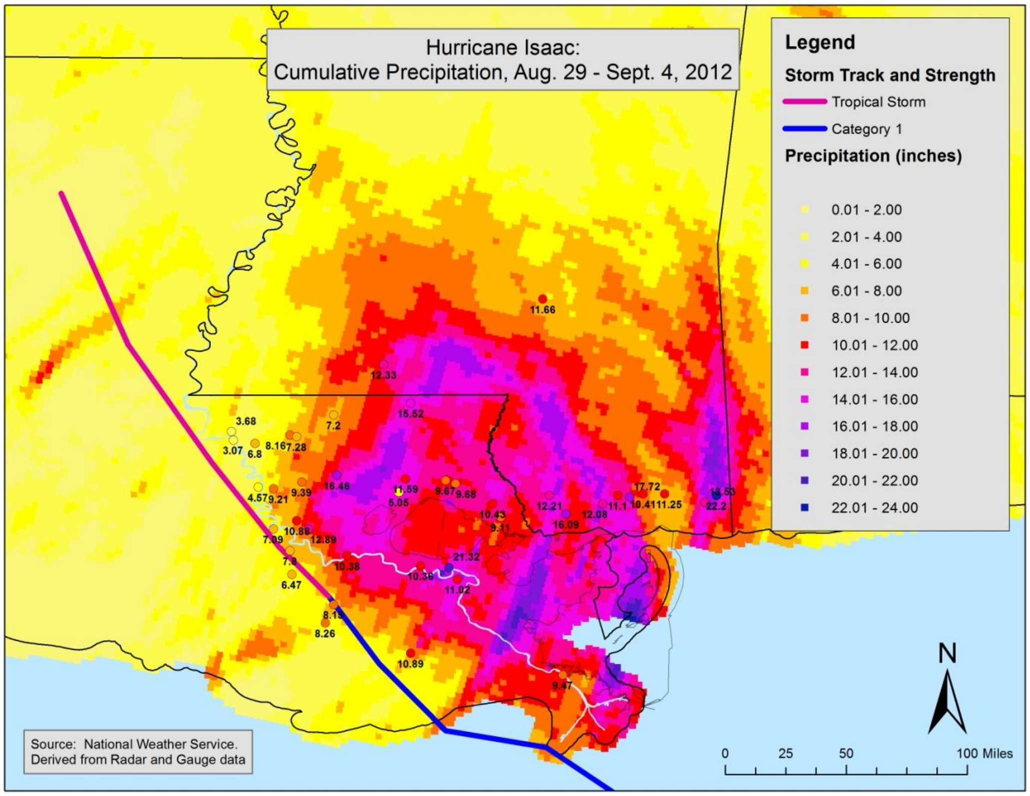


Figure 30: Cumulative rainfall for Hurricane Isaac from National Weather Service and hurricane track (Boyd 2012).

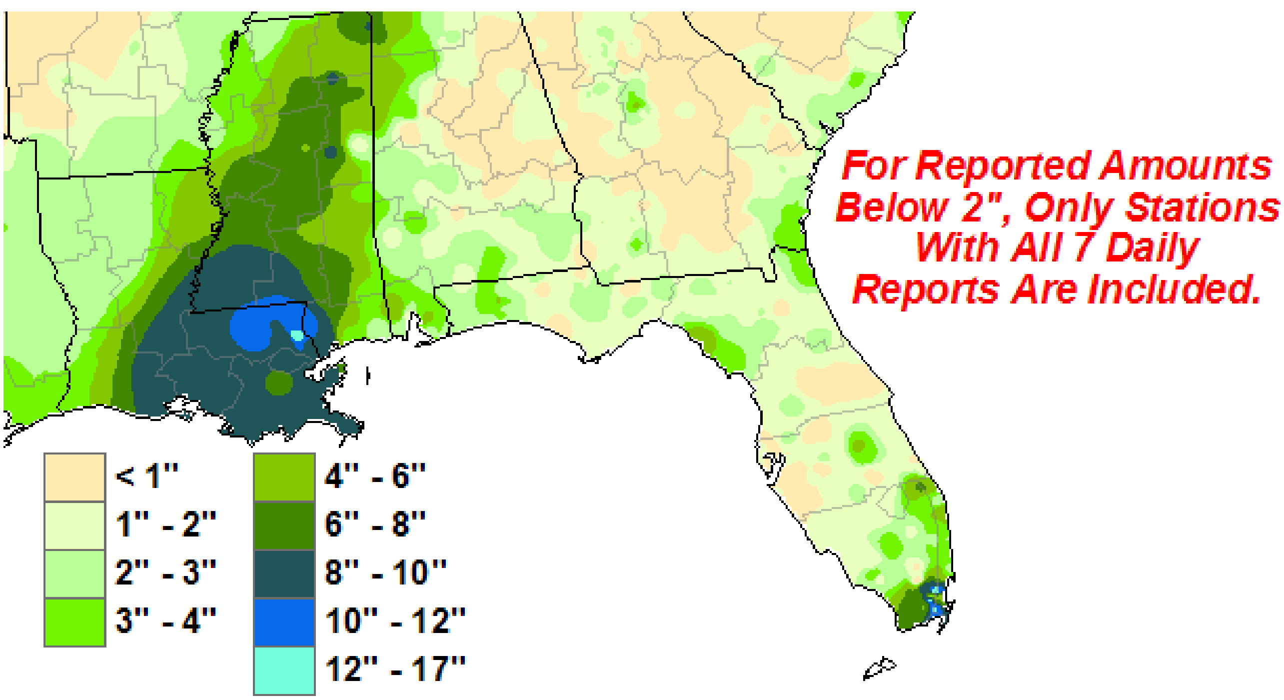


Figure 31: Observed rainfall for Hurricane Katrina from August 24 to August 30, 2005 (Source: NOAA December 2005 report Hurricane Katrina) .

When a major storm surge initially starts to recede, the natural ridges are submerged and act as weirs which impede drainage but do not completely stop it. However, once the surge recedes to the point that water levels are below the crown of the natural ridges, drainage from the lakes is constricted to tidal passes. Surge waters from Lake Maurepas drain through Pass Manchac into Lake Pontchartrain (**Figure 32**). From Lake Pontchartrain, drainage is limited to Chef Menteur Pass and Pass Rigolets through the New Orleans East Landbridge (**Figure 33)**.

