Plaquemines Spillways

The impact of the lower Mississippi river levees on storm surge during hurricanes

February 2009
Final Report

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SUMMARY

The Mississippi river runs through Louisiana towards the Gulf of Mexico where it becomes a bird-foot delta. Various settlements of often no more than 2 km in width exist along the lower 125 km of this river; this area is known as Plaquemines Parish. Nowadays levees protect the Parish from storm surges and high Mississippi river discharges. During major hurricane events in the Gulf of Mexico the levees block the storm surge and this leads to a build-up of surge locally but also forces the water to flow upriver towards New Orleans. By creating spillways within the levees of Plaquemines Parish the maximum water levels in and around New Orleans can be reduced during hurricanes. To gain insight into the quantitative effects of the spillways on storm surge the Advanced CIRCulation flow model (ADCIRC) has been used to perform storm surge simulations.

The commonly used SL15 ADCIRC grid for Louisiana encompasses approximately two million computational nodes and therefore a parallel computing environment is required to run the model. For this study a smaller computational grid has been created with approximately one million nodes; this grid is based on the IHNC grid (also known as the SL15 light grid). The bathymetry and grid resolution from this IHNC grid have been increased within the bird foot delta in order to improve model results near Plaquemines Parish.
In comparison with other larger ADCIRC studies a simplified modeling strategy has been applied in order to improve the balance between computational speed and model accuracy.

The model has been validated by performing a hind-cast of hurricane Katrina. A regression analysis shows that the modified IHNC model performs better than the older S08 model and somewhat similar to the SL15 model and the original IHNC grid for locations in Louisiana and Mississippi. The regression analysis in itself is however not representative for the quality of the model near Plaquemines Parish since very few measurements are available within this area. This is a problem common to all models. The local modelling errors in Plaquemines Parish are smaller for the modified grid compared to the original IHNC grid so the validation gives an indication that the modified model performs better than the Original IHNC grid for Plaquemines Parish. There is too few reliable data available to statistically confirm this.

Hurricanes in the Gulf of Mexico can be very different from each other. To be able to capture the most important storm surge processes three storms have been selected which capture a range in water levels at each of the focus areas, these are: Plaquemines Parish, Jefferson Parish, St Bernard and the Mississippi River. The storms differ from each other in terms of track and landfall location.

The modified grid was used to simulate five spillway scenarios and three different hypothetical storms. The spillway locations have been selected according to a hydrodynamic analysis on the formation of storm surge; the locations of important areas within Plaquemines Parish have also been considered while selecting the scenarios.

Model results show that the spillways are capable of reducing maximum surge levels locally in Plaquemines Parish as well as in regions closer to New Orleans and on the Mississippi River; the length of the spillways in the northern part of Plaquemines Parish was found to be very important for the reduction of the surge in these areas.

PREFACE

At the moment of writing, approximately six years after I started my Civil Engineering and Management study at Twente University I am about to finish my M.Sc. thesis. It seems almost like yesterday that I went to Enschede because I wanted design bridges and buildings. At that time I would not have guessed I would end up doing research on a far more interesting subject, hurricane storm surge in Louisiana.

When I was about to start searching for an interesting topic for my thesis last year, my traineeship supervisor at Royal Haskoning contacted me and told me he had moved to New Orleans to work on the levee system over there. Since I wanted to go abroad for my M.Sc. thesis I did not need much time to decide where to go to.

Being born in Zeeland and having heard many stories about the great flood of 1953, I have always been interested in flood risks. I remember watching a CNN reporter at the time Katrina made landfall, defying the wind while trying to present the latest news. Later it became clear that not the wind but the surge had caused the bulk of the damage and loss of life, just like in 1953. New Orleans appeared to have a similar vulnerability like the Netherlands, a risk of flooding. I found a subject related to these flood risks therefore very interesting and decided to focus on the modelling of storm surge caused by hurricanes. This is weather phenomenon that we fortunately do not have to deal with in the Netherlands; let's hope the predicted climate change does not affect this and that I don't have to use my Hurricane modelling experience here in the Netherlands any time soon.

I look back at an exciting and interesting period which I will not easily forget. The three months I spent in the United States have made a great impression on me and I would like to thank Royal Haskoning and Mathijs in particular for inviting me to come to New Orleans. I not only liked working on my graduation project over there but also enjoyed the "off duty" time which we spent with the Royal Haskoning crew during e.g. the European Championship games, the celebration of Independence Day in the swamps of Louisiana and of course the great many famous barbecues at Maarten and Ester's place. Especially the relaxed and informal atmosphere made me feel at home instantly. So Mathijs, Maarten, Ries, Ray, Bas, Marjan, Ester, Angela, Siem, Marcel and Mats; Thanks!

During the period I spent in the United States I was also able to visit the University of Notre Dame in South Bend, Indiana for one week. Without the help, hospitality and effort of the computational hydraulics research group at Notre Dame it would not have been possible to complete my research. The computer cluster which I was allowed to use provided the means by which I could perform my research. In particular I would like to thank Casey Dietrich who helped me out every time I got stuck with Unix commands and who warned me about power grid failures in South Bend. The advice of Joannes Westerink regarding ADCIRC and regarding the quality of restaurants in New Orleans was greatly appreciated. I would also like to thank him and Diane for letting me stay their home for a week.

Next I would like to thank my supervisors in the Netherlands. The relaxed attitude and constructive criticism of Wiebe proved to be very helpful and motivating. I appreciated the meetings I discussions I had with Jan who always tried to keep me on track. Suzanne, thank you for your critical attitude and your comments on the report.

Last but not least I would like to thank my parents, my brother, my sister, my roommates and my friends for supporting me throughout the six years of my study.

Marcel van de Waart
Enschede, februari 2009

CONTENTS

LIST OF ABBREVIATIONS

ADCIRC	Advanced Circulation Model
HWM	High Water Mark
IPET	Interagency Performance Evaluation Task Force
LACPR	Louisiana Coastal Protection and Restoration Authority
MSL	Mean Sea Level
NAVD 88	North American Vertical Datum of 1988
STWAVE	Steady State Spectral Wave Model
SWAN	Simulating WAves Nearshore model

1 INTRODUCTION

Storm surge caused by hurricanes, typhoons or cyclones has always been a threat for most coastal areas in the tropics. Recent storms in the Gulf of Mexico like hurricane Gustav (2008), hurricane Ike (2008), hurricane Rita (2005) and especially hurricane Katrina (2005) together with cyclone Nargis in the Indian Ocean (2008) have one again revealed the fact that surge is a crucial factor when it comes to flood damage and loss of life. Predicting this storm surge, or mean water level, can therefore help to identify risks and to give timely warnings in case of impending evacuations. This study will focus on the Plaquemines spillways, one of the possible measures which are being considered to reduce storm surge in southern Louisiana.

This chapter provides an introduction to the subject of this master thesis; storm surge modelling of the Plaquemines spillways. In the first section the framework of this study will be presented. In section 1.2 the idea and the purpose of spillways will be introduced. Then, the problem will be discussed and the research objectives will be given. Consequently some research questions are formulated; these questions will be answered later on in this report. In section 1.6 the spatial scope and study area will be discussed and finally the outline of the remainder of this report will be presented.

1.1 Framework

1.1.1 Historical Hurricanes

On the morning of August 29 2005 hurricane Katrina hit New Orleans. The event clearly showed the vulnerability of the city regarding hurricanes. It was the costliest storm ever to strike the US coast and with over 1800 lives lost and still 700 people missing it is among the five most deadly storms ever in the United states (LDHH, 2006)

Katrina made its first landfall as a category three hurricane, near Buras, Plaquemines Parish, Louisiana. Plaquemines Parish is an administrative subdivision of the state of Louisiana and is located south of New Orleans (Figure 1).
Consequently Katrina continued in northward direction and made its second landfall near the Louisiana and Mississippi border, approximately 20 km from the town of Slidell. When Katrina hit the coast the hurricane had decreased from a category 5 storm on the Saffir-Simson scale to a large category 3 storm. Wind speeds of more 200 km/h were measures in Buras (Fritz et al., 2008). Before Katrina the previous highest high water mark in the area had been set by hurricane Camille at Biloxi and was about 4.8 m NAVD 88. NAVD 88 is the commonly used vertical control datum in the United States (see Annex A). Camille was a category five storm when it reached land and although Katrina was ‘only ‘ a category three storm the measurements have shown that water levels reached up to 8.5 m NAVD88 along the Mississippi coast and were therefore much higher.

Large parts of New Orleans flooded and it had appeared that the Hurricane Protection System which had to protect New Orleans failed on multiple locations and due to multiple reasons. Some of the levees were overtopped, others failed completely. Since Katrina, New Orleans has repaired most of its levees to their original state but Katrina however demonstrated that the current design levels for the hurricane protection system will not be sufficient to prevent flooding in case of another hurricane.

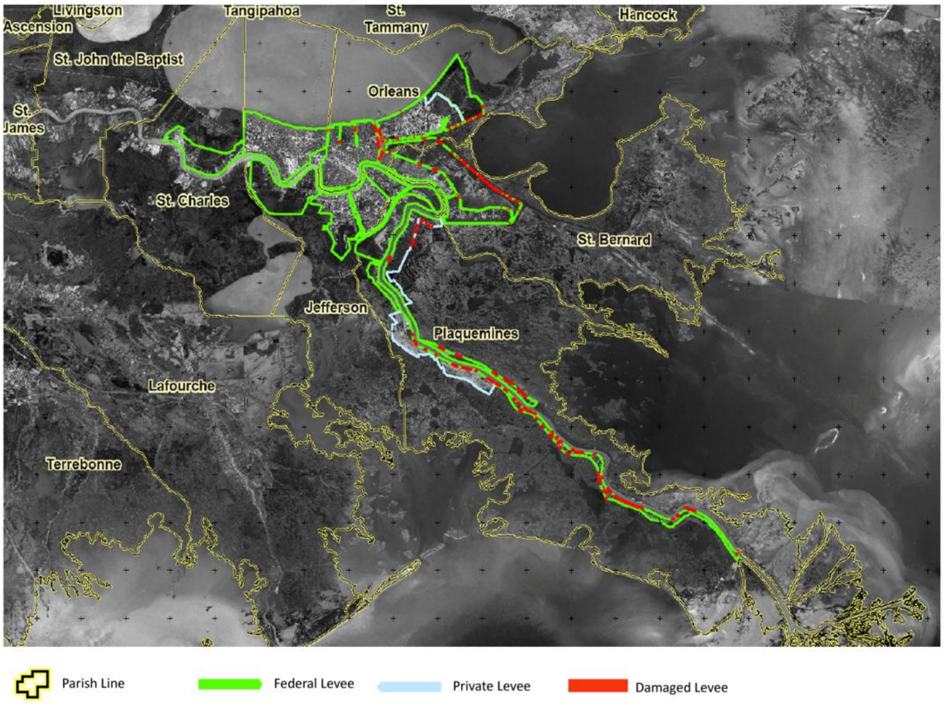


Figure 1. Damaged levees during hurricane Katrina in New Orleans and Plaquemines Parish

1.1.2 Topography and surroundings

Louisiana is like other states along the Gulf of Mexico vulnerable to flooding caused by hurricane induced storm surge. The local geography makes southern Louisiana and especially the city of New Orleans susceptible to flooding since most of the area lies below mean sea level (MSL) and the region is surrounded by water bodies like swamps, lakes, bays, estuaries, manmade canals and bayous. Also the 6^{th} largest river in the world in terms of annual discharge, the Mississippi, flows through New Orleans down to the Gulf of Mexico. Figure 128 in Annex L shows a map with the most important water bodies in South Louisiana

Mississippi River

The Mississippi river watershed covers approximately 3.2 million square kilometres, and encompasses a large part of the United States and a small part of Canada. The rain and melting water out of this region flows within the Mississippi towards the Gulf of Mexico. Before the Mississippi reaches the Gulf its splits into two branches: the Mississippi river and the Atchafalaya river.

The river has formed a large deltaic region which extends almost to the continental shelf break. The river carries a large amount of sediments and due to the disposition and erosion of these sediments the location of the bird-foot delta has shifted multiple times during the last 5 millennia (Figure 2).

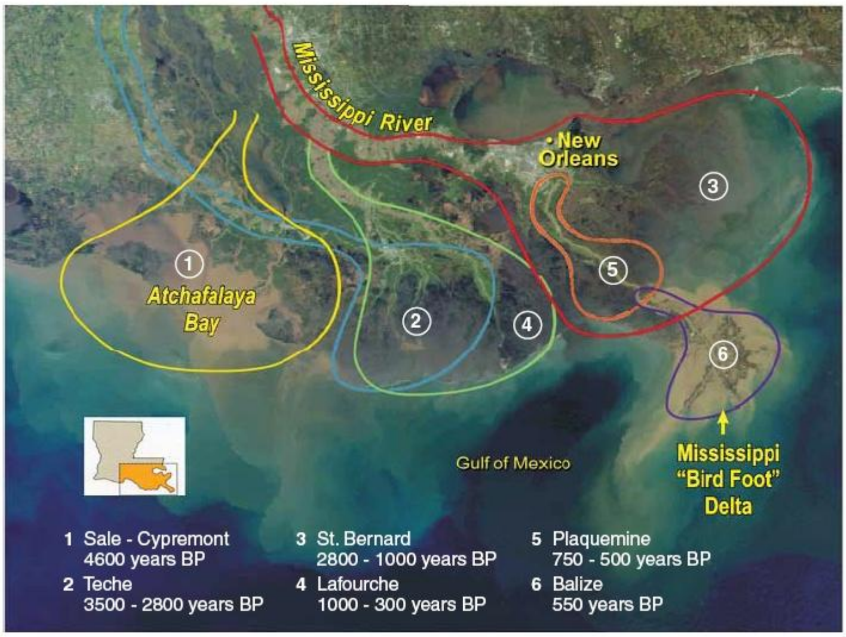


Figure 2. Several diversions of the Mississippi river over time.

Geological research has shown that the major course of the lower Mississippi river changes every 1000 to 2000 years. Remainders of the old alignments have now developed into large wetland areas (Coleman et al., 1998).

During periods of high discharges, sediments were deposited next to the river. Natural 'levees' of 1 to 2 meters were formed in this way. French settlers in the 18th century started to increase the height of these levees for their own interests. In that time landowners were responsible for their own levees. These levees could however not withstand the Mississippi flood waters and many were damaged over time which resulted in many deaths (Kemp, 1999).

In the 19th century the responsibility for the levee system was for the most part turned over to the Army Corps of Engineers (USACE). Despite criticism by experts at the time the USACE concluded that the best way to improve the flood safety in the region was to raise the levees. The levees along the Lower Mississippi were raised to 8 meter NAVD88 in 1928, 10 meter in 1940 and finally to 12 meter after the 1973 flood (Smith and Winkley, 1996) The reduction of the amount of floods due to these measures resulted in the fact that the region became very attractive to live in; this was also the goal of the national government, who considered the Mississippi delta region to be a crucial part of the United States economy.

The importance of shipping became clear when congress authorized several navigational improvements, like cut-off meanders and the construction of groins. According to Smith and Winkley (1996) these human interventions have changed the freely meandering river into a highly trained and confined meandering channel.

In 1963, the Old river control was built with the task of controlling the current discharge distribution between the Atchafalaya and the Mississippi rivers. If this structure would not be there today, the Atchafalaya River would capture the main flow of the Mississippi and the current delta would be abandoned.

A significant effect of the human interventions is that less sediment became available and that the sediment cannot be deposited into the wetlands anymore because of the levees which have been constructed over time. This shortage of sediment together with rapid erosion has resulted in a declination of the total area of wetlands in the region of about 4900 km^2 since the beginning of the 20th century, and each year an additional 100 km^2 of wetlands will be lost due to erosion. (Day et al., 2007)

1.1.3 Plaquemines Parish

The protected strip of settlements of often less than 2 km wide on both sides of the Mississippi southwest of New Orleans is known as Plaquemines Parish. Plaquemines is an administrative subdivision of the state of Louisiana and consists of the southernmost 125 km of the Mississippi river. A total of 184 km of River levees protect the parish from high Mississippi discharges and another set of levees of approximately the same length on the side of the Gulf of Mexico give some protection for hurricane storm surges. The levees protect the 30.000 people who inhabit the area as well as utilities and pipelines for the offshore oil industry in the Gulf. (Seed et al., 2008) The government is not responsible for all levees; about 61 km of Hurricane protection levees is in private control. Table 1 gives an overview of the length of the levees in Plaquemines while Figure 1 shows their location.

Table 1. Federal and Private levees in Plaquemines Parish

Length of the levees in Plaquemines (km)		
Water Body	**Federal**	**Private**
Gulf of Mexico	120	61
Mississippi river	184	0

Levees in a large part of Plaquemines breached or were overtopped by storm surge and wind waves during Katrina (Figure 1). More recently, according a local newspaper from New Orleans the Times Picayune, hurricane Ike and Gustav have both flooded parts of Plaquemines Parish again due to overtopping.

According to Seed (2008), one of the lessons to be learned from the devastation in Plaquemines Parish is that we must learn to accept that it might not be economically feasible to protect a highly exposed area like Plaquemines. Seed argues that living in such areas is unadvisable, especially with a projected rising sea level and the continuing warming of the Gulf which is expected to significantly increase the hurricane risk.

To reduce the chance for flooding in the future, new plans are being developed for Louisiana which aim at increasing the protection against hurricane storm surge to a more reasonable level. For most of Louisiana, the goal is achieve a safety level of 1:100 year. Congress authorized US Army Corps to re-build the levees for Plaquemines Parish up to the pre-Katrina authorized level. At that time, the levee elevations were designed to withstand a specific design hurricane. Based on the current insights, the flood frequency of these levee elevations is in the order of 1/25 - 1/50 years.

1.2 Problem Analysis

1.2.1 Storm Surge during Hurricanes

When Katrina approached Louisiana, Plaquemines was quickly surrounded by water from the Gulf of Mexico which then penetrated the wetland areas and reached the levees. An enormous amount of water was pushed onto the eastern levees in Plaquemines parish, blocking the flow in western direction.

Figure 3 shows the maximum water levels for Katrina. A hind cast with the ADCIRC model shows that there is a large difference in maximum water levels east and west of the Mississippi river. East of Plaquemines levees the maximum surge levels were about 4 to 6 meter (NAVD 88), while west of Plaquemines the surge was only 0.5 m in some areas.

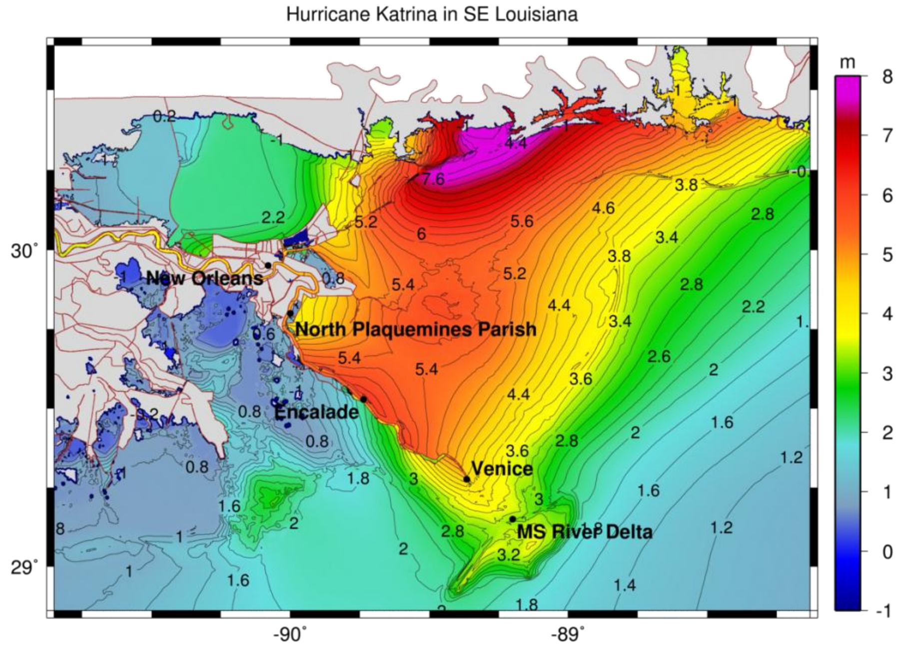


Figure 3 Computed maximum surge levels during Hurricane Katrina, note the difference between surge levels east and west of the lower Mississippi river.

Table 2. Levees West and East of the Mississippi river.

Length of the levees in Plaquemines (km)		
Water Body	**East Plaquemines (East of Miss. River)**	**West Plaquemines (West of Miss. River)**
Gulf of Mexico	54	127
Mississippi river	59	125

The length over which levees are present east of the Mississippi is much smaller than west of the Mississippi (Table 2). The levees in east Plaquemines are only present north of Encalade while in west Plaquemines they stretch all way south to Venice. The configuration of these levees, together with the fact that levees in East Plaquemines are lower than in West Plaquemines, can potentially produce another problem when a hurricane enters the area. A north-westerly directed wind pushes the water in westward direction where it is blocked by the western Mississippi river levees, the water can therefore only flow to the northwest. This principle forces the surge to propagate upriver toward New Orleans, thereby raising water levels in the city itself.

Fortunately the initial water level in the Mississippi river was low during Katrina, due to a low discharge, 4650 m^3/s. The annual average discharge is 14000 m^3/s (Walker et al., 1994). As a result, the river levees in New Orleans did not overtop. But if a Hurricane would coincide with a larger discharge these levees could become overtopped as well.

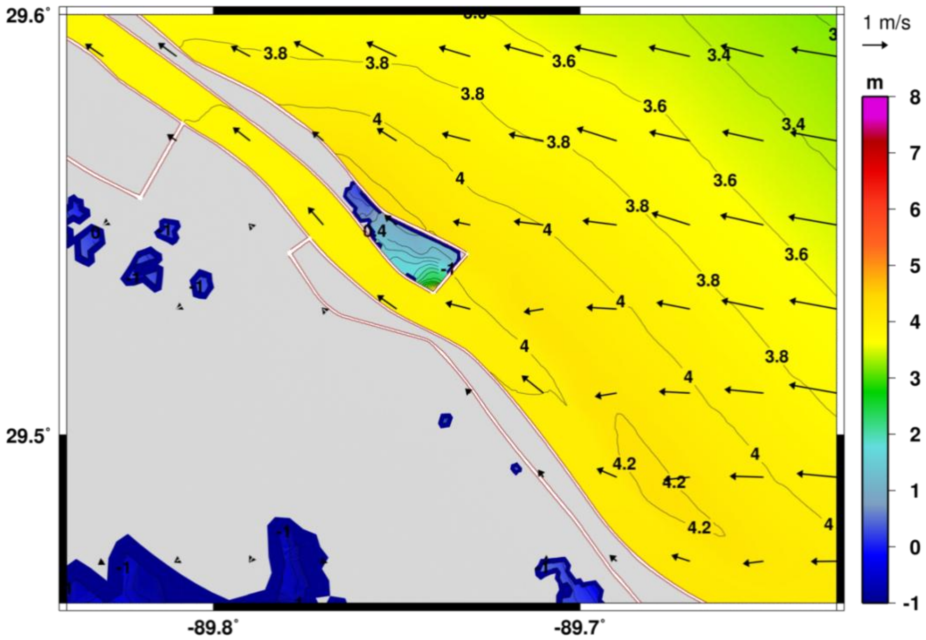


Figure 4. Storm surge elevation and flow velocities during Katrina, Brown lines indicate levees; grey areas represent areas where there is no water. On the eastern side water is pushed into the Mississippi river and onto the levees. On the Western side Katrina's wind pushes the water away from the levees.