Figure 32: Once surge waters start to recede from Lake Maurepas, a railroad embankment atop the Maurepas Landbridge both acts as weirs. When the water levels drop below these terrain features, drainage is limited to Pass Manchac (Data Source: NOAA 2010).

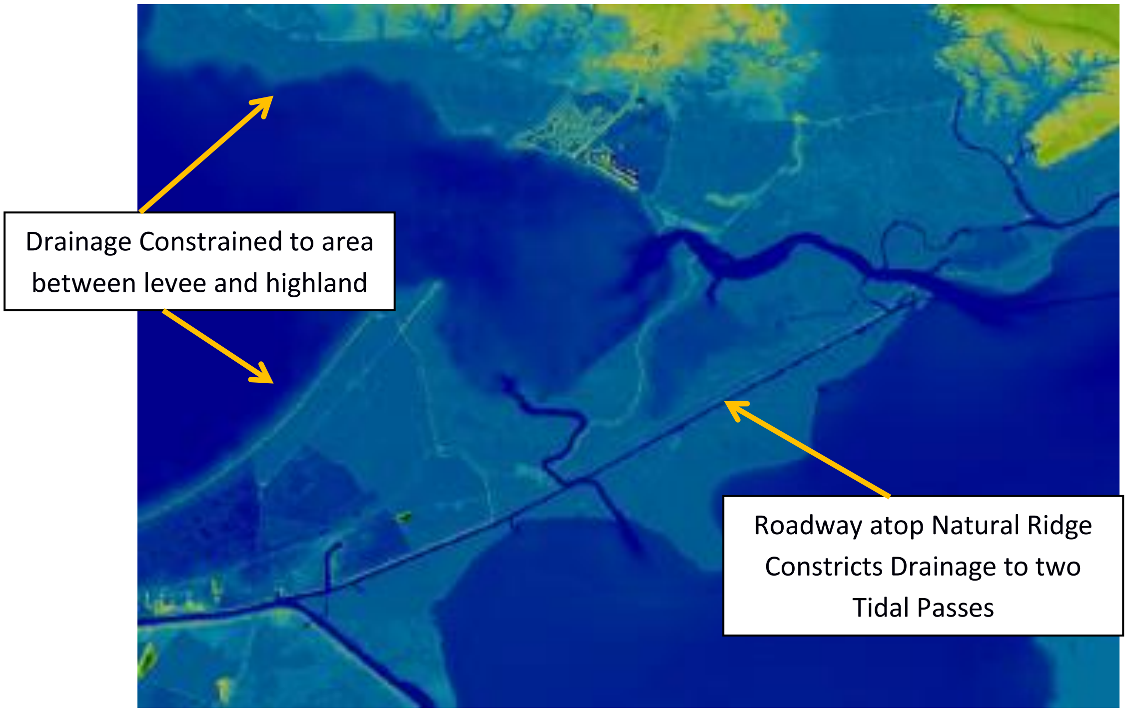


Figure 33: Storm surge outflow from Lake Pontchartrain is impeded by landscape features, such as the HSDRRS levee, and high ground on the north shore, The CSX railroad, the Hwy 90 roadbed atop the natural ridge. Once surge elevation lowers, outflow surge is limited to two tidal passes.

Case Study:
Motorist Drowning During Outflow Surge of Hurricane Isaac

As a case study in the risks created by the complex surge dynamics of this unique landscape, a fatality that occurred in Slidell during Hurricane Isaac due to an abrupt rise in water levels during the outflow surge is presented. This case was described by the Times Picayune|Nola.com as follows:

> "Hurricane Isaac floodwaters claimed the life of a 75-year-old Slidell motorist who drove off a submerged Interstate 10 on-ramp into a flooded ditch… [while] attempting to enter I-10 from Oak Harbor Boulevard south of Slidell when he steered his vehicle off the left side of the inundated on-ramp and ended up in 9 feet of water in a roadside ditch... The accident occurred at 7:40 p.m. Thursday." (Thibodeaux 2012)

Figure 34 gives the approximate location of this incident along with the elevations of the highway on ramp. Elevations along the on ramp varied between 3 and 5 ft.

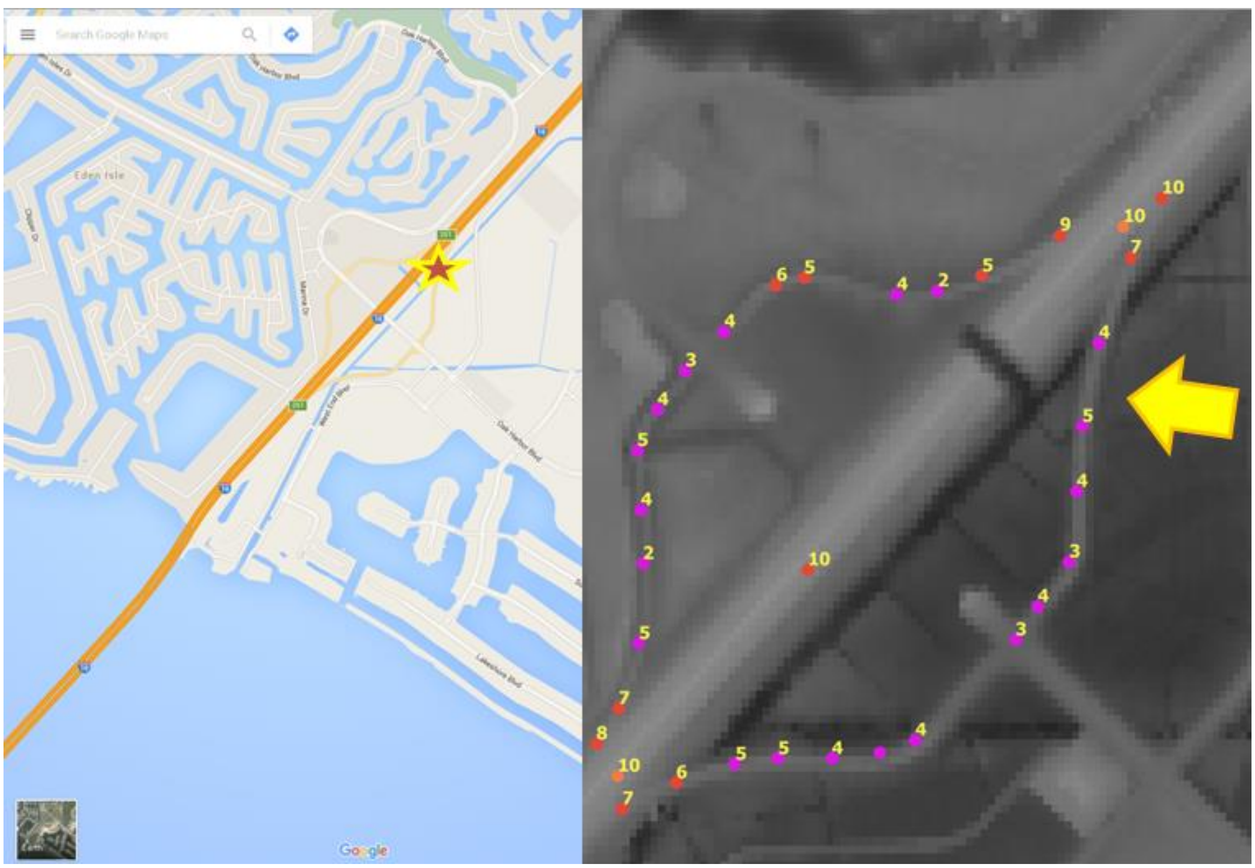


Figure 34: Approximate location of the vehicular fatality that occurred south of Slidell, LA during Hurricane Isaac (left) and elevations along the interstate and on ramps. From the description above, it is believed that the driver drove into a drainage ditch in the vicinity of the arrow (Source: Google, NOAA).

Examination of the surge hydrograph (**Figure 35**) shows that this incident happened as the surge was generally receding from Lake Pontchartrain. This individual was not killed by the peak surge that is depicted in most flood risk maps. Instead, this fatality resulted from dynamic fluctuations in the water surface, in this case a slight rise during the outflow surge that was just enough to re-submerge the interstate on-ramp. By this time, Hurricane Isaac had moved ashore, and the winds along Lake Pontchartrain and Lake Maurepas changed direction to create an outflow surge in Slidell. Importantly, the Maurepas Landbridge was inundated as were the coastal wetlands on the outskirts of Baton Rouge. The fetch for a consistent westerly wind essentially stretched from the outskirts of Baton Rouge to Slidell, approximately 75 miles. Further examination of **Figure 35** shows a small spike in the water levels, possibly due to a seiche oscillation or a wave generated by a westerly wind that travelled across two inundated lakes before reaching Slidell. By the time it reached Slidell, it had further fetch to increase height. In this regard, it is important to keep in mind that the peak surge height is a function of the storm characteristics while the shape and fluctuations in the hydrograph are a function of the lake geometry. Many, but not all, Slidell residents know from experience that just when it starts to seem that the worst is over and the storm has moved north, Slidell often experiences its highest storm water of the event. However, those who are not aware of this effect can get caught off guard, with unfortunately deadly consequences.

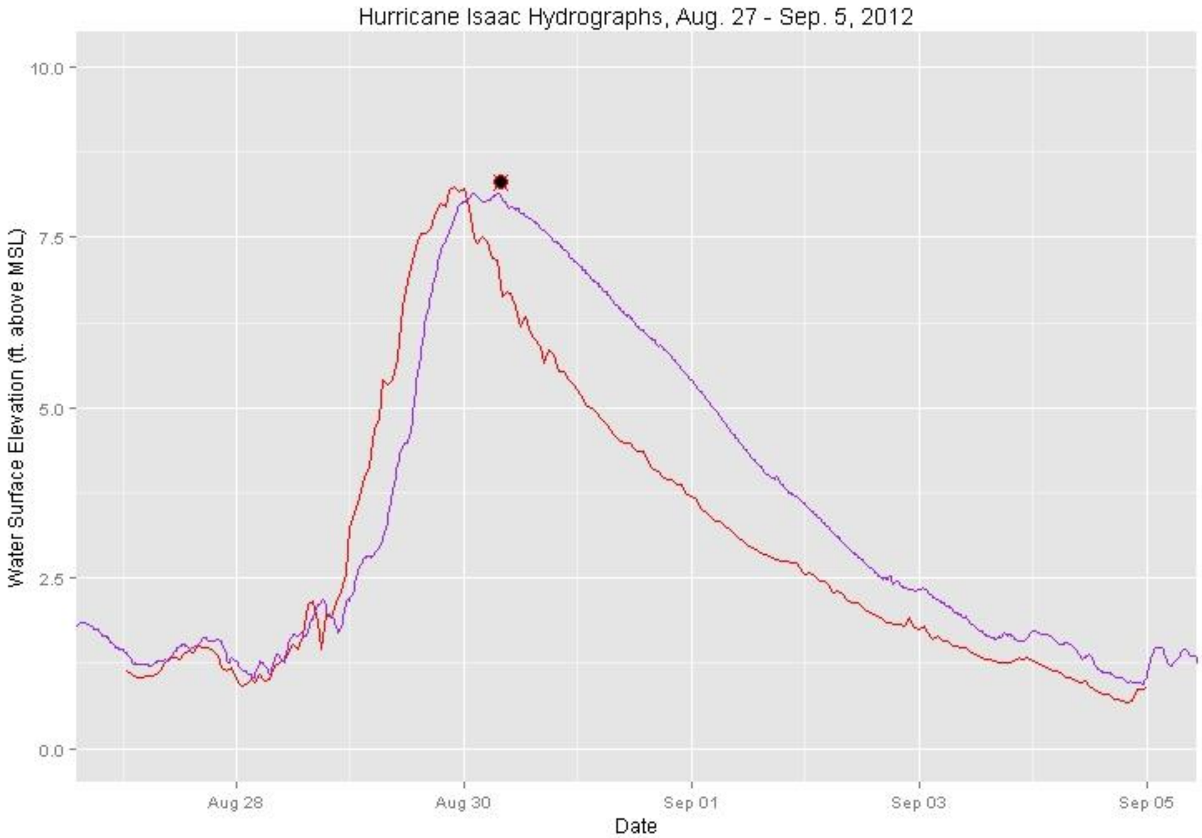


Figure 35: Hurricane Isaac surge hydrograph for the Mandeville (red) and Bayou Liberty in Slidell (purple) gauges with the approximate time of the Slidell fatality (red and black point). The hydrograph shows that the fatality occurred during the outflow surge in Slidell. Mandeville had receded by 2 ft. when the fatality occurred in Slidell. As the surge started to wane at Mandeville, it reached its peak in Slidell approximately 4 hours before the fatality. However, Slidell experienced a peak nearly twice as long as Mandeville. After an initial drop (about 0.4 ft) from the initial peak, there was a slight rise that occurred at the Bayou Liberty gauge immediately before the fatality. Notably the Mandeville gauge shows a similarly shaped rise approximately 4 hours prior to the rise in the Slidell gauge. This could indicate a wind driven wave that propagated east or a seiche oscillation (Data Sources: USACE, USGS).