1.2.1 Spillways

As an alternative for increasing levee heights or to simply reduce the costs of the levees for the new protection level the construction of spillways along the lower Mississippi can be considered. A spillway is defined as a lowered levee where water can flow freely from one side of Mississippi to the other side, without being blocked by levees. The creation of these spillways would lead to a larger amount of separate ring levees in the region.

The Louisiana Coastal Protection and Restoration Authority of Louisiana (short: LACPR) has done research on the effect of spillways along the Mississippi river on storm surge. This research has shown that with the creation of spillways a reduction of surge can be achieved near Plaquemines and on the river in New Orleans of more than 1 meter. (de Jong, 2007). This spillway study was however limited to one specific levee alignment.

The design of the modelled spillways was not optimal; the study recommends to investigate the effect of a fourth spillway and to consider alternative spillway configurations. Another option which has been suggested is to study the possibilities of minimizing the total length of the levees in Plaquemines. This would mean that only levees would remain around some of the existing settlements.

1.2.2 ADCIRC model

For the LACPR research the ADCIRC SL15 model with a time step of 1 second was used. This model uses high performance parallel computing environments to calculate flows and water levels in coastal regions and in oceans. The SL15 model produces very accurate results when it is compared to measurements from Katrina and Rita (Westerink et al., 2008a).

Although this model produces good results the use of it also has a downside. Due to the size of the computational grid, approximately 2 million nodes, it can only be run on a supercomputer. For the Interagency Performance Evaluation Task Force studies (IPET, 2007) and for several other storm surge studies either a supercomputer from the Army Corps of Engineers (USACE) or from the University of Texas was used. These computers all have multiple processors and split the work load between 256 nodes.

For FEMA a hurricane storm set of 152 storms has been developed which captures a range of different storms that might hit the Louisiana coast in the future. 152 simulations have been performed and they have produced a statistical distribution of water levels at different locations. The LACPR report has used 18 of these storms for the spillways study.

Model sensitivity studies often require a large number of model runs, the need to use a supercomputer and the costs which are accompanied by this make it difficult to perform these types of studies, especially if the model runs have to be performed for a multitude of storms.

An Apple G5 cluster at the University of Notre Dame with 128 nodes is however available to perform further study on the Plaquemines Spillways. The use of the standard ADCIRC SL15 model on this computer would take a very long time and therefore it is desirably to search for ways by which the speed can be improved or the amount of model runs can be reduced.

1.3 Problem formulation

From the description above a problem can be defined.

Improving levees in Plaquemines Parish and New Orleans to a protection level of 1:100 year is very expensive. Research has shown that spillways in the Lower Mississippi River levees might be effective in reducing storm surge and that hereby the costs for levees could be reduced; the influence of different levee alignments on storm surge remains however unknown and the hydraulic effectiveness of the spillway configuration which was studied within the LACPR report was not optimal. An Apple G5 cluster is available to investigate more spillway configurations but due the computational burden of the standard ADCIRC SL15 model and due to large number of possible hurricanes in the region it is difficult to study multiple alignments within reasonable time while maintaining accurate results.

1.4 Research Objective

For this thesis the following objective can be defined:

The objective of this study to gain insight in the influence of multiple spillway alignments along the lower Mississippi river on the capability to reduce storm surge during hurricanes, by adapting the ADCIRC model to improve the balance between model speed and model accuracy.

1.5 Research questions

Based on the problem definition and the research objective four main research questions have been defined.

1. *How can the ADCIRC model be adapted in order to obtain a good balance between model accuracy and model speed considering the fact that multiple levee configurations need be studied within a limited amount of time? (chapter 2)*
2. *How does the adapted model perform with respect to the Katrina measurements and the other ADCIRC models? (chapter 3)*
3. *Which storms should be modelled in order to give an indicative overview of potential effects of spillways on the maximum surge levels near Orleans, St. Bernard, Jefferson and Plaquemines Parish? (chapter 4)*
4. *Which factors are important for determining spillway configurations and what are the quantitative effects of the selected spillway configurations on the maximum storm surge levels during hurricanes near Orleans, St. Bernard, Lafourche, Jefferson and Plaquemines Parish? (chapter 5)*

1.6 Scope and study area

1.6.1 Scope

The LACPR study created spillways by removing levees at certain locations; in addition to that the natural river banks were also lowered in order to improve the hydrodynamic connection between both sides of the Mississippi River. So when new spillway configurations are to be defined, there are two aspects which can be altered:
- The length/location of the spillways.
- The elevation of the spillways.

This study focuses on the effects of spillways on water levels during hurricanes, so both properties of the spillways will be investigated.

Besides maximum surge levels other subjects are also important when determining the potential benefits or negative aspects of spillways. Some examples of these subjects are:
- The influence of the spillways on navigation on the Mississippi River during low flow stages;
- The influence of spillways on the growth/erosion of the wetlands.
- Flood protection in case of high riverine discharges;
- Salt intrusion in the delta;
- Economic development in the region.

It is recognised that these other subject are also important but they will not be included in this study.

1.6.2 Study Area

The spillways which will be studied during this study are located in Plaquemines Parish. The effects of these spillways on storm surge will however also influence water levels elsewhere. This study will focus on maximum water levels close to the levees of the following protected areas:

- Plaquemines Parish;
- South and East of St. Bernard Parish;
- Orleans Parish on the Mississippi River;
- Jefferson Parish on the Westside of the Mississippi, often referred to as the West Bank.
- Lafourche Parish

These protected areas are displayed in Figure 5.

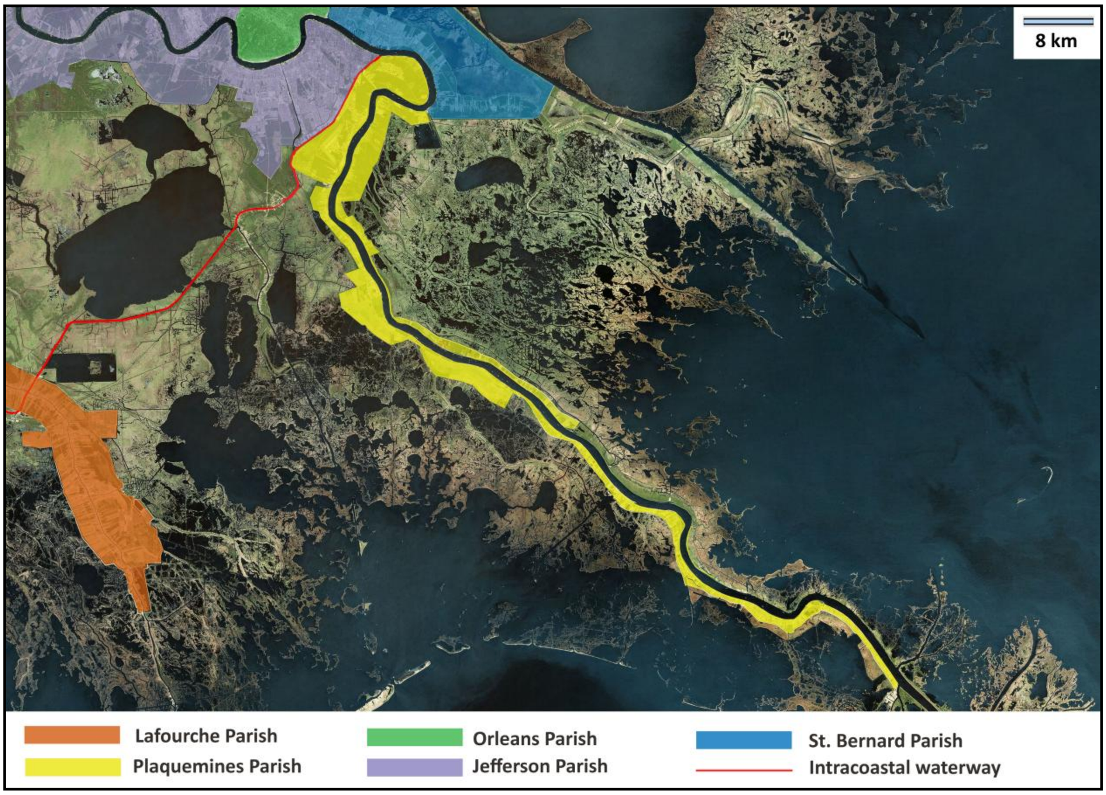


Figure 5. Protected regions within the Study Area (Satellite image acquired from Microsoft Virtual Earth™,2008)

2 STORM SURGE MODELING

The main research question which will be answered in this chapter is:

How can the ADCIRC model be adapted in order to obtain a good balance between model accuracy and model speed considering the fact that multiple levee configurations need be studied within a limited amount of time?

First some theory about storm surges and the ADCIRC model will be presented. This will be done according to the following questions:

- Which physical processes contribute to the formation of storm surge? (section 2.1)
- Why has the ADCIRC model been chosen for this study? (section 2.2)
- What are the main properties of the ADCIRC model? (section 2.3)
- What are the computational requirements for ADCIRC? (section 2.4)

Simulation time can be reduced in a number of ways. One of the methods in which this can be achieved is by selecting a computational grid with a limited amount of computational nodes; the selection of a suitable grid will be carried out in section 2.5. Another way in which to reduce calculation time is to analyse the common ADCIRC modelling strategy and to adapt this strategy in several ways, this will be explained in section 2.6. In section 2.7 the main research question will be answered and this chapter will be concluded with a discussion.

2.1 Storm Surge

Storm surge is the abnormally high water level which can occur during a hurricane. Storm surge has a period and length roughly the same as those of the generating storm (Holthuijsen, 2007). To select an appropriate storm surge model for this study it is necessary to understand the importance of the different processes that determine storm surge. In case of Louisiana the two most important factors that determine the water levels are the wind and the local geometry (IPET, 2007). At the boundary between the water surface and the atmosphere wind friction causes water to flow in the direction of the wind. The effect of wind on surge is largest in shallow water, so storm surge is also highly dependent on local geometry within a region.

Other factors that also contribute to the formation of storm surge are wave set-up due to breaking waves, the Mississippi river discharge, atmospheric pressure within a hurricane, astronomical tides and precipitation. The estimated contribution of the various processes to the storm surge during Katrina is given in Table 3. The contribution of the Mississippi river discharge was limited during Katrina because of a low river discharge of 4640 m^3/s. This contribution could potentially be higher in case of high water levels in the Mississippi river. The effects of the wind together with the local geometry exceed the combined effects of all the other factors. A physical description of all processes can be found in annex B.2.

Table 3. Estimated contribution of various processes to storm surge in southern Louisiana during Katrina (IPET, 2007)

Process	Estimation of the contribution to storm surge during Katrina
Wind and geometry	5 to 6 meter
Breaking wind-waves	up to 0.6 m

Mississippi river discharge	0.3 to 0.9 m
atmospheric pressure	0.3 to 0.6 m
astronomical tides	0.15 to 0.45 m
precipitation	up to 0.30 m

2.2 Hydrodynamic Models

By creating spillways the local levee alignments in Plaquemines will be altered. To determine the effects of various spillway alignments it is important to select a hydrodynamic model which is capable of simulating the processes mentioned in Table 3. Since by creating spillways the local geometry will be altered and since the local geometry together with the wind forcing has the largest influence on the total surge it is essential to use detailed bathymetries and correct representations of the geometry in the region. The use of a Finite Element model with an unstructured grid enables modelling of small geographical features while minimizing computational costs.

The processes that lead to the build-up of surge against the levees in Plaquemines Parish are complex. In the past storm surge predictions heavily relied on observations and on simple relationships between measured data. Since reliable measurements are rare and the amount of potential hurricanes is very large, these old methods lack the accuracy which is needed to properly predict storm surge events. The use of these old methods was one of the reasons why New Orleans was not prepared for a Hurricane like Katrina (Resio and Westerink, 2008).

Nowadays computational models are used to predict surge events. Early computational models often used structured grids where the domain was limited to the continental shelf. The locations of the continental shelf in the Gulf of Mexico are presented in Figure 6. According to Westerink (2008b) a limitation of a model to the continental shelf alone will underestimate surge predictions. Structured grids are also relatively coarse and this may lead to storm surge over-prediction because local geographic and topographic controls cannot be distinguished properly within the model. Another downside of models with a domain limited to the continental shelf is that the model performance heavily relies on local calibrations, these early computer models were tuned for specific historic storms with specific boundary conditions. Because the forces that drive storm surges are very different for each hurricane, and therefore the boundary conditions are also diverse, the applicability of these regional models is limited.

Decision makers are interested in tools which can help to determine levee heights, or which can support decision making in case of a potential evacuation during an approaching storm. The new advancements in computer technology in the last decade have created new opportunities for these decision makers because of the possibility to use a different modelling strategy. This strategy incorporates the use of Finite Element methods with a larger domain, higher grid resolution to capture local features and more straightforward boundary conditions so it can be used for other storms then historical storms. Annex C.1 gives an overview of the differences between structured and unstructured models.

Figure 6. Bathymetry and topography of the Gulf of Mexico region. Light blue colors indicate the location of the continental shelf; dark blue areas are deeper regions. The red dot indicates the location of New Orleans.

Several Finite Element hydrodynamic models with unstructured grids are able to model most of the processes mentioned earlier. Various storm surge studies for Louisiana have used the ADCIRC model to determine surge elevations and flow velocities (de Jong, 2007; IPET, 2007; Westerink et al., 2008a). ADCIRC is the standard storm surge model used by the USACE. These ADCIRC models have already been calibrated and validated and are available for use. This gives the ADCIRC model a significant advantage over the other models although ADCIRC also has some disadvantages. ADCIRC can for instance not model precipitation and to simulate the effects of breaking wind waves the separate wave model STWAVE is often used. Currently the ADCIRC model is being coupled with the SWAN wave model by researchers at the University of Notre Dame and at Delft University of Technology (personal communication with Casey Dietrich, 2008). A fully functional coupled version of ADCIRC and SWAN was not yet available for this study. A comparison with other hydrodynamic models and a clarification of the choice for the ADCIRC model can be found in annex C.2

2.3 ADCIRC Model properties

2.3.1 Numerical solution

ADCIRC uses an unstructured finite element (FE) based method to solve the shallow water equations. Early unstructured FE models needed artificial dampening because the solution algorithms created spurious modes; dual wavelengths were generated for one wave frequency (Dresback et al., 2005). In the past 20 years four numerical solutions have been developed which are at least second order accurate in space and do not create these non physical waves. These are the Generalized Wave Continuity Equation (GWCE), the Quasi-Bubble formulation; the Raviart-Thomas based solutions and the Discontinuous Galerkin Method (Westerink et al., 2008a).

Lynch and Gray (1979) introduced the Wave Continuity Equation. Kinmark added a numerical parameter G to the equation which improved the propagation characteristics of the solution, this numerical solution is known as the Generalized Wave Continuity

Equation (1984). ADCIRC uses the GWCE solution to calculate flow velocities and water levels. The governing ADCIRC continuity equation in its non-conservative form and the momentum equations for a spherical coordinate system are given in annex D.1. The discretization and solution techniques of the ADCIRC 2DDI model are discussed in detail in Luettich et al. (1992) and Westerink et al. (1992)

2.3.2 Model domain

The evolution of the ADCIRC model for Louisiana has led to multiple computational grids or meshes. As computational power increased over time, the availability of geographic data improved, and new storm surge measurements were collected, the accuracy of the model was enhanced. New data from Ike and Gustav and new Mississippi river measurements are today being used to further improve the grid. The selection of an appropriate grid for this study is explained in section 2.5.

What all these grids have in common is that the domain incorporates the Western Atlantic Ocean, the Gulf of Mexico and the Caribbean Sea. Figure 7 shows a typical ADCIRC model domain. The primary reason to use this large domain is that simple boundary conditions can be used .The boundary is dominated by the astronomical constituents, nonlinear energy is limited due to the large depth and the boundary is not located near tidal amphidromes or within a resonant basin like the Gulf of Mexico (Westerink et al., 2008b). In southern Louisiana the boundary lies inland so that overland flow can be simulated. Detailed plots of the grid can be found in annex

Within the grids, approximately 85% of the computational nodes are located in Louisiana and Mississippi, so the computational overhead due to this large domain is only about 15%.

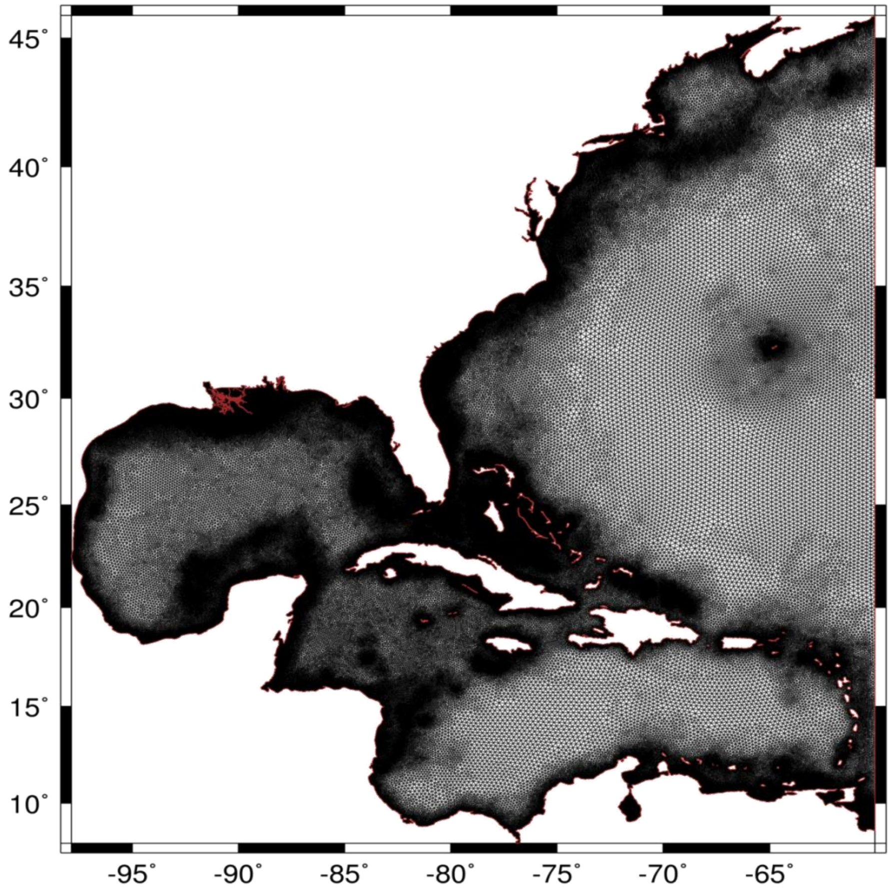


Figure 7. Computational domain of the modified SL15-light ADCIRC model. The brown lines indicate sub grid features and boundaries.

All significant levees and (rail)roads are included in the model. Because they cannot be captured in the grid due to their scale they are modelled as sub grid features. At these barriers large vertical accelerations can occur. ADCIRC uses basis weir formulas to calculate flows over these barriers (Westerink et al., 2001). These weir formulas are also used at external boundaries where water is allowed to flow out of the computational domain in case of overtopping of levees. A wetting and drying algorithm is used to allow regions flood within the domain. Figure 8 shows the location of the sub grid features near Plaquemines and New Orleans as well as the bathymetry of the area.

To capture momentum diffusion and dispersion due to unresolved lateral scales and to account for the effects of depth averaging a spatially variable horizontal eddy viscosity is used (Westerink et al., 2008a).

2.3.3 Riverine and tidal forcing

The ADCIRC models for coastal Louisiana are able to model the tides. The eastern boundary in the Atlantic Ocean is forced with the K1, O1, M2, S2, and N2 tidal constituents. ADCIRC interpolates tidal amplitude and phase from Le Provost's Finite Element Solutions global tidal model (Le Provost et al., 1998). To properly model the resonant behaviour of the Gulf of Mexico the model must be run for 18 days prior to hurricane forcing to create a correct tidal response.

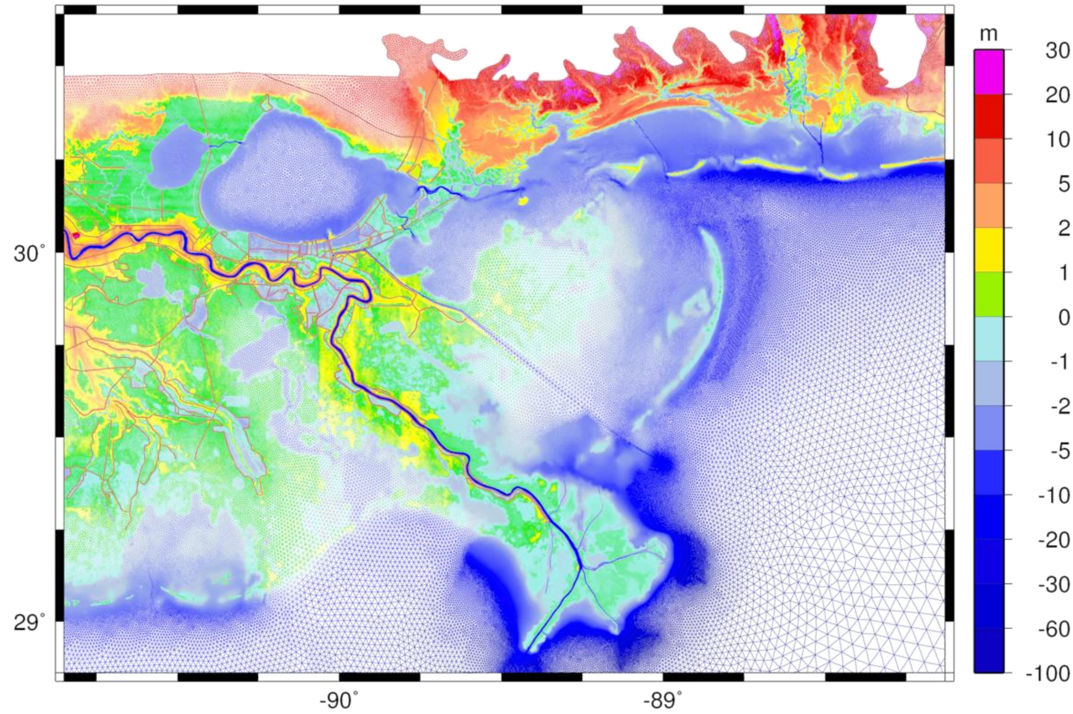


Figure 8. ADCIRC grid in Southern Louisiana with the corresponding bathymetry/topography. Brown lines indicate levees, (rail)roads and other sub grid features.

The ADCIRC models in Louisiana incorporate the river flow in the Mississippi river as an external flux boundary. In some of the models the discharge of the Atchafalaya river are also modelled Figure 8 shows the vicinity of New Orleans as it is included in the ADCIRC model.

2.3.4 Roughness

Roughness plays an important role when modelling hurricane storm surge. Friction takes place at two boundaries, the boundary between the water and the bottom, and the boundary between the air and the underlying surface.

ADCIRC uses a hybrid friction relationship for the water flow friction. It uses a Manning type friction law for depths lower than the wave breaking depth and a Chézy friction law in places outside the wave breaker zone. The Manning n values for the New Orleans area and are displayed in annex G.2.

In the case of air flowing over a rough surface, the wind at 10 meters above ground level is used to compute the surface drag. Two types of wind models are used to produce wind speeds that force the ADCIRC model, these are the H*Wind and the PBL models. The H*Wind model uses measured data from historical storms to calculate the reference wind speeds and the PBL model uses hypothetical input parameters like the minimum central pressure within a hurricane, the maximum wind speed and the storm location to determine the 10 meter above ground wind speeds.