Discussion

In hindsight, it seems obvious that the "urban myth" of lake sloshing in a simplistic seesaw fashion was driven by a lack of explicit spatial and temporal data on storm surges. A more nuanced view and terminology has been presented based on patterns visible in time-lapse snapshots from the ADCIRC model along with empirical surge observations. In lieu of an explicit spatial-temporal analysis, maps of surge heights from a specific event over the duration the event were often examined to understand trends. Such maps tend to show the high surge water on either side of the lake and overlook the passage of lower heights of surge on the north and south shores.

From our assessment of ADCIRC simulations, SURGEDAT, and storm surge hydrographs, we've identified three main dynamic processes that impact surge risk along Lakes Pontchartrain and Maurepas. The **surge rotation** refers to the rotation of the peak surge around the Lake Pontchartrain shoreline, based on the changing windfield during the storm's passage. **Surge focusing** refers to observation that the highest storm surges are observed along the northeast and southwest corners of Lake Pontchartrain. We posit that this pattern is a manifestation of the surge rotation along with the lake's unique landscape. Finally, the term **outflow surge** refers to a late stage rise in water levels on the eastern shoreline of Lake Pontchartrain that impacts Slidell after the storm has moved north of the lakes. The surge rotation around Lake Pontchartrain and the phenomena of outflow surge are the dominant patterns of the maximum surge for the PMSC region.

Viewed as a continuum of surge movement around the lake, it is also clear there are two prototype surge scenarios, depending on whether the storm passes east or west of Lake Pontchartrain. In both cases the easterly or westerly winds tend to amplify surge along the elongated east-west PMSC Region, but when the storm is at the same latitude the wind patterns are in the opposite direction, thus resulting in opposite rotations (**Figure 36)**. The net result is as follows:

- East passage: The effective wind rotation is East > North > West, resulting in counter clockwise rotation
- West passage: The effective wind rotation is East>South> West resulting in clockwise rotation

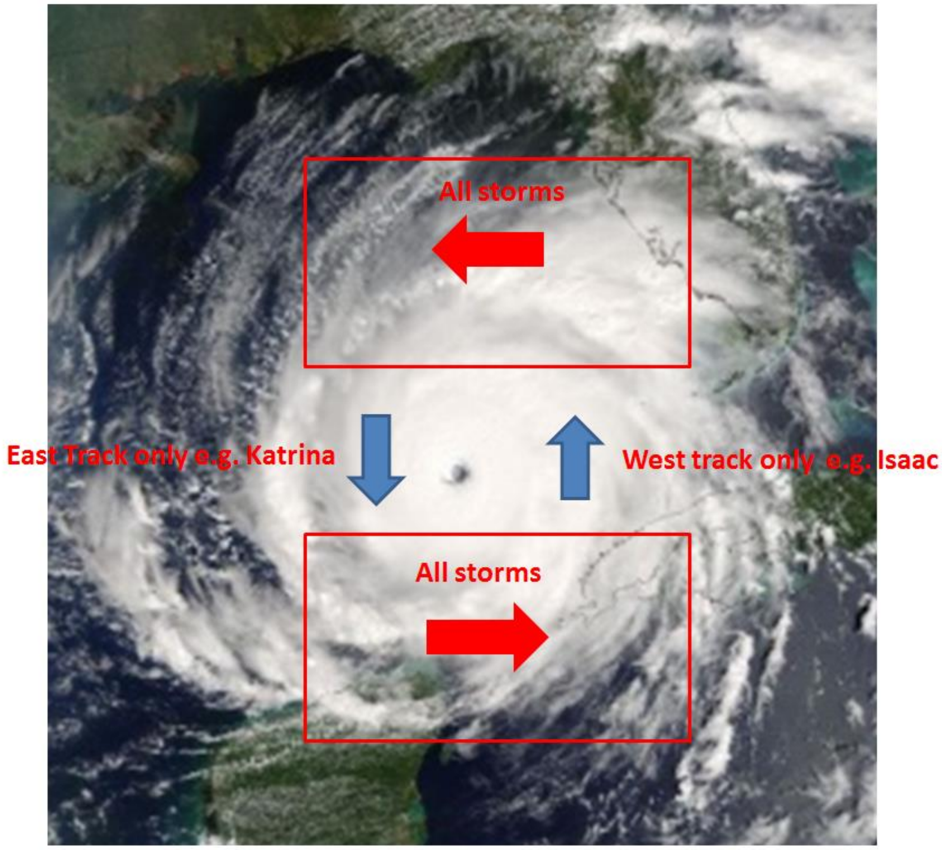


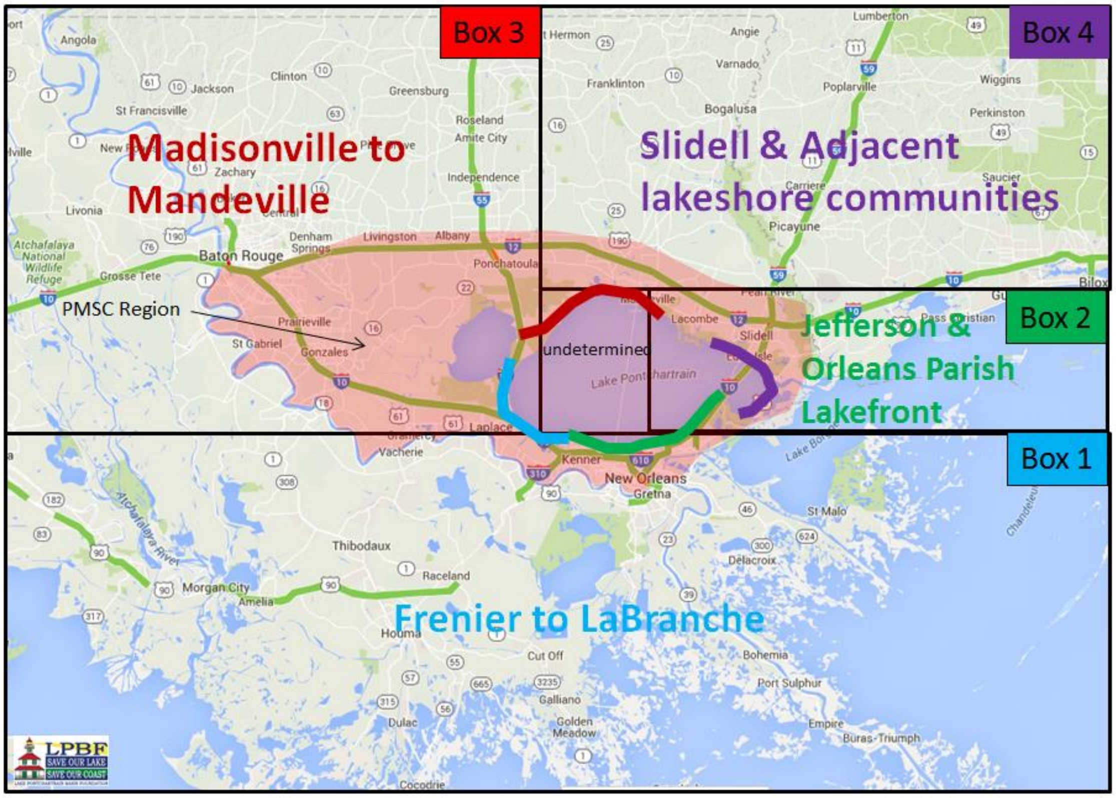
Figure 36: The circular pattern of wind around any storm dictates that the winds are in opposite directions for an east and west passage once at the same latitude as the PMSC region. This creates the opposite direction of rotation of surge within the PMSC region.

While straightforward, the foregoing analysis does not adequately explain the total behavior of surge in the PMSC region. For example, the model would suggests that in general the highest surge would be on the west side of the PMSC region because it would generally be exposed to the most intense hurricane quadrants (northeast or northwest), but in fact we find the highest surge tends to occur on the east side of the lake, especially for storms passing east of Lake Pontchartrain. Further, in Hurricane Katrina, the highest waves were also on the southeast side of the lake when the storm was well inland. Therefore, secondary drivers of surge have also been discussed.

The most important secondary effect is the contrasting boundaries of the PMSC region. The west side of the PMSC region possesses absorptive and equidistant boundaries, while, the east side contrasts with strong convergent and deflective shorelines. In the west, the shoreline absorbs and diffuses and dissipates surge energy, while in the east the boundaries focuses water and surge energy toward a focal point near Slidell. This produces the most unusual aspect of the surge dynamic of the PMSC Region: the greatest surge heights often occur during the outflow surge when the weakest quadrant of the wind field is over the lake and when the storm has weakened after landfall. This outflow surge often creates the most severe conditions in the lake. It was a major contributor to the Interstate -10 damage during Hurricane Katrina and likely linked to the fatality that occurred in Slidell during Hurricane Isaac.

Figure 37 illustrates the basic physical implications for the various regions around the PMSC region of the surge model introduced in this report. This map represents a generalization, and all storms have their own set of unique conditions that may deviate from our simplified conceptual model. Based on the location of the eye of the storm at that time, each box helps identify areas of the PMSC region most at risk from the surge related flooding. The boxes are labeled 1 through 4 to aid in the discussion.

> ***When the eye is within Box 1****, remote forcing due to the outer wind bands causes the storm surge to build up within the PMSC region, and water levels rise disproportionately along the southwest quadrant of Lake Pontchartrain. The duration and degree of surge buildup during this phase influences the surge height and extent for the remainder of the event. In general, any parameters, such as slow forward speed and lower barometric pressure, that facilitate more buildup of surge while the storm is within Box1, magnifies the potential surge risk beyond when the storm moves from Box 1. For example, while in Box 1 if the storm stalls, accumulates rainfall, facilitates focusing of surge toward the PMSC region, then more surge may build in the PMSC region and will be subject to the surge rotation with greater consequence while in Boxes 2, 3 or 4.*
>
> *After the storm moves through Box 1, it will likely either move to Box 2 (east passage) or Box 3 (west passage).*
>
> ***If the eye then moves into Box 2****, such as a track like Hurricane Katrina, wind shifts and blows increasingly with a northerly component which rotates surge from the southwest quadrant to the south shore. On this easterly passage the storm will most likely have more rainfall east of the PMSC region, although this was not the case in Hurricane Katrina.*
>
> ***If the storm passes from Box 2 to Box 4,*** *the outflow surge event occurs with substantial surge build up near Slidell, which is what happened during Hurricane Katrina. The seiche and astronomical tides may increase or decrease the peak surge depending on the exact timing of these secondary factors, but overall these combined effects are probably less than 20%. With an east passage, the southeast shore will see exceptional wave heights due to the proximity of the shoreline to the deepest portion of Lake Pontchartrain.*
>
> ***If the eye moves from Box 1into Box 3*** *instead, such as the track of Hurricane Isaac, the wind shifts follow a different pattern, blowing increasingly with a southerly component. This wind pattern then rotates surge from the southwest quadrant to the northwest quadrant of Lake Pontchartrain. On this westerly passage, it is more likely that the PMSC will have significant rainfall. The rainfall adds directly to surge height within the inundated areas of the PMSC region, but drainage from north shore rivers will likely peak 1 to 4 days after the storm passage. This may prolong flooding, but likely will not add to the peak surge of the event. However, the drainage will cause increased backwater flooding during the peak surge events in the upper reaches and exacerbate riverine flooding in these watersheds.*



Color highlighted shoreline areas are the areas most at risk from surge when the eye is within the corresponding color coded boxes

Figure 37: The map is based on the general behavior of surge described in this report, which suggests what areas most are at risk from surge based on the location of the hurricane eye. As a storm moves inland, multiple boxes will be crossed, and so the figure does not show which communities were most at risk for the entire passage of a storm, but only when the hurricane eye is located within that box.