The wind models which produce the wind speeds used in ADCIRC assume open ocean conditions. Over land however the friction is generally higher and the wind speeds will therefore be smaller. To compensate ADCIRC uses formulations which take into account the land use of an area, such as urbanized areas, forests or marshlands. A storm and the accompanying wind speeds do not adjust instantaneously when another surface type is encountered. When wind is for example blowing offshore towards the sea, the roughness value is smaller on the ocean compared than on land, but it takes some distance for the wind in the boundary layer to adjust to the new roughness conditions. Therefore ADCIRC uses directional roughness coefficients in 12 directions to accommodate for the change in winds speed caused by changes in upwind roughness. These directional roughness coefficients from 2 wind directions are presented in annex G.2.

When inundation in an area takes place, roughness caused by forests and vegetation will slowly reduce as the roughness elements are submerged. ADCIRC computes a wind reduction factor to take these effects into account.

In some areas the wind cannot penetrate the roughness elements and no momentum will be transferred from the wind to the water column. This can be the case in heavily forested canopies. Hence, no wind stresses are applied at the water surface in these areas (Reid and Whitaker, 1976). These areas are displayed in G.3.

2.4 Computational requirements

As mentioned in the previous section it is necessary for the models to have sufficient resolution to capture the physical processes correctly. The ADCIRC grid with the least spatial detail for Louisiana has approximately 316 thousand computational nodes, the most recent and best performing model in terms of surge prediction has 2.4 million nodes. To accommodate for the high spatial resolutions the use of a small time step is required since a Courant, Friedrichs, Levy parameter less than 0.5 is desired when running the ADCIRC model (Courant, 1967; Westerink et al., 2008a). Due to these reasons hurricane storm surge modelling is not possible on a normal desktop or laptop computer, as a result the use of supercomputers is required.

Storms surge studies which have been carried out by the USACE and the University of Notre Dame have used high performance parallel computers at the University of Texas at Austin or at the Army MSRC Engineer Research Development Centre in Vicksburg (University of Notre Dame, 2007). The IPET, LACPR and FEMA studies were carried out on these computers, for these studies 256 computational cores were used.

For the purpose of this study an Apple G5 cluster is available which is located at the University of Notre Dame; this supercomputer has 64 processors with 2 compute cores each, 36 GB of aggregate memory and 5 TB of total disk storage (see Figure 128.)

Apple G5 Dual-Core Xserve Compute Cluster	
Processors	64 dual G5 processor compute nodes (128 cores)
Aggregate memory size	36 GB
Disk Storage	5.0 TB
Network	2x64 port 1GB Ethernet Cisco switches

Figure 9. Apple G5 Dual-Core Xserve Compute Cluster with 128 Compute Cores (codename: Athos) at the university of Notre Dame, image courtesy University of Notre Dame

The final goal of this study is to gain insight in the influence of different spillway alignments along the lower Mississippi river on the capability to reduce storm surge during hurricanes. Previously it has been discussed that for this goal it is necessary to conduct a large number of models simulations since numerous levee configurations will be studied for various hurricanes.

Even if supercomputers are used it can take a long time to for a model run to finish. The SL15 model grid has 2.137.978 nodes and 4.184.778 elements and uses a time step of 1 second. On the above mentioned supercomputers in Vicksburg and in Austin it takes 1.08 wall-clock hours to perform one day of simulation time (Westerink et al., 2008a). Since the number of nodes on the Apple G5 cluster is smaller and also the computer clock speeds are lower it is expected that a day of simulation time on the Apple G5 cluster with the same grid will take considerably more time. Details on the performance of the Apple Cluster with the SL15 model are not available since the cluster has never been used with a model of this size.

2.5 ADCIRC grid selection

In order to reduce the calculation time it is best to select a computational grid with a small number of nodes. But for the accuracy of the model a larger number of nodes is desired. A numerical convergence study by Blain et al. (1998) has shown that under resolution on the continental shelf leads to significant over prediction of the storm surge, and that under resolution in deeper areas will lead to an underestimation of the storm surge. So a model has to be selected which is both fast enough to run on an Apple G5 cluster and also produces reliable data. A balance needs to be found between model accuracy and model speed.

This section will answer the following questions:

- Which ADCIRC grids are available for this study? (Section 2.5.1-2.5.4).
- Which ADCIRC grid provides the best balance between speed and accuracy?

First four different available ADCIRC grids are discussed. Looking at both performance and speed the decision has been made to create a fifth grid. This grid is based on one of the existing grids but some enhancements have been applied in the Mississippi delta region. At the end of this section this choice will be further explained.

2.5.1 S08 grid

Several grids have been developed for coastal Louisiana. One of the early grids was the s08 grid. This grid has 316 thousand nodes and 602 thousand elements (Table 4). It has been validated with measurement data from hurricane Andrew and hurricane Betsy. The linear regression coefficient which is a measure of the accuracy of the model (R^2) was found to be 0.804 (Annex F.1.1) Westerink et al. (2008b) states that model errors appear to be associated with regions where the bathymetric and topographic data are sparse and with regions where raised features had not been included in the model. Among these areas is Plaquemines Parish.

Table 4. Number of nodes and elements for various grids.

Grid	Number of Nodes	Number of Elements
S08	316.240	602.765
SL15	2.137.978	4.184.778
SL15 version 7	2.401.238	4.704.701
IHNC	951.507	1.845.775
Modified IHNC	1.193.926	2.329.641

2.5.2 SL15 grid

The SL15 grid has been used to determine the 1:100 year water levels for New Orleans (IPET, 2007). It was also the base grid for the LACRP spillway study (de Jong, 2007) and the FEMA insurance study (Westerink et al., 2008a). The SL15 grid is an evolution of the S08 model. The detail of the mesh has been greatly increased and the model accounts for 2.137.978 nodes and 4.184.778 elements.

In general newer ADCIRC models have a more detailed bathymetry/topography and more computational points. The developers of the ADCIRC model use physical parameters as input for the models and only calibrate by changing or adding nodes to the model or by adapting the formulas for the physics within the model. It could happen that for a particular hurricane a better hind cast could be achieved when e.g. Manning n values were changed. Although these local changes could potentially catch other modelling deficiencies and improve the results, the reason for these improvements would not be clear. Westerink states that it is important to make sure that the model is in fact correctly simulating the physics, so that there will also be confidence in the results in case of different storms for which the model has not been calibrated. So while the grid was improved over time, more computational nodes were added and the computational requirements increased as well. When the computational time required for a model run is assumed to be linear to amount of nodes, a simulation with the SL15 would take approximately 8 times longer than a similar run with the S08 model.

The SL15 model has been validated with data from Hurricane Rita and hurricane Katrina. High water marks collected during Hurricane Katrina have been compared with the modelled elevations for the IPET study. For this a dataset is used which has been collected by the USACE, the average absolute error was 45 cm and the square of the correlation coefficient (R^2) between the observed and the modelled data values was 0.931. Previous large modelling studied like the FEMA and LACPR studies have selected the SL15 model over the S08 model due to the improved results.

2.5.3 SL15 version 7 grid

The SL15 version 7 model is an updated version of the SL15 model. The major change in the SL15 version 7 grid consist of an updated bathymetry and resolution near the Mississippi bird foot delta, this was considered necessary to improve the results within the Deltaic region.The SL15 version 7 model is at this moment still under development by people for the Computational Hydraulics group at the University of Notre Dame. The grid is being developed with the goal of validating the SL15 model for riverine discharges, tides and surges in the Mississippi River and Delta and the Atchafalaya River and Delta. The study also focuses on the influence of high riverine discharges on surge levels propagating up these rivers and through their distributaries (University of Notre Dame, 2008). Since this study is still underway no definitive performance values can be presented here, but it is expected that this model will better represent the storm surge in the Mississippi river and in the deltaic region where the spillways would be located.

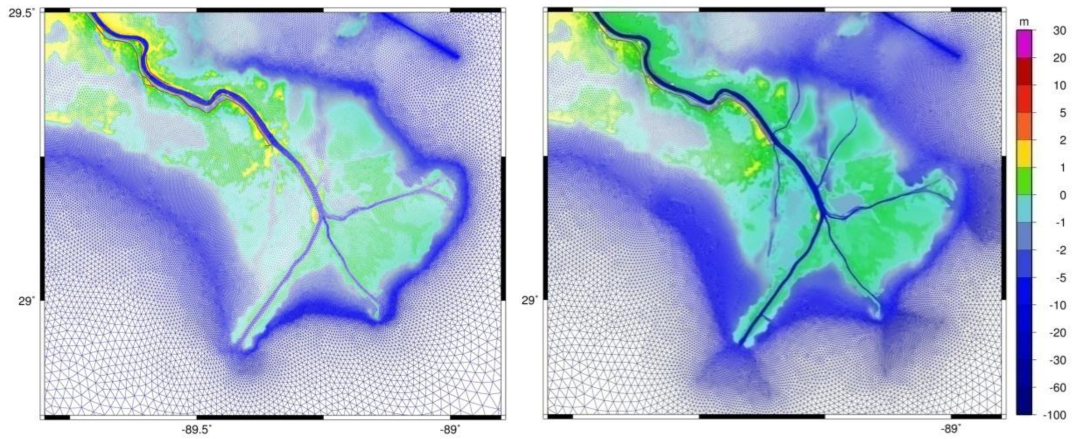


Figure 10. (left) Bathymetry (m NAVD) and computational grid in the SL15 model. (right) Updated bathymetry and computational grid in the SL15 version 7 grid.

2.5.4 IHNC grid

The IHNC model is based on the SL15 model and was developed to allow the Hurricane Protection Office (HPO) to simulate the effects of many new structures within the Inner Harbor Navigation Canal (IHNC). With this model the computations can be done much more quickly than with the full-scale SL15 model. The IHNC grid was created by coarsening the grid in places which were of less interest for this study. Figure 11 shows the location where this coarsening took place. The IHNC grid is also known as the SL15 Light grid.

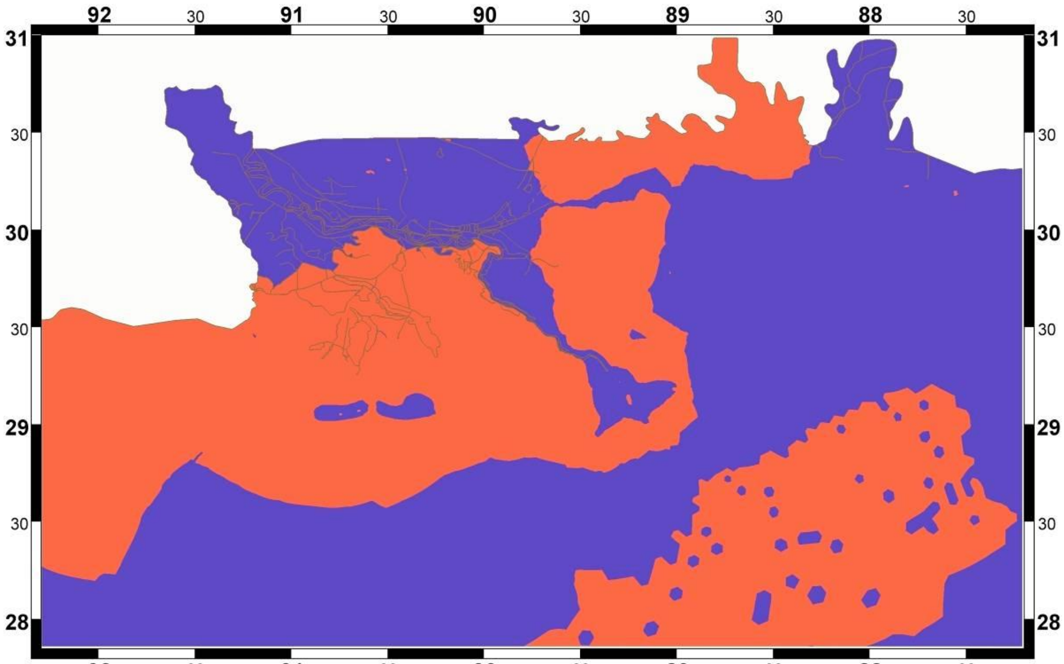


Figure 11. Nodes in Southeastern Louisiana that are identical in both the SL15-IHNC and the original SL15 grid are shown in blue, Nodes in areas that have changed from the original SL15 grid are shown in red. Image courtesy: (Bender et al., 2008)

A validation study of the IHNC grid has been carried out and this study showed that on the east side of Plaquemines there were little to no changes in maximum water level elevations compared to the full-size SL15 model. The IHNC grid has not been validated with historical storms so no correlation coefficients which compare the model results with measured data are known. Instead hypothetical storms have been used to compare the results of the IHNC grid with the results from the SL15 grid.

The validation study by Bender et al. showed that southwest of Plaquemines Parish there were water level differences up to 50 cm between the IHNC grid and the SL15 grid (Bender et al., 2008). These differences have arisen due to the coarsening of the grid in these locations.

2.5.5 Modification of the IHNC Grid

This section will answer the question which grid would provide the best balance between model speed and model accuracy.

In order to perform this research the possibility of reducing the model to a size which would make it possible to run on a normal computer has been explored. A model which can be used on a laptop or desktop computer could have a maximum amount of nodes in the order of 10.000 to 100.000, depending on the chosen time step and the maximum desired runtime. Current models which are used for storm surge modeling have far more computational nodes and therefore use parallel computing environments. A study on the s08 model shows that even for this model (316.000 nodes) the results are not optimal; it is therefore unlikely that reliable results can be expected when the size of the model is reduced to a practical size for a laptop computer.

A model which performs better is the SL15 grid. This model would however also not be ideal for this study on the Plaquemines spillways since a single 7 day hurricane run with a time step op 1 second would approximately take 60 hours to complete on the Apple G5 cluster.

Like the S08 grid the IHNC grid also had significantly less nodes than the SL15 model, but this model still has approximately 3 times more computational points than the S08 model. Although this grid was not specifically designed for Plaquemines it does seem to produce similar results on the eastside of the Mississippi river when it is compared with the SL15 model. On the southwest side of Plaquemines near the bird-foot delta differences of up to 50 cm show. It would take approximately 28 hours to complete a seven day hurricane simulation with the IHNC grid.

The s08, the SL15 and the IHNC grid are not validated for the propagation of storm surge onto the Mississippi river. This validation for surge and riverine flow is currently being conducted by the computational hydraulics research group at the university of Notre Dame. Preliminary results indicate that by increasing grid resolution in the bird-foot delta the river processes are captured better (Personal communication with Joannes Westerink, 2008).

All things considered, in order to get the best balance between model speed and model accuracy it is best to use a grid with enough resolution in the Mississippi Delta , while the grid has less resolution in less important areas of the model domain. Therefore this study will use a modified version of the IHNC grid. The IHNC grid already uses less computational nodes in less important areas compared to the SL15 model and provides similar results in most areas compared to this model.

In order to improve results specifically in the bird foot delta and near Plaquemines Parish the IHNC grid has been modified to include a more detailed bathymetry and topography of these areas. The grid from the bird-foot delta region has been copied from the SL15 v7 model into the IHNC grid, this resulted in a new grid with 2.329.641 elements and 1.193.926 nodes. Figure 12 shows the grid sizes of the INNC grid and the modified IHNC grid in m. This figure shows that the distance between the computational nodes in the bird-foot region is decreased in the modified IHNC grid. Grid sizes vary in this region from 50 meter within the river to 5000 meter in the Gulf of Mexico.

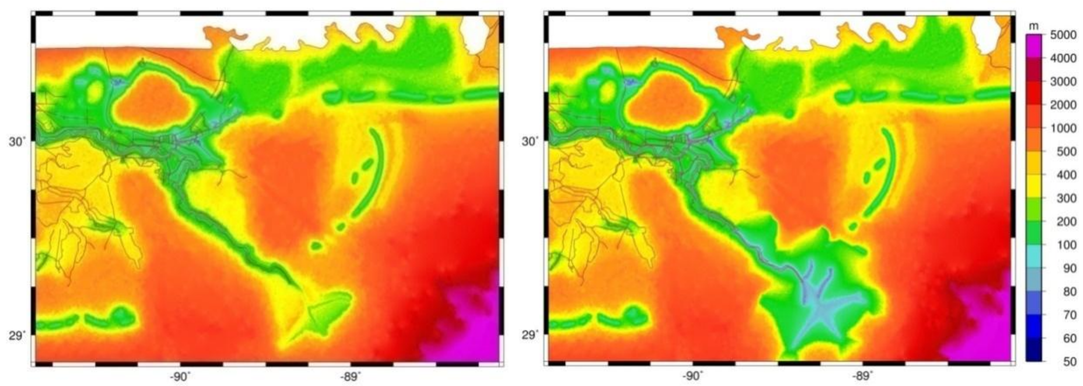


Figure 12. (left) Grid spacing in the IHNC grid (m), (right) Grid spacing in the modified IHNC grid (m).

The modification of the IHNC grid has led to an increase of approximately 250.000 nodes compared to the original IHNC grid. The amount of time needed to perform a model run is therefore still considerable. It is estimated that it would still require 34 wall clock hours on the Apple G5 cluster to complete a single run. Therefore some other modifications are desired in order to reduce computational time further. These modifications to the common ADCIRC modelling strategy will be discussed in the next section.

An alternative approach to the modification of the IHNC grid would be to increase the resolution of the S08 model at the important areas in order to improve the accuracy of the model. Such an approach would however take longer to perform and has therefore not been selected.

It should be noted that this modified IHNC grid has only been used as a base grid for all simulations. Each levee/spillway configuration requires a separate grid since the new subgrid features (levees) need to be incorporated into the mesh.

2.6 Modeling strategies

To be able to perform the storm surge simulations the calculation times need to be reduced further. First the modeling strategy for the recent FEMA and LACPR studies will be explained (section 2.6.1), this is necessary to determine how the calculations time can be improved. Section 2.6.2 gives an estimation of the run times on the Apple G5 cluster if the same modeling strategy were to be applied. Section 2.6.3 will present the new modeling strategy as it has been applied throughout this study.

2.6.1 FEMA/LACPR strategy

Figure 13 shows the strategy of the FEMA flood insurance study (Westerink et al., 2008a). The goal of using ADCIRC for that particular study was to calculate water levels with a return period of 1:100 years for all locations in south East Louisiana; maximum storm surge elevations for a total of 152 storms were calculated and were used as input for a statistical model (step 6). These water levels are then again used to calculate the desired levee and floodwall elevations, as well as to determine overtopping behavior (Step 7). Water levels from ADCIRC are used as input for the statistical model.

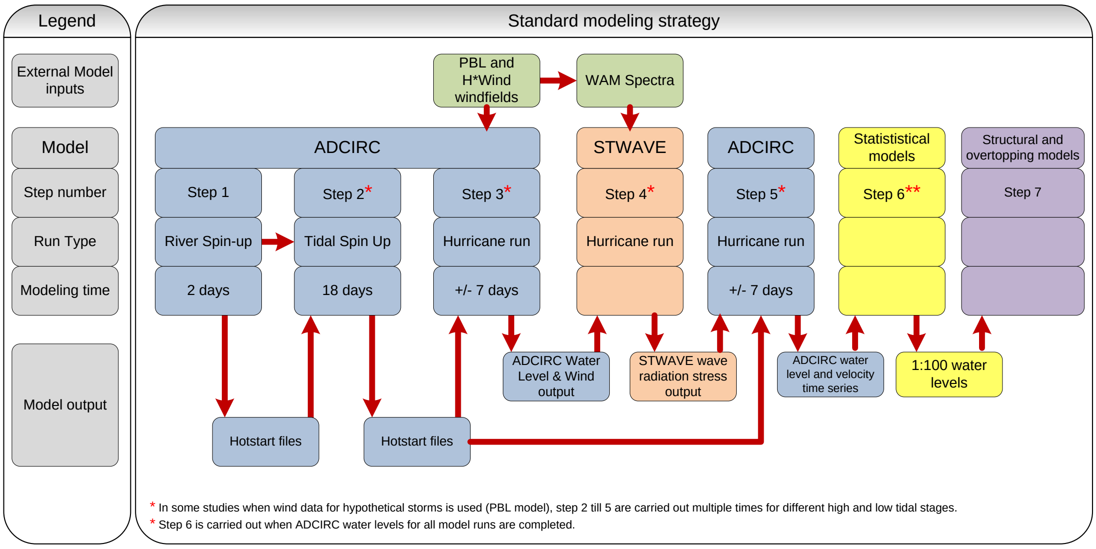


Figure 13. Modeling strategy for the FEMA and LACPR projects

The Apple G5 cluster is estimated to take approximately 4 hours and 50 minutes of wall clock time with a 1 second time step to compute one day of hurricane simulation with the modified IHNC grid, so for a normal 7 day hurricane simulation it will take approximately 34 hours to complete, this 7 day hurricane run is indicated in the figure above as step 3 only. Additional to this 7 day hurricane simulation additional steps are taken.

- ADCIRC starts with a river spin up simulation of two days (+/- 9 wall clock hours). This spin up run is needed to stabilize the radiation boundary forcing function of the Mississippi river.
- When the river spin up has completed the tidal forcing will be started. The length of the Spin up run is 18 days, (+/- 86 hours wall clock time). This spin-up run lets the model adjust to the tidal forcing functions so a proper tidal response in the resonant Gulf of Mexico basin can be established (Westerink et al., 2008b). The tidal spin up run will in most cases only be performed for historical storms and not for hypothetical storms.
  When historical storms are simulated a specific landfall time is known, the timing of the hurricanes landfall can thus be set. Hypothetical hurricanes can occur

during ebb tides as well as during flood tides, the specific timing of a hypothetical storm is arbitrary when PBL winds are used (hypothetical storms) each run (step 3 till 5) is carried out three times, each with a different steric water level adjusted to a high, low or medium tidal water stage. Step 2 is thus not carried out for hypothetical storms; instead step 3 till 5 are carried out multiple times.
- The riverine and tidal spin-up simulations do only have to be carried out once for every grid. This is because after step 1 or 2 ADCIRC writes output in the form of hotstart files. Hotstart files can later be used as an initial condition for new ADCIRC simulations. The benefit of using hotstart files becomes clear when multiple hurricanes are simulated for one single grid. The hotstart files can be used as an initial condition for multiple hurricane runs.

In section 2.2 it had already been mentioned that currently wind waves are not included in the ADCIRC model itself, therefore boundary friction between the water surface and the air due to wave action is neglected, also wave set up is not integrated in the model itself. This lack of wind wave modelling is partly resolved by using the external STWAVE model to calculate wave setup.

Therefore additional steps need to be taken:
- First, ADCIRC is run without wind forcing (step 3) to calculate water levels, these water level are written to the hard drive.
- Subsequently these water levels are used as input for the wave model (step 4). The wave model calculates the wave radiation stresses.
- The output from STWAVE is then as a final step used as input for another ADCIRC model run (step 5). The hurricane ADCIRC simulation is thus carried out twice, one time with and one time without wave forcing.

2.6.2 Total required time

If the strategy from Figure 13 were to be applied to this study on the Plaquemines spillways the time which would be required to perform the model runs with historical storms would be as follows:

For each different spillway configuration;
- A river spin-up run is needed (2 simulations days)
- A tidal spin up run would need to be performed (18 simulation days)

So an additional 20 simulation days need to be computed to prepare the model for the hurricane runs, this will take approximately 96 wall clock hours on the Apple G5 cluster

For each Hurricane run:
- An ADCIRC simulation would have to be carried out without wave forcing (7 simulation days)
- Wave radiation stresses will be computed
- An ADCIRC simulation would have to be carried out with wave forcing (7 simulation days)

So a total of 14 simulation days need to be calculated for each hurricane run. This will require approximately 67 wall clock hours per hurricane run plus the time needed by the STWAVE model to calculate the wave radiation stresses.
If hypothetical storms are used the spin up would be less (about 86 wall clock hours) but the hurricane runs would have to be carried out multiple times for different still water levels which represent the different tidal stages.