It is important to note this conceptual model is limited to surge within the PMSC region and that the New Orleans' Eastbank can also be threatened by storm surge from Lake Borgne, which is outside of the PMSC region. Likewise, as a simplified conceptual model, the surge rotation model generalizes the other forces and processes, such as remote forcing, which can influence the dynamics of storm surges within the lakes. In detail, every storm has a unique set of conditions that will result in variations from this general model. Nevertheless, the processes described here help explain surge and wave patterns that are unusual and may defy simple intuition. Dangerous outflow surge occurs when the storm is inland and weakened yet often produces the highest surge and largest waves.

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Appendices

Appendix A: SURGEDAT Processing and Analysis Steps

SURGEDAT is a global storm surge observation database created by Dr. Hal Needham and maintained by the LSU Climate Center (Needham et. al 2015). The database contains over 8,000 surge observations from more than 700 events from 1880 – 2012. For Louisiana, the database contains over 2,000 observations from 86 different storms. For this analysis, the dataset was obtained on May 11, 2015. **Table A.1** below lists the fields contained in the database. However, not every field is complete for all events. Of the available fields, `stormtide_ft` was the most complete and hence was used for the analysis. The `lat` and `long` fields were used to enter the observations into a GIS project.

Table A.1: List of fields included in SURGEDAT. For the analysis, only stormtide_ft observations with a listed datum that could be converted to NAVD88 were used.

storm_id	waves_ft	Lat	source_2
surge_id	waves_m	Long	Notes
storm_name	sig_waves_ft	Basin	notes2
Year	sig_waves_m	Conf	notes3
Date	Datum	Tropical	
Time	obs_type	Published	
surge_ft	station_id	Researcher	
surge_m	Location	source_type	
stormtide_ft	county_parish	collecting_agency	
stormtide_m	State	source_1	

To identify spatial trends in storm surges within the PMSC region, the first step was to identify SURGEDAT observations inside the PMSC study area. For points with a geodetic datum, the NOAA program VERTCON was used to convert to NAVD88. For points referenced to a tidal datum, information from NOAA's New Canal tide station was used for the conversion. Next, to isolate just surge effects along the shoreline (as opposed to riverine discharge or levee effects), the points were manually classified as "Shoreline", "Levee Protected", "Open Water", "Interior Riverine", and "Outside Lakes" based on satellite imagery. After this step, 392 points classified as "Shoreline" where used to examine evidence of surge focusing in the empirical record. Next, points without a standard vertical reference were discarded, and the recorded storm tide value was converted to NAVD88.Finally, summary statistics of the storm tide values were calculated for different sections of the shoreline.

Figure A.1: All Louisiana surge observations contained in the SURGEDAT database.

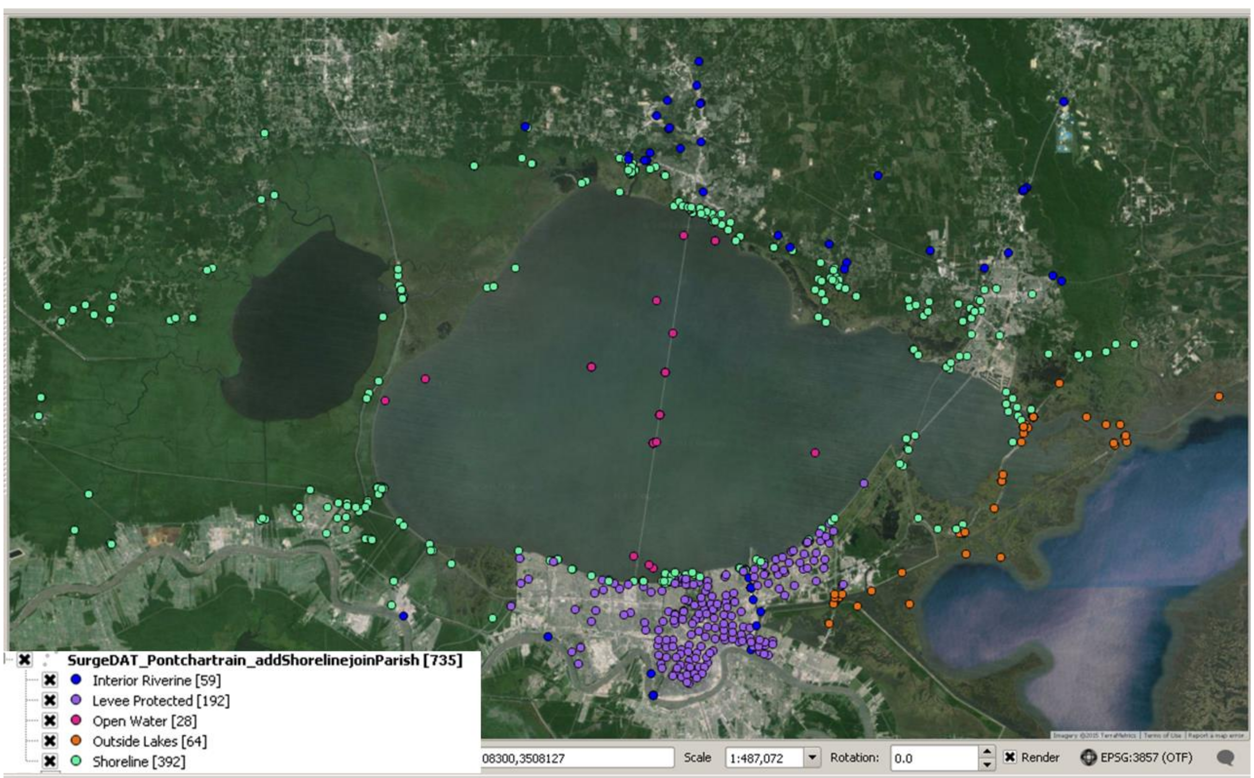

Figure A.2: PMSC surge observations contained in the SURGEDAT database, colored by category.

Figure A.3: PMSC shoreline surge observations contained in the SURGEDAT database, colored by storm tide (ft).

Appendix B: Surge Cross-section Area Calculations

To calculate the cross sectional area at various transects along the lakes, NOAA's greater New Orleans terrain dataset was used, which merges (land based) elevation with (water based) bathymetry into a single dataset covering most of the PMSC study area. With this dataset, the terrain profile tool in QGIS was used to extract elevations along characteristic transects. This data was then imported into an Excel spreadsheet (see **Figure B.1**).