2.6.3 Modified strategy

Because these time periods are clearly too long, another modelling approach needs to be adopted. To further reduce the time needed for the calculations the following decisions have been made:

- A time step of 2 seconds has been chosen instead of 1 second. The largest flow velocities during a hurricane are approximately 3 m/s and the smallest spacing between two grid nodes is approximately 30 meters, the courant restriction $\left(\frac{v*\Delta t}{\Delta x}\right)$ will still be met since $\frac{3m/s*2s}{30m} < 0.5$. Bender et al. (2008) have tested the IHNC grid with a 2 second for four hypothetical storms. Differences near the Plaquemines levees and on the Mississippi river were smaller than 1 foot. (1 foot is equal to 30.48 cm).
- For all model runs (except for the validation runs in chapter 2.8) hypothetical storms will be used, this eliminates the need to do 18 day spin-up runs to correctly model the tidal response. The sensitivity of spillways toward the tidal range will not be investigated.
- This study will be limited to the use of the ADCIRC model, no coupling with STWAVE will performed. In this way the ADCIRC model only has to be used one time for each hurricane and the amount of simulation days is reduced from 14 days to 7 days.

Table 5. Wall clock hours needed for simulations with a 1 and 2 second time step.

Simulation Days	Wall clock Hours (1 second time step)	Wall clock Hours (2 second time step)
18	86.4	43.2
7	33.6	16.8
1	4.8	2.4

2.7 Conclusion

To perform storm surge simulations for multiple levee configurations within a limited amount of time a new modeling strategy has been chosen and a new grid has been created. In this way the model is expected to produce accurate results while keeping calculation times within limits.

The IHNC grid has been used as a basis for a new grid. The grid resolution near the Bird-foot delta and the corresponding bathymetry and topography has been improved in order to increase the accuracy of the model near Plaquemines Parish. The benefit of using the modified IHNC grid compared to the widely used SL15 grid is that it does not have as many nodes and is therefore faster.

The modelling methodology has been reduced to two steps; a river spin-up run (4.8 wall clock hours) and a 7 day hurricane run (16.8 wall clock hours). Hereto a time step of 2 seconds will be used in contrast to most other studies which use a time step of 1 second. The effects of tides and short-crested wind waves will not be modelled in order to save time. Figure 14 shows the methodology which has been applied throughout this study.

Bender et al (2008) tested the original IHNC grid with a time step of 2 seconds but the results were not compared to measured data. Because a new grid has been created and because a time step of 2 seconds has been chosen it is important to check if the model performs as expected. Because of this reason the grid and time step are therefore compared to measurements from Hurricane Katrina in the next chapter.

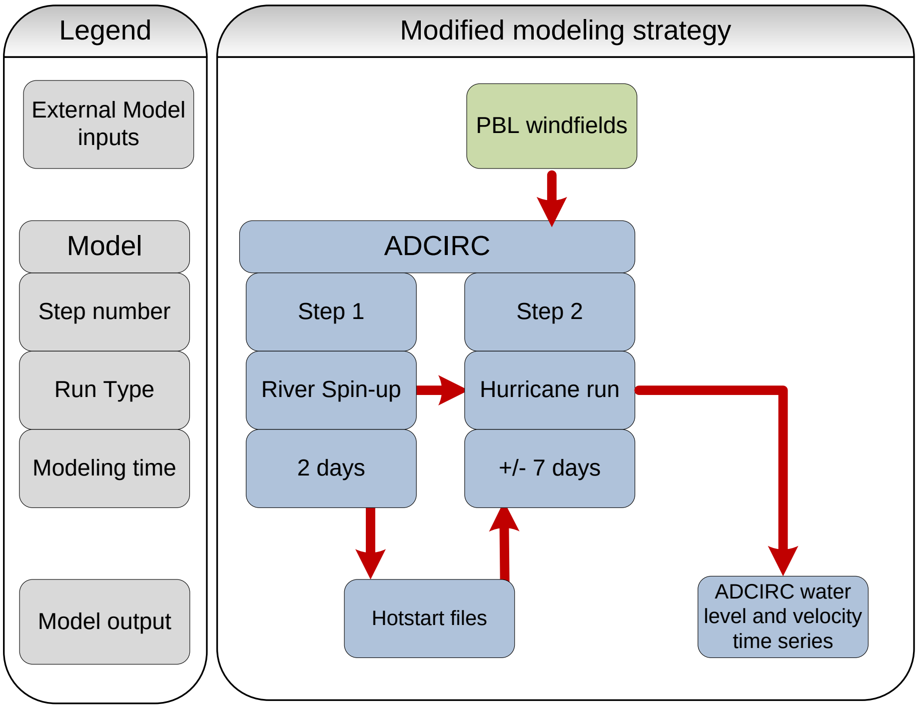


Figure 14. Modeling strategy for this study.

2.8 Discussion

The computed surge levels for this study will be underestimated since no wave set-up is included in the calculation. The IPET report (IPET, 2007) has shown that the magnitude of this underestimation near Plaquemines Parish is approximately 15 to 30 cm. Figure 15 shows the differences between a hind cast for Katrina with and without wave forcing. Unfortunately not only the maximum water levels change due to short short-crested waves, but also the timing of the peak storm surge and the drawdown effects are different if wave setup is included in the computations. Wind waves travel faster than surge and the peak of a combined wind and wind-wave surge will arrive at the shore earlier then a solely wind driven surge. (Weaver and Slinn, 2005). These effects however tend to be less important for stronger storms (Komen et al., 1994), for the purpose of this study only strong storms will be selected so these effects will be minimized (see chapter 4).

After the peak level has passed drawdown is also reduced. Onshore directed waves tend to reduce this process (Weaver and Slinn, 2005). In case of spillways near Plaquemines Parish especially the peak surge levels are vital, drawdown is considered to be less important.

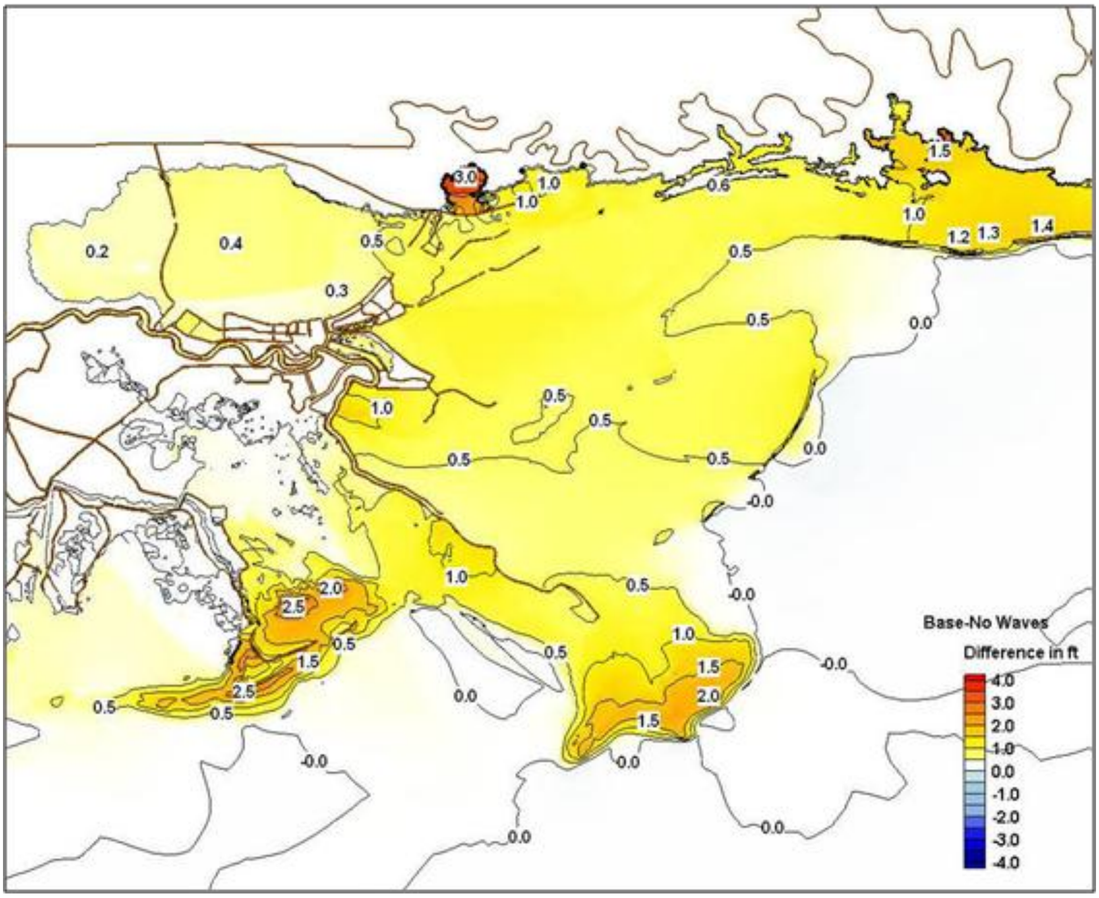


Figure 15. Difference in peak surge between the base simulation and the sensitivity simulation without wave forcing using the S08 model, foot is equal to 30.48 cm.

Tides will not be incorporated into the model. Neglecting these tides is considered acceptable because the tidal range in Louisiana is only small, approximately 15 to 45 cm. Also the time at which a hurricane makes landfall is arbitrary for hypothetical storms; this makes it difficult to implement the tides into the model.

To get a good overview of the response of surge with different spillway configurations it is most important to capture a realistic range in water levels east and west of the Mississippi levees. The actual physical processes which contribute to these water levels, e.g. the tides or various storm parameters are of less importance than the water levels themselves. An appropriate range in possible water levels will therefore be captured by the different hurricanes which have been selected (see chapter 3)

3 VALIDATION WITH KATRINA HIGH WATER MARKS

Model validation has been carried out in other studies for four ADCIRC models; these have been discussed in section 2.5. For this study the IHNC grid has been altered to incorporate a better resolution of the Mississippi delta with the aim of improving storm surge propagation on the Mississippi river and in the delta in general. Although the validation of the model is not the main focus of this study it is important to check if the modified grid does in fact represent the physics accurately since some changes have been made in the model.

Therefore the following research question will be answered:
How does the adapted model perform with respect to the Katrina measurements and the other ADCIRC models?

Section 3.1 presents the methodology which has been used for the validation of the modified IHNC model. Storm surge measurements have been performed during Katrina, these measurements or High Water Marks will be discussed in section 3.2, section 3.3 will discuss the modelled differences between the measurements and the IHNC and modified IHNC model, in the final section some conclusions will be drawn.

3.1 Methodology

Figure 16 shows the methodology which is used for this validation. Note that this is essentially the same methodology as was used for the FEMA study (Figure 13), except for the fact that STWAVE radiation stress is not calculated with the use of output water levels from the modified IHNC and the IHNC ADCIRC models, but with the output from a SL15 model which was performed for the FEMA study. These STWAVE calculations had already been executed and did not have to be repeated. Opposite to the other ADCIRC simulations throughout this study wind data from the H*WIND model has been used instead of wind data from the PBL model and wave radiation stresses as well as tides were included in the validation runs.

The IHNC grid has been validated with a time step of two seconds and the global differences for this model with the SL15 model are known, therefore the IHNC grid with a 2 second time step has been chosen as the ‘base case’ for this validation. Two simulations have been carried out, one Katrina hind cast with the IHNC grid and one Katrina hind cast with the new modified IHNC grid.

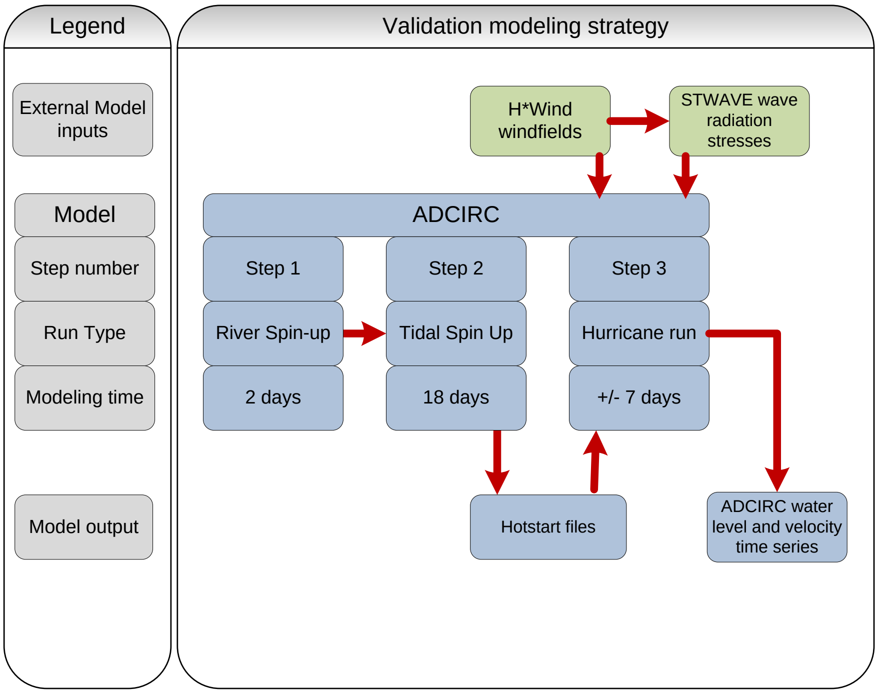


Figure 16. Methodology for the validation of the modified IHNC model.

3.2 High Water Marks

For this validation High Water Marks (HWM) have been used which were collected by the USACE (IPET, 2007). HWMs are measurements which capture the peak water levels of a storm. They are identified by for example mud lines on walls or by debris which has been left behind after the storm. HWMs do not contain information about the temporal variations of the water levels. The reliability of HWMs was classified as either “Excellent,” “Good,” “Fair/Poor,” or “Unknown”. The reliability of the High Water Marks is often uncertain because it can be unclear if HWMs do in fact capture the maximum surge levels or if they are influenced by wind forces or short waves.

To properly validate the model only the HWM which were characterized as ‘reliable’ or ‘good’ have been included in this analysis. The HWM’s which were located outside of the grid have not been incorporated in the following analysis. It should be noted that some of these HWMs were included in the validation of the full scale SL15 model, while they are not included in this validation study. This is due to the fact that the grid coarsening has led to changes in bathymetry at the edges of the grid, hence these areas did not inundate with the IHNC and modified IHNC model.
According to IPET only 2 reliable HWMs were available in Plaquemines (IPET, 2007), these two were located close to each other at Empire Lock (Figure 17). The reason why so few reliable measurements were available is because large parts of Plaquemines flooded during Katrina. The levees failed at a large number of locations (Figure 1) and ADCIRC does not model levee breaches. Therefore ADCIRC would underestimate water levels inside the ring levees in Plaquemines.

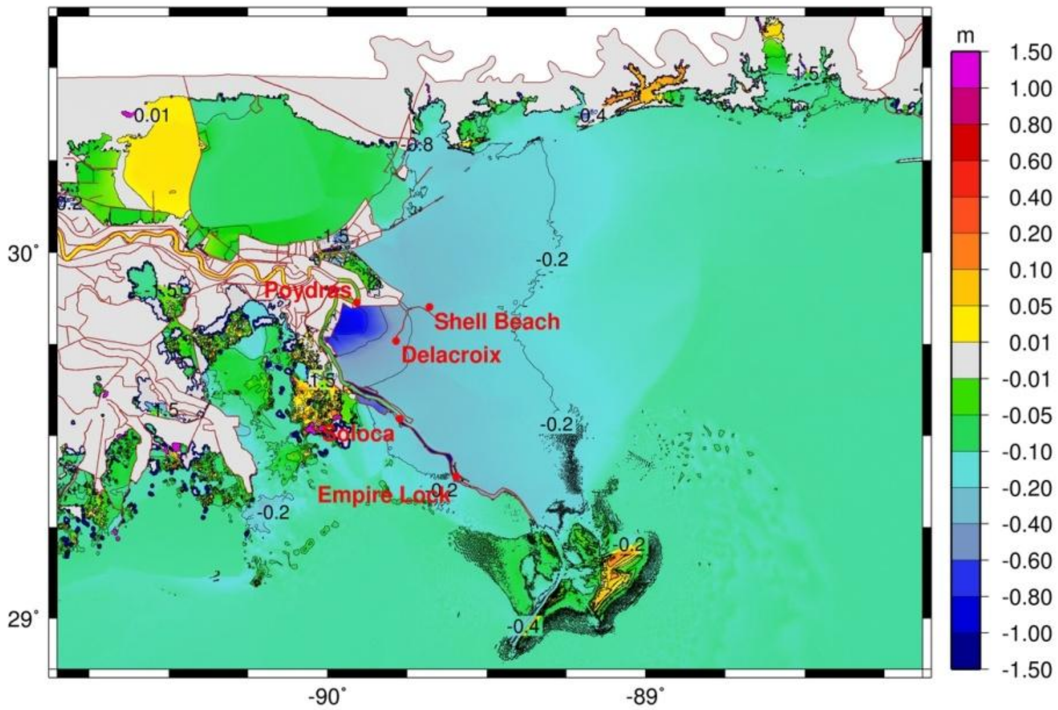


Figure 17. Maximum storm surge differences between the Modified IHNC grid and the IHNC grid.

3.3 Comparison with measured data

Overall Statistics

When the measurements are compared with the model results from the IHNC and modified IHNC grids it turns out that both models perform well. The statistics show that the standard deviation of the error for both models is about 0.5 m and that the mean absolute error is 0.38 m for the IHNC model and 0.39 m for the modified IHNC model. The error of a model is defined as the difference between the computed and measured data. When an error is positive the model overestimates the maximum storm surge and when the model underestimates the surge the error will be negative. The figures in annex F.1 shows regression lines for each of the models. Only for the SL15 version 7 model there is no data available. The regression coefficients (r^2) are given in Table 1. A coefficient of 1 indicates a perfect match of the measured and computed values. As expected the S08 model performs the worst and the SL15 model performs best. Remarkably the regression coefficient is slightly higher for the original IHNC grid compared to the modified grid. It must be noted that the s08 model had been validated with other data and that is therefore not entirely accurate to compare the S08 value directly with the other values.

Table 6. Regression Coefficients.

Model	Regression coefficient
S08	0.803
SL15	0.937
IHNC	0.927
Modified IHNC	0.914

Literature indicates that under resolution in finite element models leads to an over prediction in storm surge on the continental shelf (Blain et al., 1998). Due to the increased resolution in the Mississippi delta in the modified grid it can therefore be expected that the maximum surge levels for Katrina will be reduced north and northwest of the refined area when they are compared to the original IHNC model. Figure 17 shows the difference in surge levels between the grids. As can be seen there are indeed lower surge levels northwest of the bird-foot in the modified grid. These differences are as high as 0.8 meters near Poydras. Figure 18 and Figure 19 show a box plot and a histogram of the model errors respectively. What can be seen is that IHNC model slightly over predicts the surge elevation when it is compared to measurement data. The modification of the grid has lowered the water levels somewhat and the mean error reduces from 10 cm to 1 cm. The results show that the surge is indeed reduced in the area near Plaquemines Parish, this was also predicted because of previous research by Blain et. al.

Table 7. Statistical properties of both models.

Error measurements	Modified IHNC	IHNC
Number of measurements	181	181
Standard deviation	0.51	0.49
Mean Error (m)	-0.013	0.100
Mean Absolute Error (m)	0.39	0.38
Maximum Value (m)	1.31	1.52
3rd Quartile (m)	0.32	0.42
Median (m)	0.04	0.10
1st Quartile (m)	-0.30	-0.19
Minimum Value (m)	-1.86	-1.51

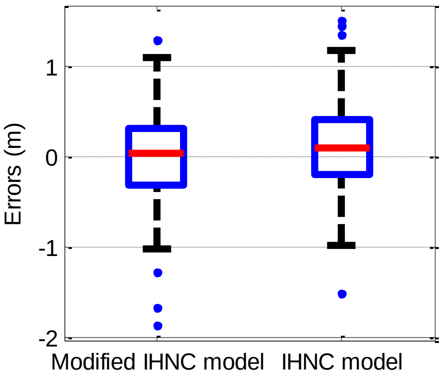
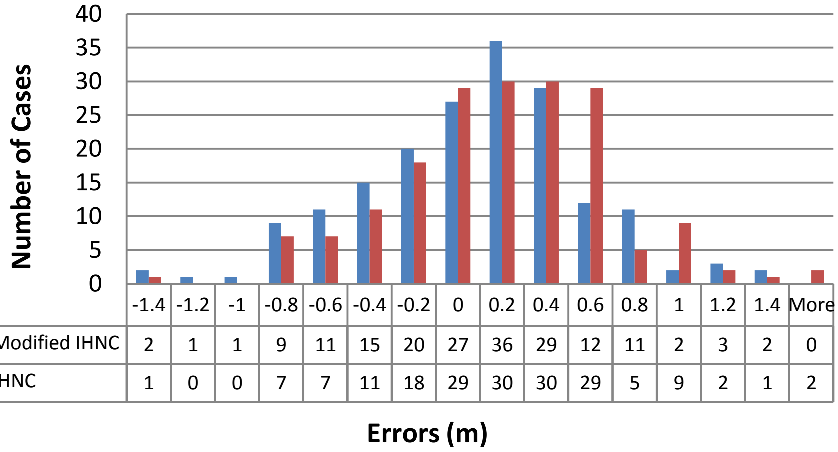


Figure 18 (right) Box plot with statistical characteristics.



	-1.4	-1.2	-1	-0.8	-0.6	-0.4	-0.2	0	0.2	0.4	0.6	0.8	1	1.2	1.4	More
Modified IHNC	2	1	1	9	11	15	20	27	36	29	12	11	2	3	2	0
IHNC	1	0	0	7	7	11	18	29	30	30	29	5	9	2	1	2

Figure 19. Histogram of the errors in the IHNC and modified IHNC models.

The regression coefficient is slightly lower for the modified grid compared to the original grid. The box plot shows that the quartile distances of the errors of both models are very similar but that in the modified grid there are more error peaks where the surge is underestimated compared to the original IHNC grid, these high errors at some locations cause this slight difference in the regression coefficient.

Local Errors

A statistical analysis of errors in surge modeling does not show all important aspects. This is because there can be a spatial variability between the errors which the above plots do not show. Therefore the errors have also been plotted on maps. Figure 20 shows the errors for the IHNC model, Figure 21 shows the errors for the modified IHNC model and Figure 22 shows the errors for the SL15 model (Westerink et al., 2008a).

What becomes clear is that in Soloca (for the location of Soloca see Figure 17) a large error is present in the modified IHNC grid while this is not the case in the original IHNC grid. In the original grid the error was close to zero for this location. This large error however also appeared for the SL15 model. It is uncertain why this error is this large in Soloca; a possible explanation could be that this HWM is not reliable. Soloca is located within one of the ring levees in Plaquemines and these ring levees were breached on many locations during Katrina. Since levee breaching is not incorporated in the ADCIRC model this could be the reason why the models predict a smaller surge. The IPET report also states that there was only one location in Plaquemines with reliable measurements and that this location was the Empire Locks (Figure 17). The same report however includes Soloca as a reliable HWM later on in the HWM tables, this is the reason why this point has been included in the validation study..