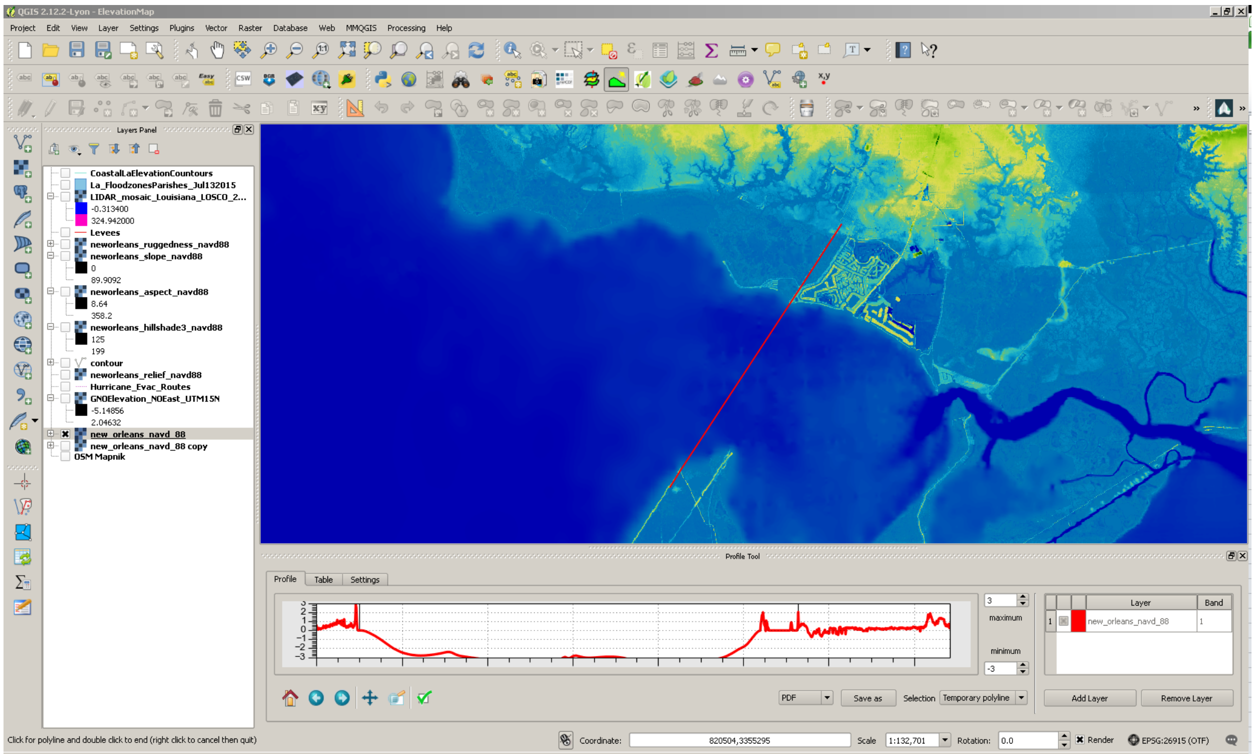

Figure B.1: Screenshot of the greater New Orleans digital elevation model along with the terrain profile tool spanning the northern tip of New Orleans East (Point aux Herbes) to the Pleistocene Terrace in Slidell. The red curve is the profile transect connecting the levee New Orleans East and to Slidell. The tool allows exporting the profile to a spreadsheet.

To have a common water surface elevation representative of surge conditions, it was decided to add 12 ft. to the elevations obtained from the profile tool. Profile points inside the levee system or north of the Pleistocene Terrace boundary were ignored. To calculate the cross-sectional area for each profile, we calculated the sum of the distance increment multiplied by the elevation plus 12 ft. **Table B.1** shows the spreadsheet from the New Orleans East cross-sectional area calculation.

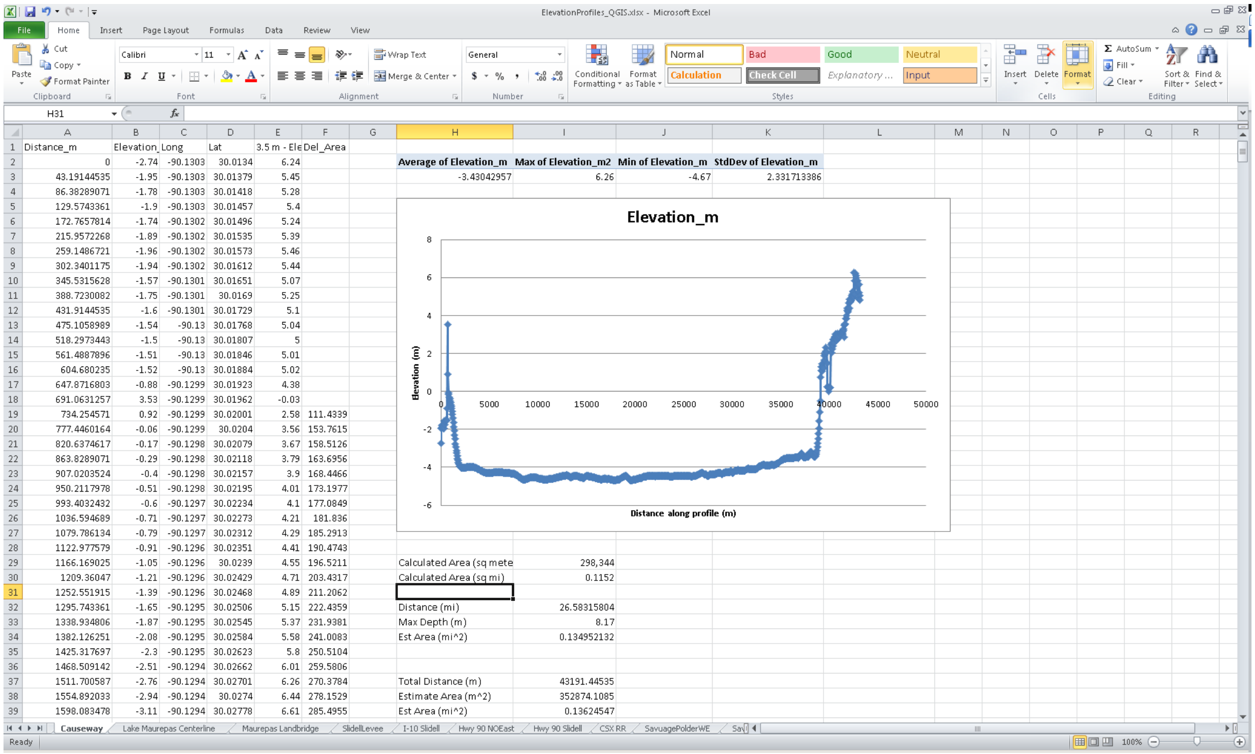

Figure B.2: Screenshot of terrain profile and cross-sectional area calculation.