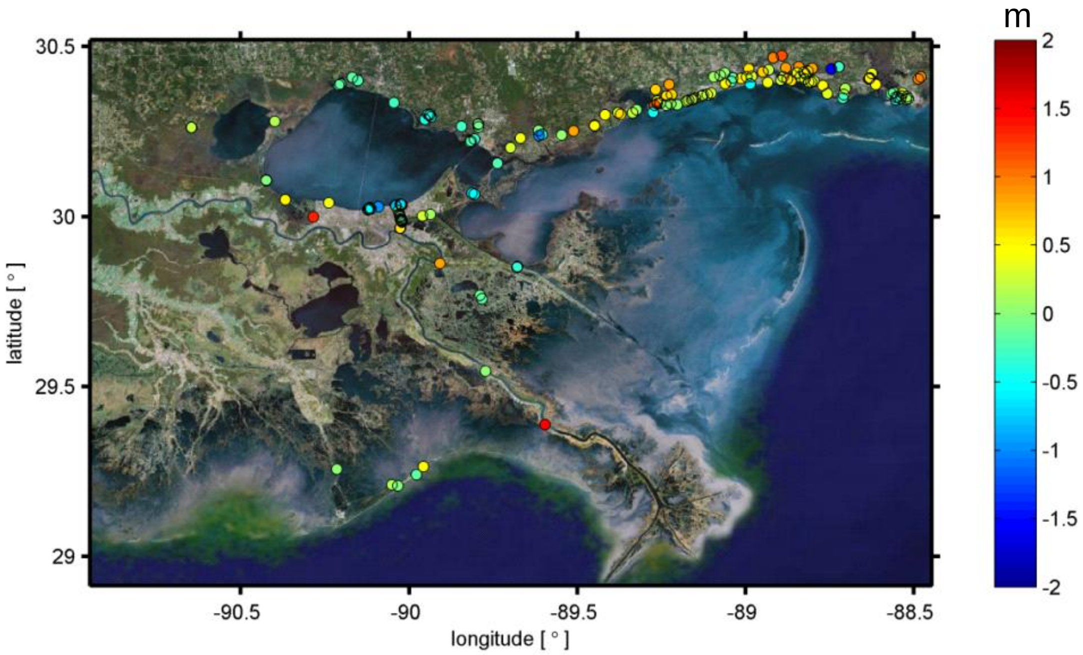


Figure 20. Difference between computed maximum water levels en measurements for the IHNC model (m). Positive values indicate an overestimation of the computed water levels and negative values indicate an underestimation.

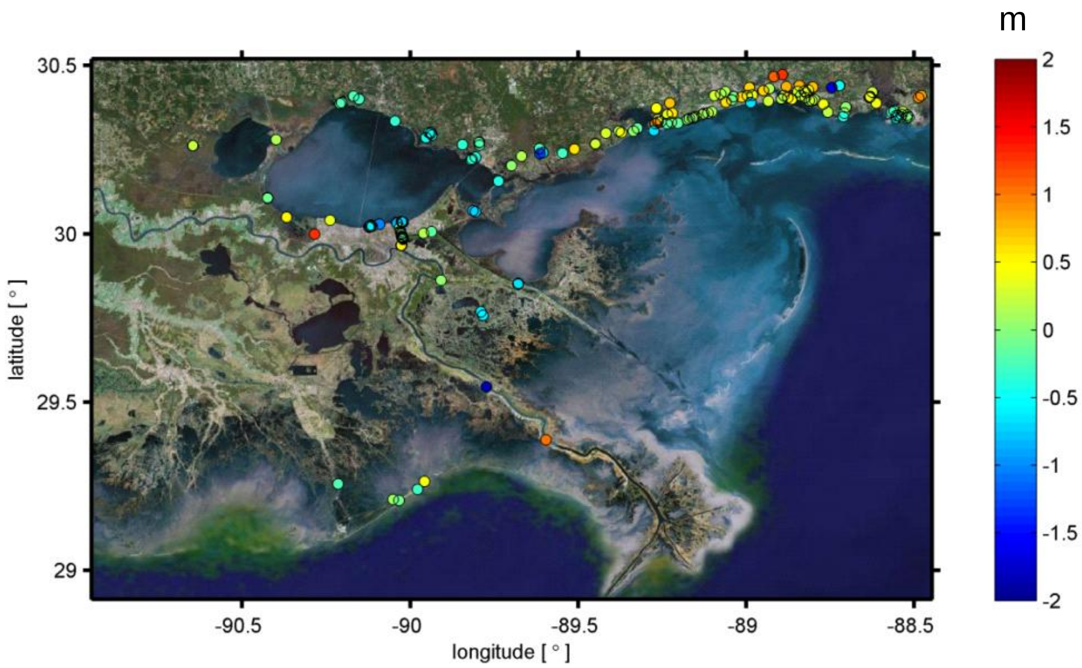


Figure 21. Difference between computed maximum water levels en measurements for the modified IHNC model (m). Positive values indicate an overestimation of the computed water levels and negative values indicate an underestimation.

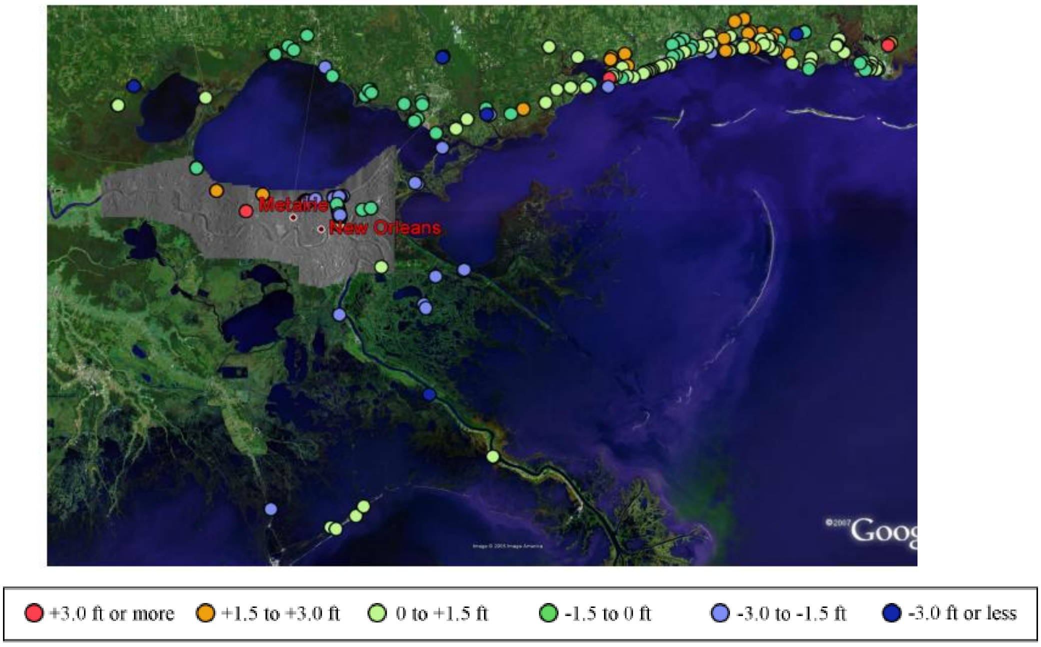


Figure 22. Difference between computed maximum water levels en measurements for the SL15 model (ft). Positive values indicate an overestimation of the computed water levels and negative values indicate an underestimation.

Water levels at the empire locks were accurately simulated with the SL15 model. There are however significant errors for the original and modified IHNC models. The original IHNC grid shows an under prediction of 1.5 meter at this location and the modified grid shows a smaller error of approximately 1 meter. A possible explanation for this could be that the grid resolution area west of Plaquemines Parish is not sufficient in both the IHNC and the modified IHNC grid. This is in compliance with the results from the study by Bender et al (2008). The increase in resolution in the Mississippi river delta did have a positive effect on the error at the empire lock compared to the original IHNC model, it reduced by 40 cm.

The modification of the grid also had an effect on the water levels South of St. Bernard near Poydras. While an 80 cm over-prediction was computed with the original IHNC model, the error was only 3 cm with the modified IHNC model.

3.4 Conclusion

The following can be concluded from the above:

- Both the original IHNC and the modified IHNC grid perform well. The average absolute error is 0.39m and 0.38m respectively.
- The modification of the IHNC grid resulted in a decrease of water levels northwest of the bird foot delta. This confirms the research done by Blain et al. which states that water levels reduce when grid resolution is increased on the continental shelf.
- The error at the HWM at Poydras is only 3 cm for the modified IHNC grid while it was 80 cm for the original IHNC grid. This provides an indication that the modification has a positive effect on the accuracy of the model results east of Plaquemines Parish but too few reliable measurements are available to effectively prove this.
- Both for the IHNC grid and the modified IHNC grid the errors at the Empire Locks are larger than for the SL15 model. In both cases an overestimation of the surge in calculated. This might be explained by the coarsened grid within the area west and southwest of Plaquemines Parish for both the IHNC and the modified IHNC grid. The enhancements in the Bird-foot delta which have been applied by modifying the IHNC model contribute to a somewhat smaller error (1 m) at the Empire Locks compared to the error of the original IHNC grid (1.5 m)
- The original IHNC has an r^2 value of 0.927, this is slightly higher than the r^2 value of the modified IHNC grid (0.914). Both models have a lower regression coefficient compared to the SL15 model (0.937) but show a better correspondence with the measurements than the S08 model (r^2 =0.803). The r^2 value is however not representative for the quality of the model near Plaquemines Parish since only a small portion of the data used for the validation originated from the Plaquemines area.

3.5 Discussion

To be able to draw conclusions on the quality of the model it is not enough to look at the regression coefficients alone. The HMW which were collected were not evenly spread over the model domain. A large part of the measurements were collected along the Mississippi coast, so the model predictions along this coast greatly influence the regression coefficient. In some areas few or no measurements were available at all, so it is unknown if the model provides accurate results in those areas as well.

Very little reliable measurements were collected during Katrina on the Mississippi river and in Plaquemines Parish, it is therefore not possible to prove that indeed the propagation of surge in the Mississippi delta is enhanced. For a proper validation of the model more data is needed and multiple storms have to be analyzed. Also a comprehensive analysis of hydrographs would be necessary; the validation in this report is limited to a comparison between High Water Marks and maximum water levels for the IHNC grid and the modified IHNC grid.

So due to a lack of reliable data from Katrina it is difficult to draw conclusions regarding the suitability of the model for Plaquemines. This is a problem common to all models, even the more detailed SL15 model. This is why currently a new grid is being developed specifically for the delta region and this is why new measurements have been done for that study. For this study regarding the Plaquemines spillways this data was not yet available.

4 STORM SELECTION

In recent history there have been multiple hurricanes in the Gulf of Mexico, all with different physical properties like storm track, storm size and minimum pressure. In theory an unlimited amount of different hurricanes could hit the Louisiana coast, and the surge levels which occur during these storms will also be very different for each storm. It is necessary to select indicative storms for the purpose of investigating the effects of spillways on storm surge.

In this chapter the following research question will be answered:

Which storms should be modelled in order to give an indicative overview of potential effects of spillways on the maximum surge levels near Orleans, St. Bernard, Jefferson and Plaquemines Parish?

To be able to analyse levee configurations and to be able to select appropriate storms it is necessary to understand the basic physical properties of hurricanes and to have an idea how these properties will contribute to the total storm surge, this will be discussed in the first section of this chapter. Section 4.2 will focus on the storm set that has been used to determine the water levels for a protection level of 1:100 per year in South-West Louisiana. In this section it will be explained that it is not possible to use the same storm set due to the limited amount of time which is available for this study. Therefore a new, smaller storm set has been selected in section 4.3. In section 4.4 the consequences of using a small storm set are discussed.

4.1 Physical properties of a hurricane

In this section the following question will be answered:
What are the basic physical properties of a hurricane and how do they influence storm surge?

Properties of a hurricane

A hurricane is characterized by a low pressure center, the eye, and by strong winds and thunderstorms circling the eye. On the Northern hemisphere the winds travel counterclockwise around the eye as a result of the Coriolis Effect (Figure 23). The winds which are directed onshore produce the storm surge, as can be seen in Figure 23 the Northeast quadrant of a hurricane is most important when storm surge is formed since the wind in this quadrant is directed onshore.

Table 8. Sustained Wind speeds and minimum pressure on the Saffir Simpson Scale

Saffir Simpson Scale	Sustained Wind Speeds (m/s)	Minimum Pressure (mbar)
1	33–42	980–989
2	43–49	965–979
3	50-58	945–964
4	59-69	920–944
5	>70	<920

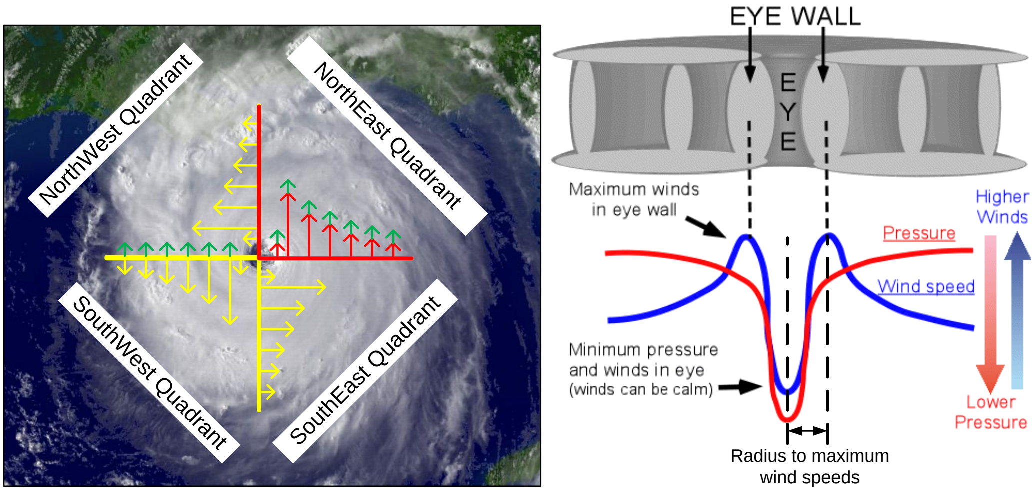


Figure 23. (left) Quadrants within a Hurricane. The red and yellow arrows indicate wind velocities. Green arrows indicate the forward speed. When the forward speed is added to the wind speeds it becomes clear that in the Northeast quadrant to maximum wind speeds will be the greatest. (right) Idealized wind and Pressure profiles within a Hurricane (University of Illinois, 2008).

The intensity of a storm is often classified on the Saffir-Simpson scale, for the strongest category storm (cat 5) the sustained winds speeds can be as high as 70 m/s (Table 8). For storm surge modeling the Saffir Simpson scale is not often used, instead a number of physical parameters of a hurricane are identified. For input in the ADCIRC model the dynamic PBL model of Thompson and Cardone (1996) is used to compute idealized wind fields. This PBL model describes a hurricane according to the following properties.

- The central pressure within a hurricane.
- The radius to maximum winds speed.
- Storm forward speed.
- Storm landfall location
- Storm track
- Storm angle relative to the Coast
- Holland B Parameter

The **central pressure** within the eye of a hurricane is lowest for the strongest storms. Katrina e.g. reached a minimal central pressure of 902 mbar during its course. Pressure increases suddenly at the eye wall and increases further but more gently towards the edges of the storm. Figure 23b shows a simplified pressure profile of a hurricane. For well developed hurricanes the highest wind speeds occur near the eye wall. The distance between the centre of a hurricane and the area with the highest wind speeds is defined as the **radius of maximum wind speed** (RMW). The **Holland B parameter** is a dimensionless parameter which controls the peakedness of the wind speed distribution (blue line in Figure 23). High values for the Holland B parameters indicate high wind speeds and hurricanes with low values for the Holland B parameter will have lower maximum wind speeds.

As Hurricanes travel across the Gulf of Mexico measurements indicate that they weaken in the last 6 to 24 hours before landfall. This shows as a increase in pressure, an increase in the radius to maximum winds and a decrease in the Holland B parameter (Westerink et al., 2008a)

The **storm forward speed** contributes to the severity of storm surge in two ways. In the northeast quadrant of a storm the hurricane winds which are circling the hurricane eye are directed towards the coast, in addition to these circular winds the storm forward speed also contributes to the total measured wind speed. In the northeast quadrant this forward speed is added to the component of the circular winds in the direction of the hurricane. In the southwest quadrant the storm forward speed will reduce the total measured wind speeds. So a large forward speed will increase the maximum wind speeds and this will increase the storm surge. On the other hand, when a storm is moving more slowly towards the coast, the maximum wind speeds will be lower, but the amount of time in which the storm surge is allowed to build up is longer and this will also increase the total surge.

The **storm landfall location** defines the location where the eye of the hurricane first reaches land. Because mainly the storm surge is created by winds in the Northeast quadrant of a storm the surge will be most severe east of a landfall location.

The **storm track** defines the location of the storm in time. Most hurricanes travelled from the Caribbean region toward the Gulf of Mexico. Some storms however followed a westerly path over Mexico and Belize before they entered the Gulf. All Hurricanes in the Gulf of Mexico travel in Northward direction towards the Gulf Coast, but variations exist in the **angle of the storm relative to the coast**. Figure 24 shows the tracks of the hurricanes which traveled through the Gulf Of Mexico and had central pressure lower than 955 mbar. For storm with greater angles it can be expected that the length of the coastline which has to deal with a storm surge will become larger due to the fact that the storm also moves partly alongside the coast.

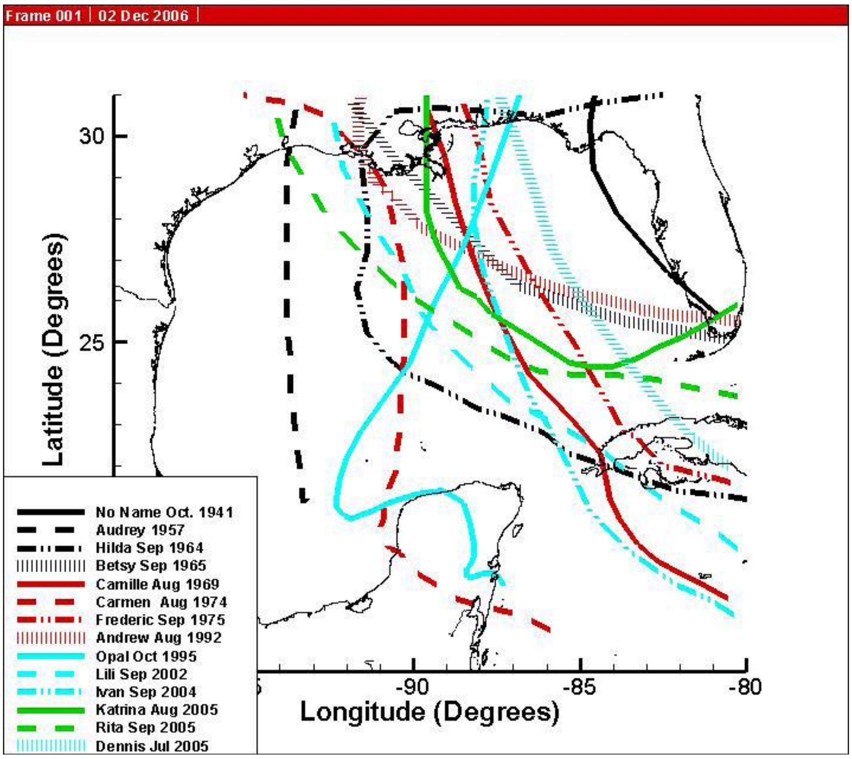


Figure 24. Tracks of all hurricanes (1941-2005) making landfall in the central Gulf of Mexico for storms that attained a central pressure of 955 mbar or lower during its transit through the Gulf of Mexico. Image courtesy: Westerink et al (2008).

4.2 Determination of 1:100 year protection levels.

Decision makers in Louisiana have decided that in the future a protection level of 1:100 year is desired for New Orleans (see Figure 25). Levees in the region will have to be able to hold back these water levels.

Recently the FEMA insurance study has computed frequency of occurrence surges at a large number of locations in South West Louisiana, for this a storm set of 152 storms has been used.

The size of the storm set had been determined by using a modified version of the JPM (Joint Probability Method) model, called JPM-OS. The original JPM was developed in the 1970s (Myers, 1975; Ho and Meyers, 1975). In order to limit the computational burden the JPM-OS was developed (Westerink et al., 2008a). For New Orleans the use of the JPM-OS could significantly reduce the number of different storms to a total of 152, the tracks of the 152 storms are displayed in Figure 26.

Each of the 152 wind fields is composed of a combination of different physical properties of hurricanes including:

- The central pressure within a hurricane (900 – 960 mbar)
- The radius of maximum winds speed. (8 – 35 nautical miles)
- Storm forward speed. (6- 17 knots)
- Storm Landfall location
- Angle of storm track relative to the coast (-45° – 45°)
- Holland B (1 -1.3)

By using a probability distribution for each of the above physical properties together with the calculated maximum storm surge for each storm a probability distribution of surge elevations has been calculated for a large number of locations in South West Louisiana.

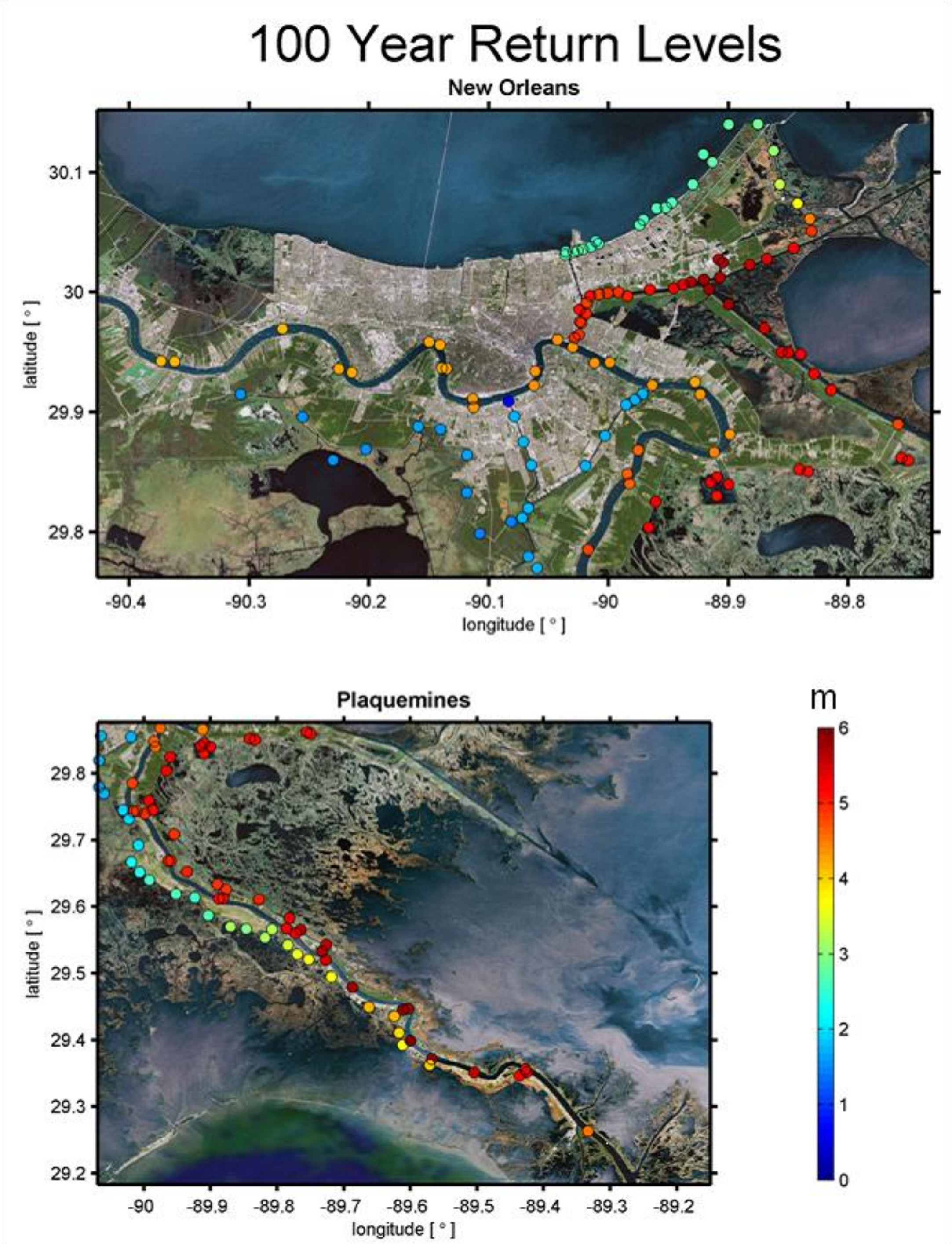


Figure 25. Surge levels with a return period of 1:100 per year for different locations (m NAVD88). A large difference can be seen between the east and west side of Plaquemines. The 1:100 year return levels are highest in Plaquemines near Empire and also near the Inner Harbor Navigation canal. On the Westbank the return levels are low, mainly because these areas are protected from the winds in the Northeast quadrant of a hurricane by the levees in Plaquemines.

Although the use of the JPM-OS methodology already reduced the amount of storms which needed to be executed, the computational burden was still significant.

For this study on the Plaquemines spillways it is therefore not feasible to use the same storm set as has been used previously for the FEMA study. In order to comply with the JPM-OS

Methodology a total of 152 ADCIRC runs would have to be performed for each spillway configuration. Since there is a time constraint a smaller storm set will be used for this study.

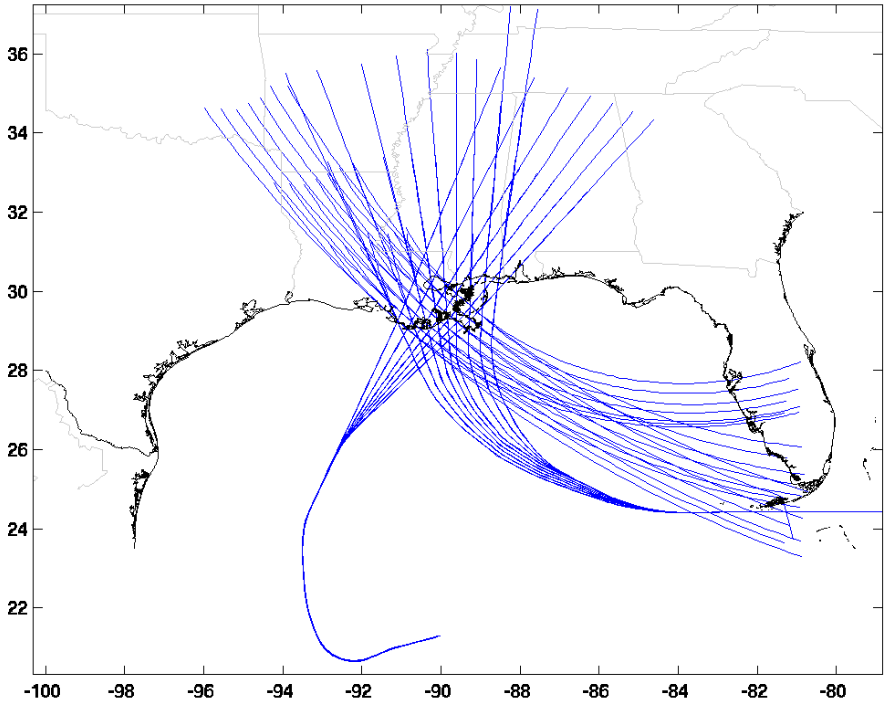


Figure 26 Summary of 152 JPM storm simulations. (Image courtesy Westerink et. al.)

A small storm set is needed to be able to do calculations for multiple levee configurations in Plaquemines. The LACPR spillways study (de Jong, 2007) used a storm set of 18 storms to calculate new 100 year return periods, since performing 18 storms still took considerable time this study was limited to 1 spillway configuration.

To be able to gain insight in the effects of more levee configurations on surge an analysis with a total of 18 storms is also not be possible due to time constraints.

4.3 Selection of indicative storms

Although it will not be possible to select a storm set which can be used to statistically represent the variability of storms in the Gulf of Mexico it is still important to select a storm set which captures the most important differences between storms. Storms with high intensity and a high probability of occurrence are preferred since they have a relatively large influence on the 1:100 year return levels.

To come to a storm selection the following questions will be answered within this section:

- Which storms have a large influence on the 1:100 year water levels?
- Which considerations are important when selecting a storm set?
- Which storms have been selected?

4.3.1 Influence of storms on 1:100 year water levels.

Since the goal of creating spillways would be to reduce the 1:100 year water levels it is desirable to select storms which can have a major impact on the 1:100 year water levels. A surge effect as a result of the creation of spillways during a hurricane with a large probability of occurrence and with high maximum water levels will eventually have a larger impact on the 1:100 year water levels than a reduction of water levels during a low energy storm with uncommon hurricane properties.

The probability of occurrence of each of the 152 storms is unknown, the methodology which was used to calculate the surge probabilities focused on the statistical distributions of the separate hurricane properties, and not on the combined properties which represent a hurricane. The probability of occurrence of each separate storm is thus unknown. The maximum water levels during each of the 152 storms are however available, and the surge probabilities at the same locations are also known. So, there can be determined if a maximum storm surge during a particular storm is higher or lower than a particular return period. For each storm a map has been plotted where the probability of occurrence of the water levels have been displayed. These maps show which storms produce relatively high water levels for each location. All maps are included on the dvd-rom which is attached to this report. Figure 27, Figure 28 and Figure 29 show these maps for the selected storms.

4.3.2 Requirements for the storm set.

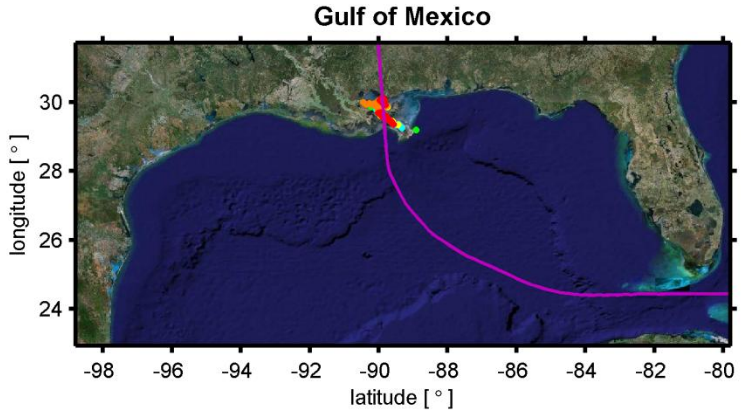
In order to select storms for this study, the following principles were applied:

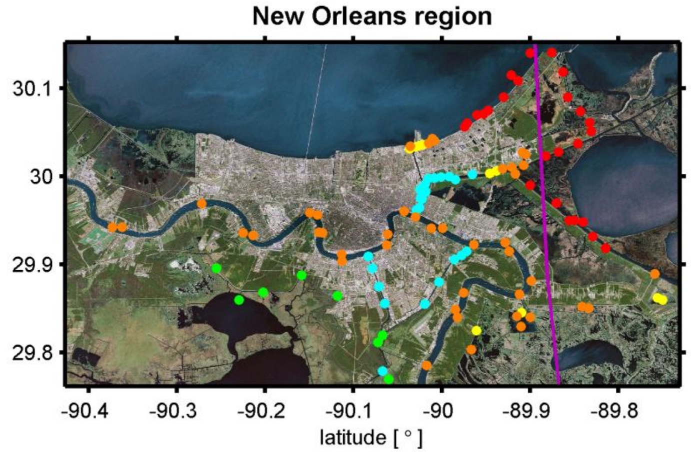
- The storm set must capture a range in water levels at each of the focus areas, these are: Plaquemines Parish, the Westbank, St Bernard and the Mississippi River.
- The storms will differ from each other in terms of track and landfall location. This choice was made because this parameter captures most of the differences between the storm surge levels. In order to reduce the number of degrees of freedom the storms have approximately the same strength, this means that they have a similar central pressure, radius to maximum winds and forward speed.
- Hurricanes with properties which are fairly common are preferred.
- Only high intensity storms are selected because for these storms spillways could have a large influence on the 1:100 year water levels.

Storm 27

Storm Track Information

Storm-ID	27
Storm track	300
Minimum pressure (mbar)	900
Central speed (knots)	11
Radius (nautical mile)	21
Holland B parameter	1.27





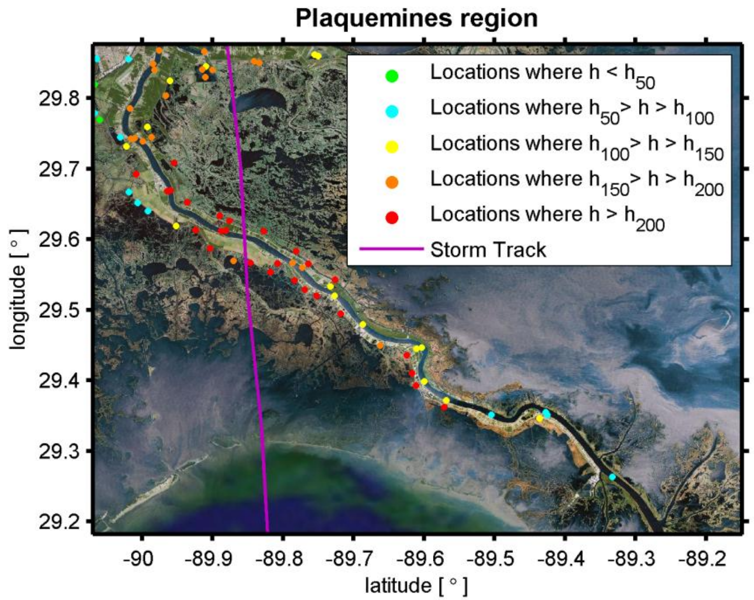


Figure 27. Comparison between surge levels an return periods for hypothetical storm 27.

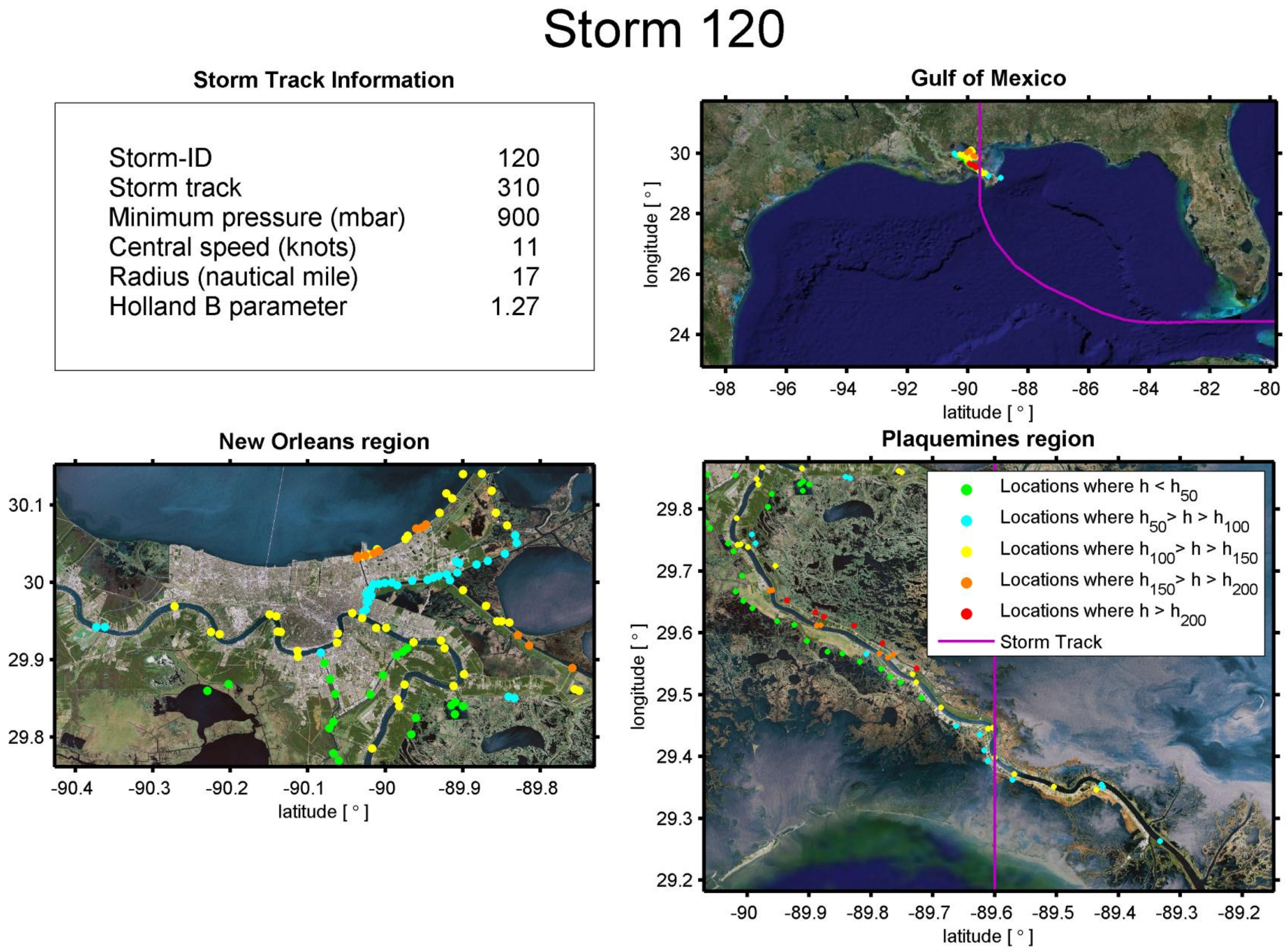


Figure 28. Comparison between surge levels an return periods for hypothetical storm 120.

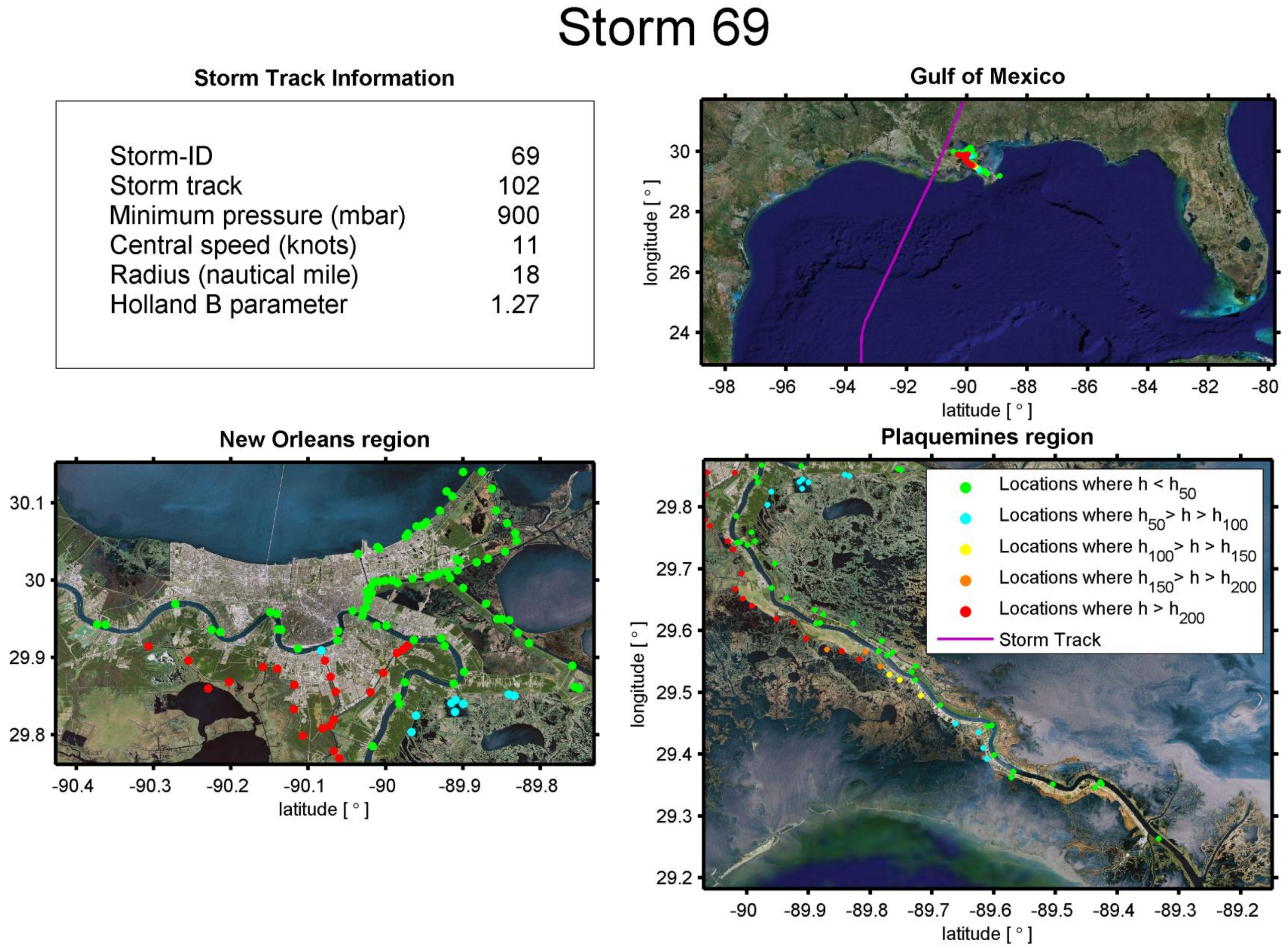


Figure 29 . Comparison between surge levels an return periods for hypothetical storm 69

4.3.3 Selected Storms

The storms which have been selected are the storms with numbers 27, 69 and 120.
Al storms have a similar strength. They have a central speed of 11 knots, and radius of maximum wind of 17-21 nautical miles. Both are average values within their range.

All storms have a minimum pressure of 900 mbar. Because of this low minimum pressure they are category 5 storms. It should be noted that the minimum pressure and various other hurricane properties change during their course and that the value of 900 mbar is the minimum pressure they reached. At landfall, hurricane 27 had a minimum pressure of 918 mbar, hurricane 69 had a minimum pressure of 920 mbar and hurricane 120 had a minimum pressure of 913 mbar. Annex H shows the variations of the various physical parameters during the track of each of the three selected storms.

Category 5 storms produce in general the highest storm surges and it is therefore interesting to investigate the effects of spillways during these storms. Storms which made landfall as category five storms were:

- Labor Day Hurricane (1935)
- Camille (1969)
- Andrew (1992)

Several other storms also reached category 5 during their course, among those are Katrina (2005, minimum pressure 902 mbar) and Wilma (2005). Wilma had a minimum pressure of 882 mbar, which is the lowest ever recorded within a hurricane.

Storm 27 produces very high water levels both west and east of Plaquemines parish, the water levels are higher than the 200 year water levels in these areas. This is because the eye travels over Pointe de La Hache and the winds in the Northeast quadrant of the storm pushes water both in western direction against the levees on the east side of the Mississippi as well as in Northern direction against levees west of Plaquemines. The water levels in the Mississippi river are also very high, between the 1:150 and 1:200 water levels. On the Westbank the water levels are very low, lower than the 1:50 year return levels, it can be expected that spillways will have a negative influence on the water levels in these areas (the water level will rise).

Storm 120 has a similar track than storm 27; the landfall location however lies east of the landfall location of storm 27. The landfall location is close to Buras, in Plaquemines Parish. The track is almost identical to the track of hurricane Katrina.
In contrast to the surge caused by storm 27 the northern directed winds do not build up a large surge west of Plaquemines. Similar to storm 27 the westerly directed winds in the Northeast quadrant of the storm produce high water levels on the Mississippi and on the east side of Plaquemines. The surge is lower in most locations because of its more western track. Storms 27 and storm 120 have been selected because they represent a process that seems to be dominant for most storms that travel over New Orleans.

Storm 69 has been selected because the maximum surges are very different from most other storms. On the Mississippi, near St. Bernard and east of Plaquemines surge levels are relatively low. Along the levees of West Plaquemines and Jefferson Parish water levels are very high. This is because the landfall location of storm 69 is located west of New Orleans and the northern winds direct the surge over the wetland towards the West bank.

4.4 Discussion

A downside of using a smaller storm set is that it is not possible to calculate new 1:100 year water levels. Spillways could be beneficial with regard to reducing maximum water levels if those water level reductions would result in a lowering of the 1:100 year water level because then the risks of flooding would be reduced or costs could be saved.

A limitation of this study is therefore that only an indication of the effects of spillway configurations on storm surge can be presented, a single water level for a new return period cannot be given; this would require many more model simulations.

The storms have however been selected in such a way that at locations near the levees of St. Bernard, Plaquemines Parish, Jefferson and on the Mississippi River high water higher than the 1:100 year water levels occur during at least one of the three storms. If those maximum water levels were to be reduced or increased due to the influence of spillways, it is likely that the 1:100 year water levels will also be influenced in a similar manner.

5 SPILLWAY CONFIGURATIONS

In this chapter the following research question will be answered:

Which factors are important for determining spillway configurations and what are the quantitative effects of the selected spillway configurations on the maximum storm surge levels during hurricanes near Orleans, St. Bernard, Lafourche, Jefferson and Plaquemines Parish?

In order to select spillway configurations two subjects have been analysed. First the location of the settlements and important sites in Plaquemines Parish will be briefly discussed (section 5.1). Secondly a hydrodynamic analysis will be presented in which the formation of storm surge during the three different storms is analysed in more detail (section 5.2). Section 5.3 describes the general conclusions from the hydrodynamic and the spatial analysis and will determine suitable locations for spillways.

In section 5.4 the results from section 5.3 are used to define five different spillway scenarios. Accordingly the ADCIRC model results of these five spillway scenarios are analyzed in section 5.5. The most significant effects of the spillway configurations on storm surge will be discussed in the final section for each of the above defined focus areas.

5.1 Plaquemines Parish area description

In this section the following two questions will be answered
- Where are the villages located?
- Are there other sites which are of importance regarding the location of spillways?

In order to determine the locations of the spillways it is important to know where villages and the industry are located so that this information can be used to determine suitable location for spillways.

Plaquemines Parish is an administrative subdivision in Louisiana and has its parish seat in Pointe à la Hache. In the year 2000 it had a population size of approximately 27 thousand and in that same year 10.481 housing units were located in the parish. In 2005 Katrina destroyed most of the houses and properties in the region and as a result a considerable part of the population has left the Parish. In 2006, the population had been reduced to 22.5 thousand; this is a decrease of 17% of the population since the year 2000.