Appendix C: Spectral Analysis of Possible Seiching During Hurricane Gustav

By: Dan Kelley and Ezra Boyd

This appendix uses a spectral decomposition, a statistical technique to identify periodic fluctuations in a time series dataset, to investigate possible seiching and related harmonic oscillations during Hurricane Gustav. It also describes the process used to create **Figure 24**. The data for this task consists of tidal gauge data for the Mandeville and West End stages during Hurricane Gustav. The analysis was completed using the R statistical program with the "oce: Analysis of Oceanographic Data" package.

This analysis utilizes USACE tide gauge data for Mandeville and West End, and actually looks at the difference in the water surface elevation values between the two locations. **Figure C.1** shows this water level difference times series along with a smoothing spline. To remove the effects of short term fluctuations, the smoothed dataset is used in the steps that follow.

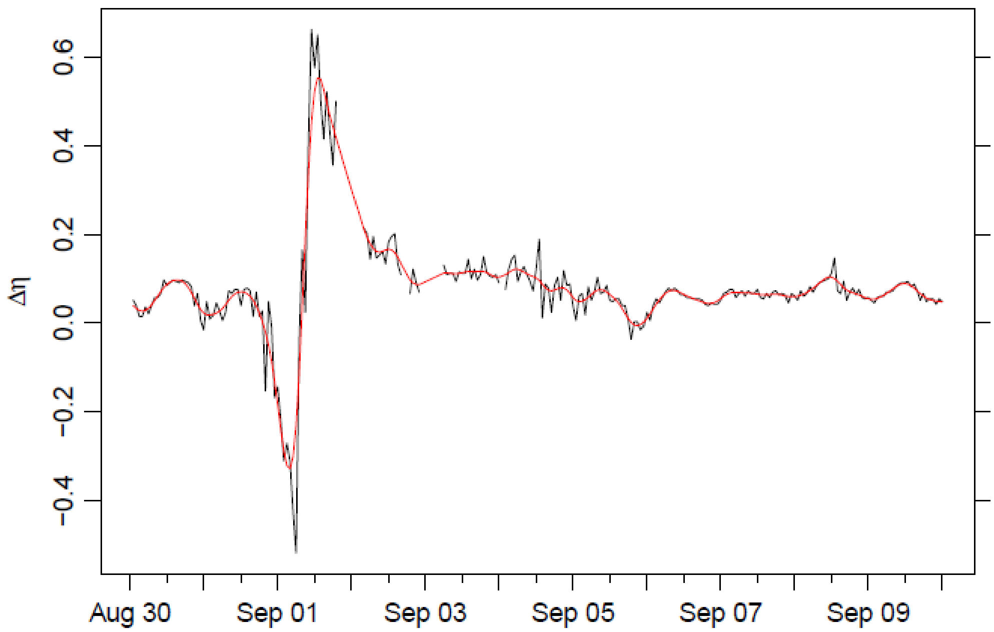

Figure C.1: Time series plot of the Mandeville water gauge minus the West End water gauge (meters) along with smoothing spline (red line.)

The reader will notice a large span of missing data during September 1 - 3. To derive a time series dataset without missing data, only the last 7 days of uninterrupted data was used in the steps that follow. Of note, while the storm surge has largely receded during this period, the harmonic oscillations continue independent of the wind field or storm surge.

Figure C.2 (also Figure 24) shows the spectral decomposition of the truncated dataset. It shows a primary peak at 2.7 hr. Additionally peaks are seen at lower frequencies, corresponding to shorter period oscillations at approximately 3.2, 4.6, and 9.1 hrs.

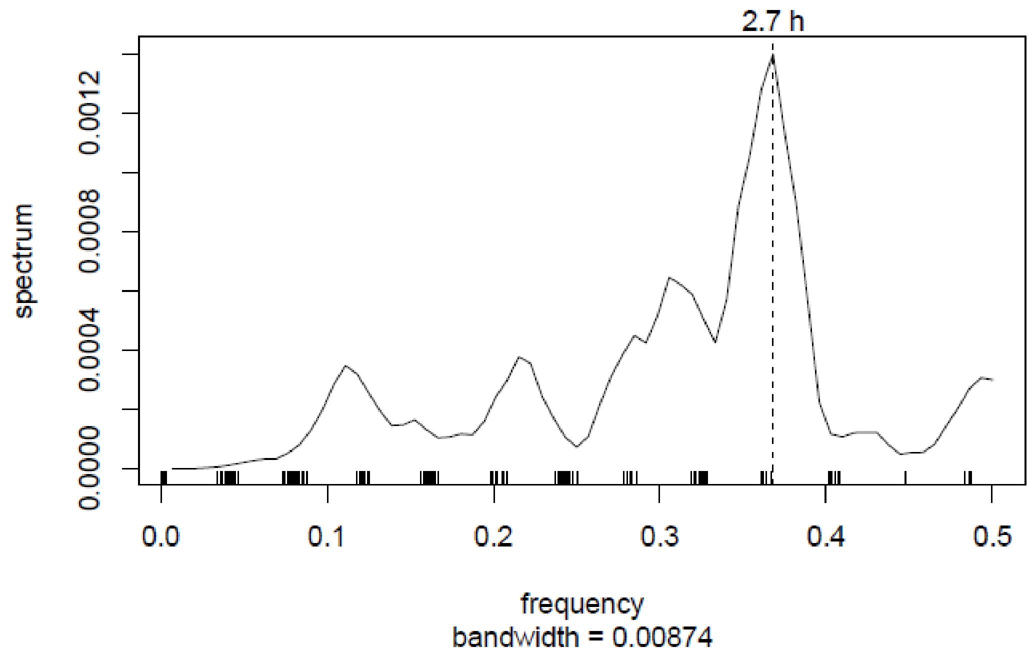

Figure C.2: Spectral analysis of 7 days of uninterrupted water level differences shows a primary peak with a period of 2.71 hrs. The tick marks along the bottom denote tidal constituents.