Table 9. Population and Housing estimates. (US. Census Bureau, 2000)

Geographic area	Population	Housing units	Area in square km			Density per square km of land area	
PLACE			**Total Area**	**Water Area**	**Land Area**	**Population**	**Housing Units**
Belle Chasse CDP	9848	3561	74	9	65	151.97	54.95
Boothville-Venice CDP	2220	933	13	6	7	333.52	140.17
Buras-Triumph CDP	3358	1408	19	6	13	258.79	108.51
Empire CDP	2211	923	20	6	14	160.46	66.99
Port Sulphur CDP	3115	1222	22	6	16	198.47	77.86
Total In CDP	20752	8047	147	33	114	182.18	70.64
Total outside CDP	6005	2434	6143	4069	2073	2.90	1.17
Total Plaquemines Parish	26757	10481	6290	4102	2187	12.23	4.79
Total New Orleans	484674	215091	907	439	468	1036.41	459.94

Most urbanized areas in the United States are defined as incorporated places and are registered under state law as a city or village (U.S. Census Bureau, 2008). Plaquemines Parish does not have recognized cities or villages. All settlements in Plaquemines are designated as unincorporated communities and are administered by the Parish government. Because an unincorporated community does not have a registered boundary, the United States Census bureau has defined Census Designated Places. These places can be seen as villages or cities, but do not have a legal status. CDP's are only defined for statistical purposes. Plaquemines has 5 CDPs, four border each other in Southern Plaquemines Parish. The 5th CDP which is the largest CDP in terms of surface area, Belle Chase, is located directly south of New Orleans in North Plaquemines (see Figure 30). 71% of all people live in these CDPs, 29% lives in other areas outside these CDPs.

When the area of Plaquemines is visited, the distinction between unincorporated settlements, CDPs and rural areas is not clear. The settlements do not appear to have central areas which could be indicated as towns. In Plaquemines Parish the houses are scattered over the entire area. The statistics however show that especially in BoothVille-Venice, the population is relatively high. In comparison, the city of New Orleans has a 3 times higher population density than Boothville-Venice.

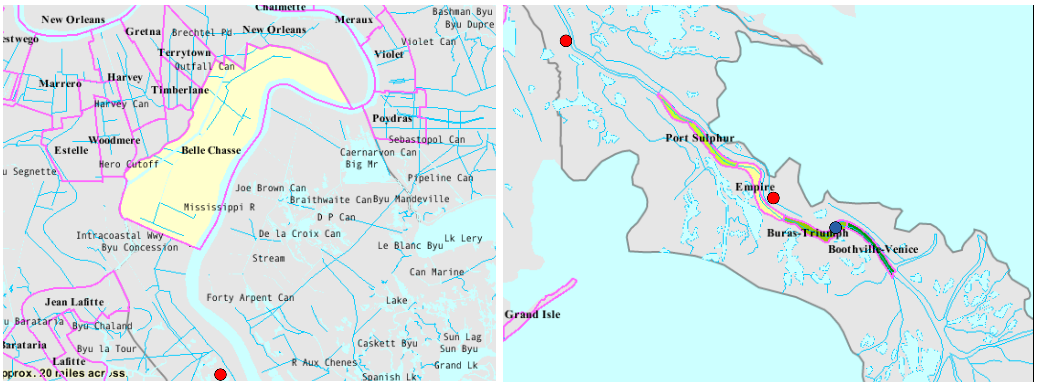


Figure 30. Location of Census Designated Places in Plaquemines Parish (U.S. Census Bureau, 2000). The location of the largest industrial plants are indicated with red dots. The location of Fort Jackson is indicated with a blue dot.

Plaquemines has a large fishing industry and oil industry. Most of the industry is located within the southern CDPs. There are major plants outside of the CDPs near Alliance and across the river at Buras. This plant at Buras does not exist inside an existing ring levee, but does have protection against high river flows.

Fort Jackson is located at the border of the CDPs Boothville-Venice and Buras-Triumph. This fort was used during the American Civil war in the early 19th century and is designated as a historic landmark.

5.2 Surge formation process during different storms.

By increasing the hydraulic connectivity between the east and west side of the Mississippi river the maximum water levels are expected to reduce near Plaquemines Parish, St. Bernard, on the Mississippi River and near the southern levees of Jefferson Parish.

To determine how the hydraulic connectivity could be improved between the east and west side of the Mississippi, the flows and water levels along the levees of Plaquemines Parish have been be analysed during the storm surge formation process. Hereto the following questions will be answered:

- What are the maximum water levels at each of the areas of interest for the Base Case, and which storm is responsible for the maximum water levels at each location? (section 5.2.1)
- What is the direction of the flow in time during each storm and which flows contribute to the maximum water levels? (sections 5.2.2 and 5.2.3)
- Where should spillways be located in order to improve the hydraulic connectivity between both sides of the river? (section 5.3)

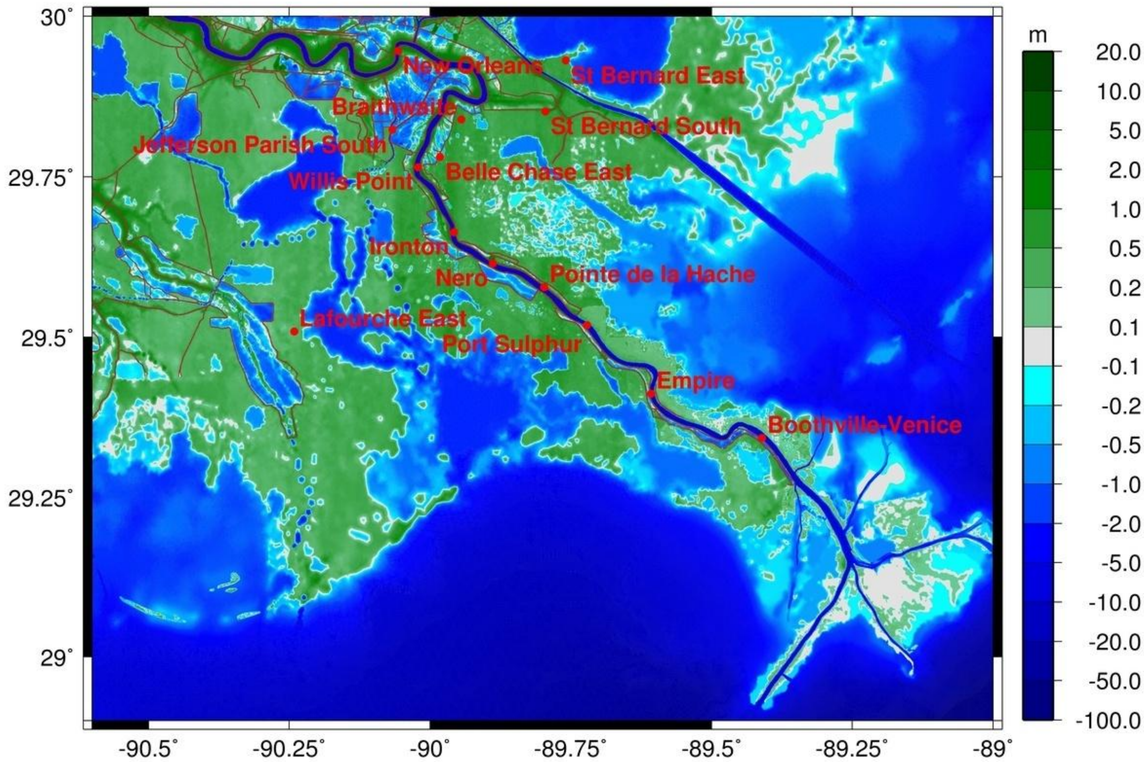


Figure 31. Selected Locations near Plaquemines, Lafourche, Orleans St. Bernard and Lafourche Parish. The colors indicate the elevation of the bathymetry and topography.

5.2.1 Maximum Water levels

Figure 32 shows the combined maximum water levels as they have been modelled with ADCIRC for the three storms with the current levee system in place. Figures of the maximum water levels of each separate storm have been included in annex I.1. Table 10 displays the maximum surge levels at some important locations within the study area.

The study area has been defined in section 1.6.2 and encompassed the area for which the surge levels will be influenced by the spillways. This area includes the southern part of Jefferson Parish and St. Bernard Parish, the Mississippi River near New Orleans, Lafourche and Plaquemines Parish. The selected locations are displayed in Figure 31 and in Figure 129 in Annex L (in order to improve readability this Annex can be folded out).

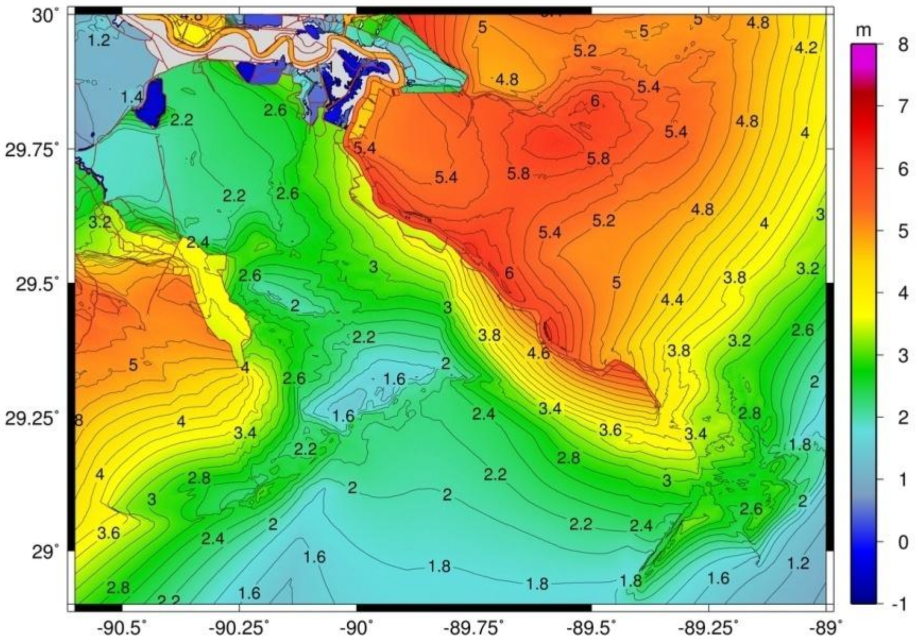


Figure 32. Composition of maximum water levels for the storms 27,69 and 120 for the current existing levees.

The model results show that east of Plaquemines Parish the surge levels can become as high as 6.3 meters. In almost the entire area west of Plaquemines Parish and south of St. Bernard water levels are higher than 5m NAVD88. The highest water level at the Mississippi river is 4.8 m. South of Jefferson Parish the water levels are much lower (3.1 m). Although these water levels are low compared to the water levels on the other side of the Mississippi, the surge elevation is higher than the 1:100 year water levels at those locations.

Table 10. Maximum surge levels for the Base Case. A dominant storm is defined as the storm which produces the highest water levels at a particular location.

		Maximum Surge Levels (m)				
Area	**Location**	**Storm 27**	**Storm 69**	**Storm 120**	**Combined**	**Dominant Storm**
	New Orleans (Mississippi River)	4,8	2,6	4,3	4,8	27
	Jefferson Parish South	1,2	3,1	0,8	3,1	69
	Lafourche East	1,4	3,2	1,0	3,2	69
St Bernard	St Bernard Parish East	5,1	1,8	4,8	5,1	27
	St Bernard Parish South	5,8	4,1	3,8	5,8	27
	Braithwaite	5,2	4,4	2,4	5,2	27
	Belle Chase East	5,2	3,6	3,0	5,2	27
Plaqumines Parish West	Willis Point West	1,2	3,1	0,8	3,1	69
	Nero West	2,7	3,6	1,3	3,6	69
	Port Sulphur West	4,6	3,5	2,1	4,6	27
	Empire West	5,1	2,4	3,3	5,1	27
	Boothville-Venice West	5,3	2,0	4,8	5,3	27
Plaqumines Parish East	Willis Point East	5,3	3,4	3,6	5,3	27
	Nero East	5,9	1,7	5,6	5,9	27
	Port Sulphur East	5,9	1,7	5,9	5,9	120
	Empire (Mississippi River)	5,6	1,4	5,9	5,9	120
	Boothville-Venice (Mississippi River)	3,8	0,8	4,2	4,2	120

The regions for which the different storms create the maximum water levels are indicated in Figure 33. This figure shows that storm 69 is dominant for most of the area west of the Mississippi River west of Pointe de la Hache.

Storm 27 produces the highest water levels of all three storms at the following locations:

- At the eastern side of Plaquemines Parish, north of Pointe de la Hache;
- On the Western side of Plaquemines Parish, south of Pointe de la Hache;
- Close to the levees of St. Bernard Parish;
- In the Mississippi River, upstream of Pointe de la Hache.
- At some locations close to the eastern levees of Lafourche Parish

Storm 120 produces the highest water levels of the three storms on the eastern side of the Plaquemines levees, southeast of Pointe de la Hache. It also has the highest water levels on the Mississippi river in this same area.

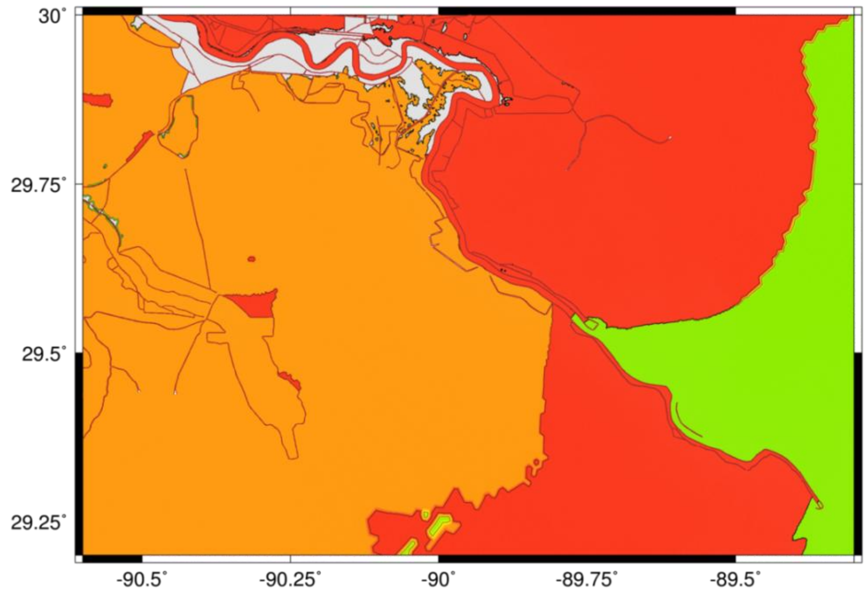


Figure 33. Regional overview of the storms which produce the highest water levels within the study area. The orange color indicates the locations where storm 69 produces the highest water levels, within red areas the water levels are highest during storm 27 and within the green indicated regions storm 120 is dominant.

In order to understand how these maximum water levels are reached, the propagation of surge will be discussed in the following two sections.

5.2.2 Surge propagation during storm 120 and 27

Although the landfall location of storm 120 and storm 27 is different, the storms surge formation processes are similar, these two storms will therefore be analysed together. The track and angle of storm 69 is very different from the other two storms and because of this reason this storm will be analysed separately since also the formation process is different from the other storms. Annex L shows the most important locations in Plaquemines Parish. This annex can be folded out in order to improve the readability of this chapter.

The model results show that during storm 120 and storm 27 in areas east of Plaquemines there is a flow towards the west during a relatively long period of time before the hurricane makes landfall. This forces the surge to pile up against the levees at Empire and Port Sulphur; winds in the Northern part of a hurricane are predominantly directed toward the west and therefore generate flows in this direction. The water levels and flows at the beginning of the storm surge formation process are shown in Figure 34 for storm 27 and in Figure 35 for storm 120. The water levels and flows which occur four hours later are shown in Figure 36 and Figure 37 respectively.

Before the eye of the hurricane makes landfall, the area west of the landfall location is influenced by the winds in the northwest quadrant of the storm. This results in the fact that water is blown away from the Plaquemines Parish levees. ADCIRC indicates that during this period these areas will become 'dry' and no flows are calculated anymore, these dry areas have a gray colour in the figures below. The northwest quadrant of the storm pushes the water from Barataria Bay onto the levees of Lafourche Parish, generating surge levels of up to 3.2 meter at this location for both storms(Figure 36 and Figure 37)

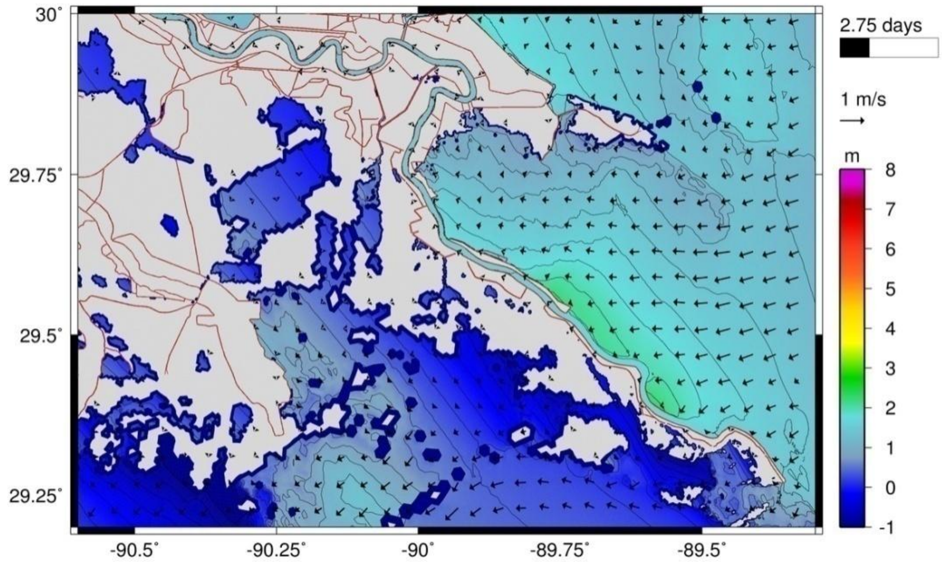


Figure 34. Surge propagation during storm 27. Arrows indicate flows, the colors represent the computed water levels.

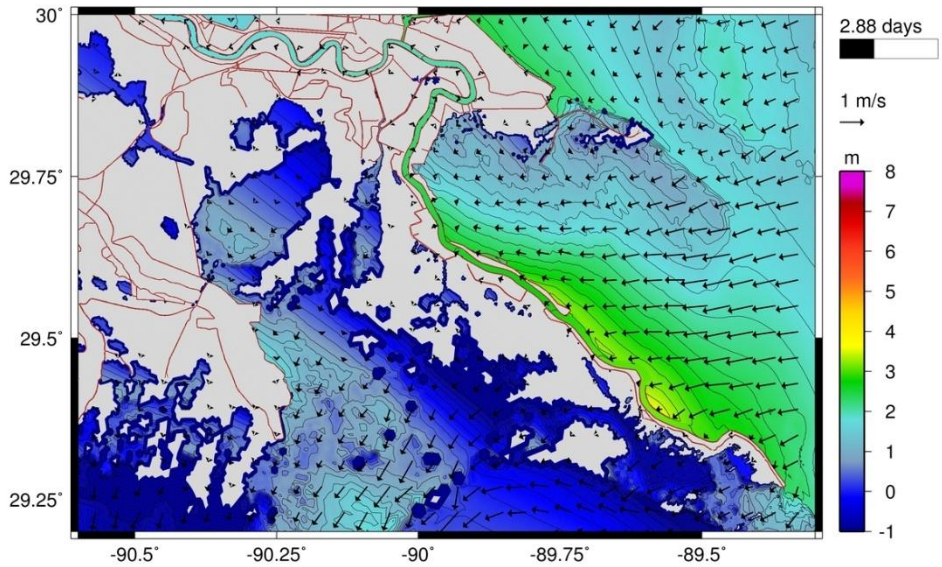


Figure 35. Surge propagation during storm 120. Arrows indicate flows, the colors represent the computed water levels.

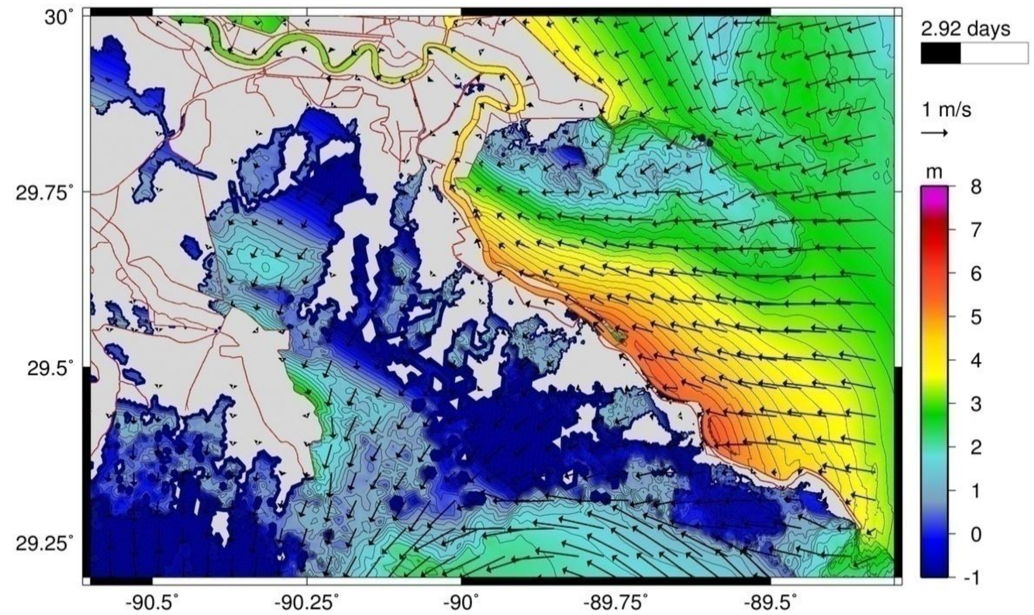


Figure 36 Surge propagation during storm 27. Arrows indicate flows, the colors represent the computed water levels. (3 hours later with respect to Figure 34)

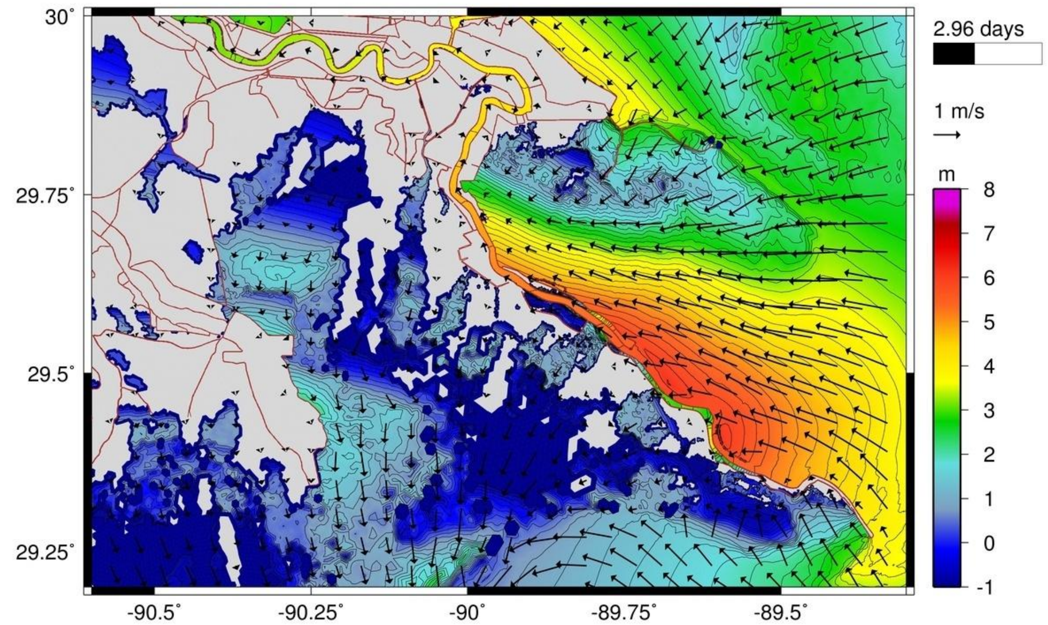


Figure 37. Surge propagation during storm 120. Arrows indicate flows, the colors represent the computed water levels. . (3 hours later with respect to Figure 35)

Changes in flows and water levels between the two storms will become larger as the hurricane reaches landfall. The most important difference between storm 120 and storm 27 is the landfall location, storm 120 makes landfall at Empire while storm 27 makes landfall west of Empire, at Nero).

While the flows in western direction keep pushing water against the levees near Pointe de la Hache, Port Sulphur and Empire the winds in the northwest quadrant will start to gradually change their direction toward the northwest. As the eye of the hurricane approaches the landfall location, the northward directed component of the wind will become more significant and flows will change their direction. The distance between a particular location and the eye of the hurricane determines the time at which winds and flows will start to change their direction toward the north (see Figure 38). If a storm moves from the south to the north, like storms 120 and 27, the direction of the winds on a location further away from the eye will change sooner than for a location close to the eye.

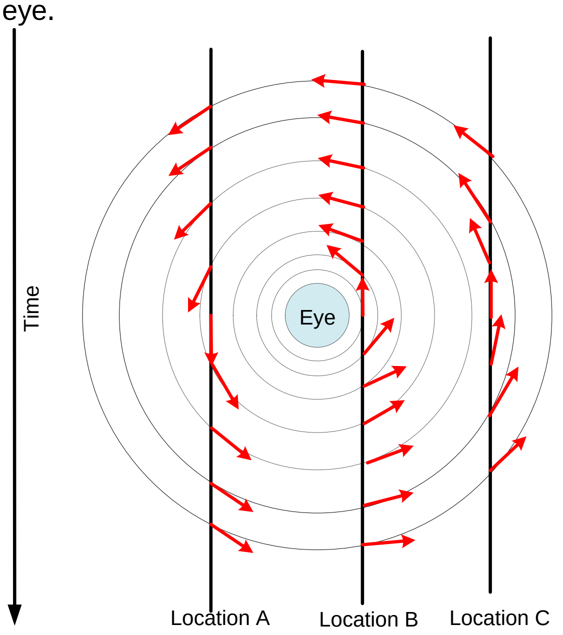


Figure 38. Changes of the wind direction in time for three hypothetical locations during a hurricane on the Northern Hemisphere. Red arrows indicate wind directions (not to scale). While the hurricane moves toward the north the wind direction changes depending the distance between the eye and the location of interest. Wind directions at locations close to the eye are predominantly directed toward the east or west during most of the time, while winds further away from the eye have a more northern (eastern quadrants) or southern direction (western quadrants).

Because the landfall location of storm 27 lies west of both Empire and Port Sulphur (the locations with the highest water levels), the winds at Empire and Port Sulphur will change sooner toward the northwest for storm 27 than for storm 120.

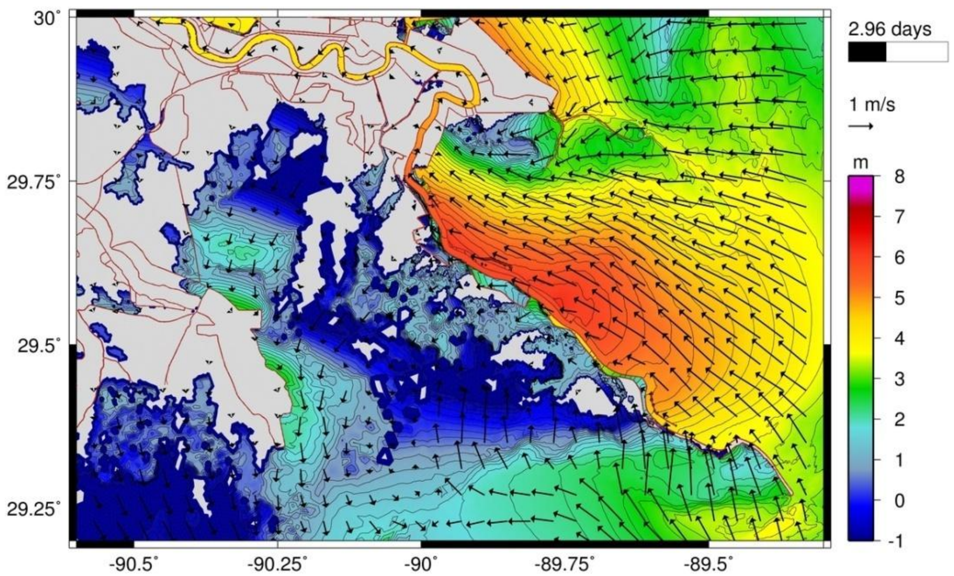


Figure 39. Surge propagation during storm 27. Arrows indicate flows, the colors represent the computed water levels (1 hour later with respect to Figure 36).

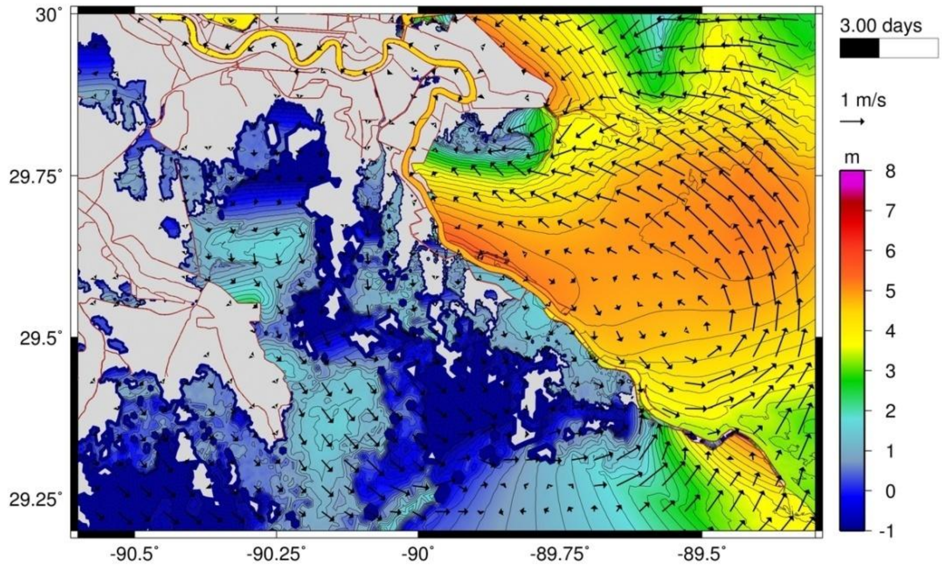


Figure 40. Surge propagation during storm 120. Arrows indicate flows, the colors represent the computed water levels (1 hour later with respect to Figure 37).

At Port Sulphur the eastern Mississippi river levees end. The Mississippi river flows from the northwest to the southeast at this location during normal conditions. A northwest directed flow is exactly opposite of the normal flow direction in the Mississippi river. Because of this wind direction a lot of water can flow upriver towards New Orleans; the model results show that this happens for both storms. Less water however flows upriver for storm 120 than for storm 27 due to the reason which is explained above (Figure 36 and Figure 37). Another reason for the differences between the amount of water which flows upriver towards new Orleans between the two storms is that during storm 120 the eye makes landfall at Empire and therefore winds speeds and flows are much lower here since the wind speeds within the eye of the hurricane are close to zero. For storm 27 the opposite is true, Empire is in this case located in the region with the maximum wind speeds, therefore large flow velocities exist and a lot of water is pushed upriver. The differences between the locations and the maximum flow velocities during this period are illustrated in Figure 39 and Figure 40.

The intensive north-western directed winds east of Plaquemines Parish in the northeast quadrant of storm 27 also force the surge to propagate towards the southern levees of St. Bernard Parish (Figure 39 and Figure 41). Since the flow speeds along the Eastern levees of Plaquemines are much lower during storm 120, water levels near south St. Bernard do not become as high as during storm 27 (see Figure 40 and Figure 42).

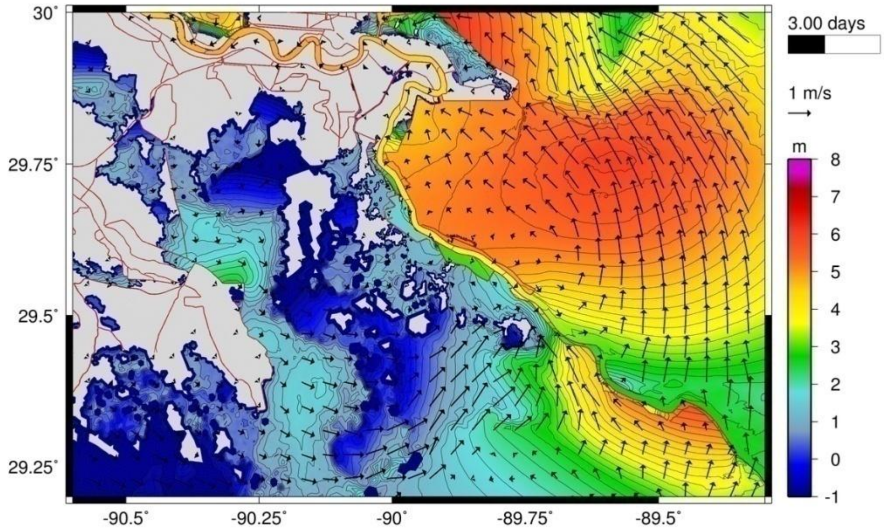


Figure 41. Surge propagation during storm 27. Arrows indicate flows, the colors represent the computed water levels (1 hour later with respect to Figure 39).

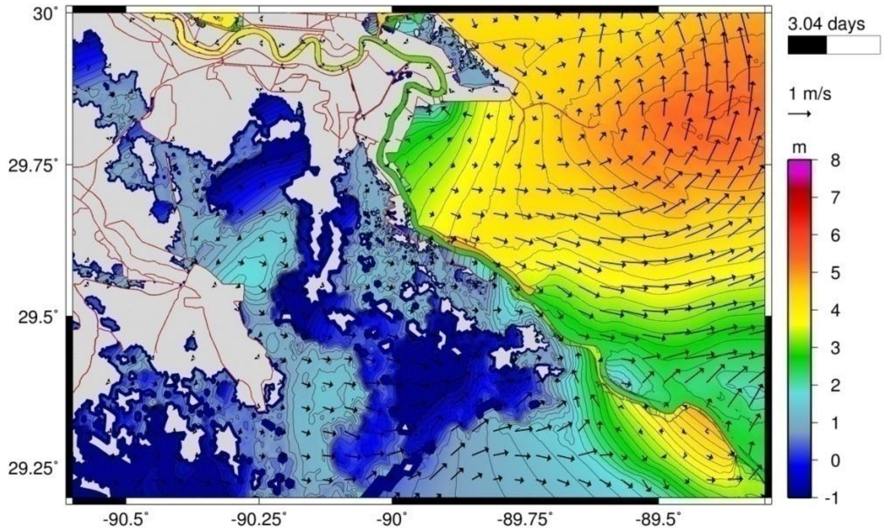


Figure 42. Surge propagation during storm 120. Arrows indicate flows, the colors represent the computed water levels (1 hour later with respect to Figure 40).

As the eye passes the landfall location, the winds in the southwest quadrant of the storm push the water of Barataria Bay onto the western levees of Plaquemines Parish. This effect can be clearly seen in the river bend near Boothville-Venice (Figure 39 - Figure 42). Since the landfall location of storm 27 lies west of the landfall location of storm 120, the length over which water is pushed onto the eastern levees of Plaquemines Parish is larger for storm 27.

When the eye passes the landfall location the winds in the north-western quadrant of the storm force the flow in the Mississippi River to once again change to its normal flow direction.

5.2.3 Surge propagation during storm 69

The landfall location and track of storm 69 is very different from the other two storms. The storm makes landfall in Houma approximately 60 km west of Plaquemines Parish and travels toward the north north-east, approaching the west of New Orleans. The eye does not travel over the city but remains at a distance from New Orleans. (See Figure 27). Therefore the entire study area is influenced by the northeast and southeast quadrant of the storm. The water levels and flows at the beginning of the storm surge formation process are shown in Figure 43. The situation 2 hours later is presented in Figure 44.

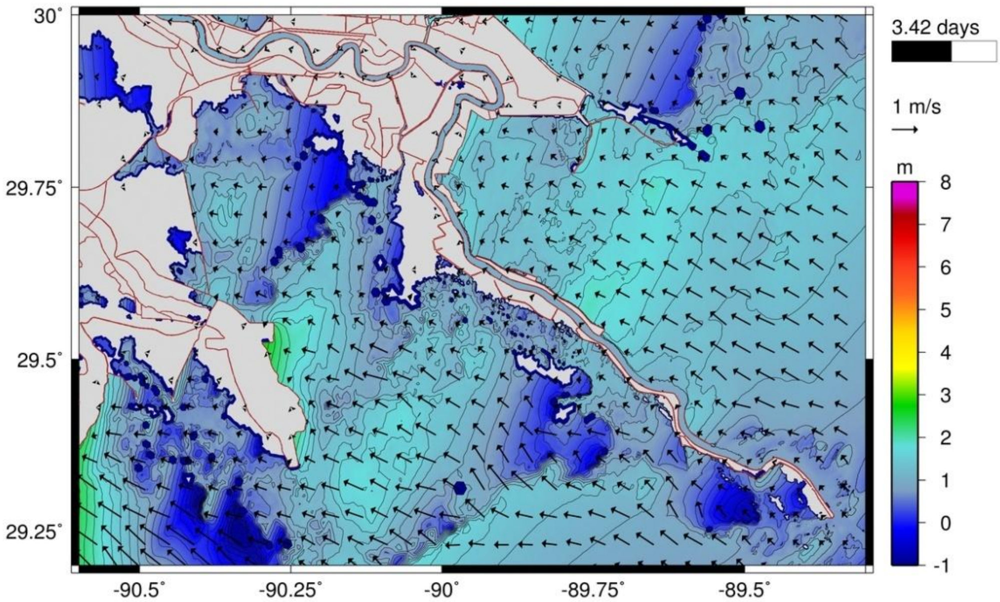


Figure 43. Surge propagation during storm 69. Arrows indicate flows, the colors represent the computed water levels .

As the storm approaches the westerly directed wind in the outer regions of the storm push the water towards the west and northwest. The model shows that water levels of 3 meter are produced on the eastside of Lafourche Parish. As the storm progresses (Figure 44) the surge also builds up east of Belle Chase in Plaquemines Parish (see Figure 31).

Because the wind speeds are not as high at large distances from the eye, the water levels will not reach extreme values like with the other two storms at most of the locations on the eastside of Plaquemines Parish.

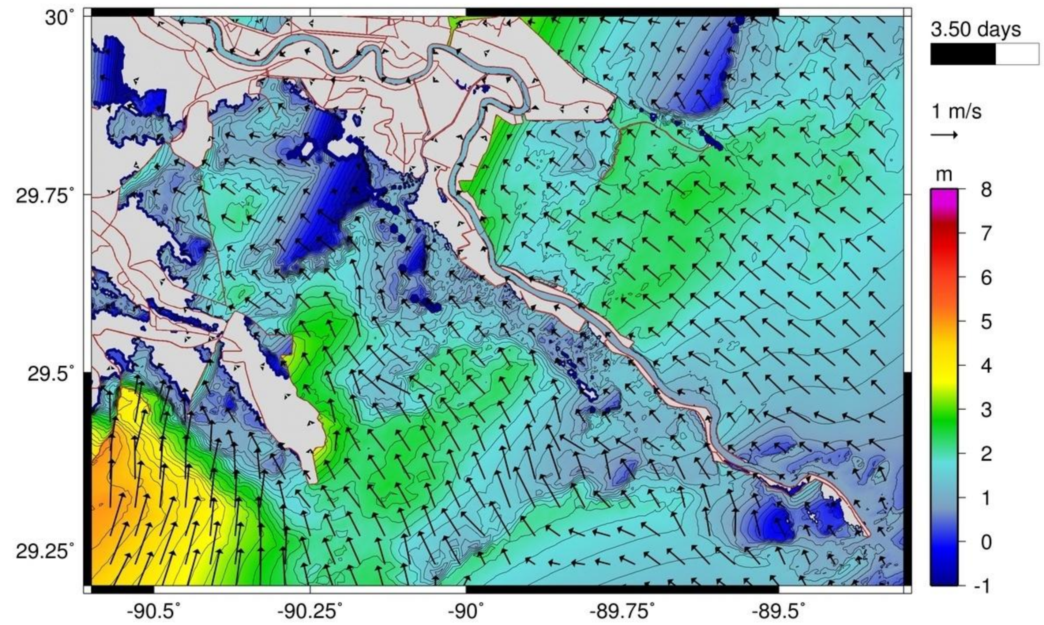


Figure 44 Surge propagation during storm 69. Arrows indicate flows, the colors represent the computed water levels (2 hour later with respect to Figure 43).

The storm approaches under an angle and therefore the winds in the northwest quadrant of the storm will move to the north as it approaches land.(and not toward the northwest like with hurricanes 27 and 120). This results in a build up of surge against the Southern levees of St. Bernard and Lafourche Parish. In Lafourche Parish the western levees are overtopped and the area floods. The same happens at the border of Plaquemines Parish and St. Bernard, in the Northwest corner close to Braithwaite (Figure 45).

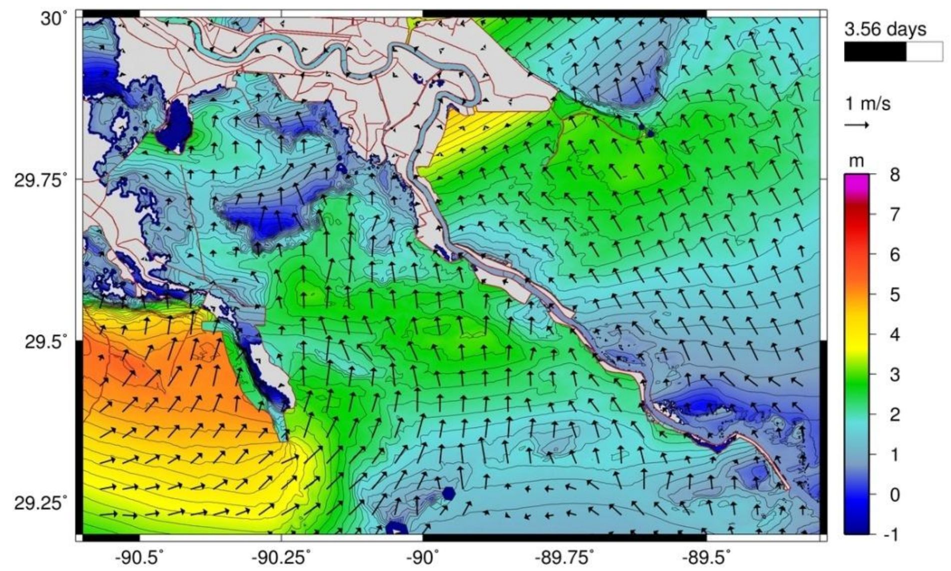


Figure 45. Surge propagation during storm 69. Arrows indicate flows, the colors represent the computed water levels (1.5 hour later with respect to Figure 44).

Northern directed winds push the water from the Gulf of Mexico and Barataria Bay also against the western levees of Plaquemines Parish and the southern levees of Jefferson Parish (Figure 45 and Figure 46).

A large surge would be expected south of Jefferson Parish because the wind forces the water to flow towards the north and the northeast. These water levels stay however relatively low because the levees of Lafourche Parish are blocking most of the flow in this direction. This is the most important reason why the absolute 1:100 year water levels are relatively low west of Plaquemines Parish and near Jefferson Parish compared to other areas (see Figure 25)

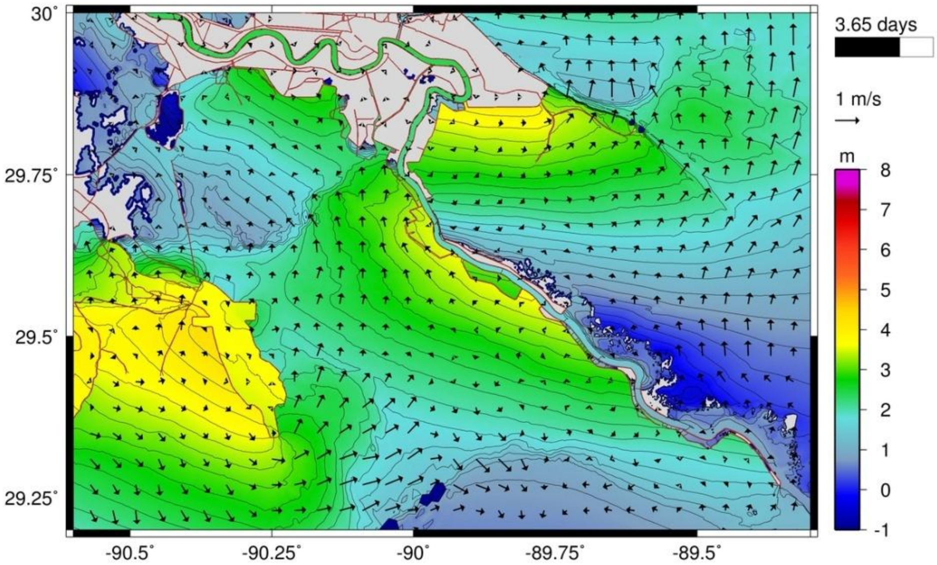


Figure 46. Surge propagation during storm 69. Arrows indicate flows, the colors represent the computed water levels (2 hours later with respect to Figure 45).

5.3 Preferred spillway locations

From the analysis above, the following can be concluded regarding the location of spillways in Plaquemines Parish.

- Spillways should preferably not be created in the most densely populated areas; approximately 71% of the inhabitants of Plaquemines live in the southern part of the Parish, south of Pointe de la Hache on Westbank of the Mississippi.
- Because the Mississippi flows from the north-west towards the south-east, a spillway would be expected to be most effective in reducing water levels at the eastern levees of Plaquemines if the spillway is located in the northwest quadrant of a storm. In this case, the winds of the storm would push the water in a direction perpendicular to the flow direction of the Mississippi, and this could create flows through the spillways across the river. A spillway in the western quadrants of a storm would allow this (e.g. location A in Figure 38). A spillway at the most western part of Plaquemines might therefore be a good choice.
- In order to reduce water levels at the western levees of Plaquemines Parish a flow towards the Northeast would allow the surge to cross the river. These flows can be generated by winds in the southeast quadrant of a hurricane. A spillway located east of a landfall location will therefore be most effective in reducing these surge levels (see location B and C in Figure 38). A location in the south of Plaquemines Parish might therefore be suitable to reduce water levels at the inner bend of the river close to Boothville-Venice.
- Flows are the strongest when windspeeds are large. A spillway at a location with high flow speeds (in the correct direction) will also have a large effect on the storm surge. The area with the highest windspeeds is located near the center of a storm, at the eye-wall. Since there is a high variability of potential landfall locations and storm sizes, a single geographical location with maximum flow speeds cannot be identified. A multitude of smaller spillways throughout Plaquemines Parish could therefore increase the chance that a spillway is located near area with the maximum wind speeds.
- During both storm 27 and storm 120 the surge builds up at approximately the same location (at Empire) this location would therefore be ideal for a spillway.

5.4 Selected Spillway Configurations

With the preferred spillway locations in mind, a total of five spillway scenarios have been selected. These five spillway scenarios are explained in this section.

5.4.1 Plaquemines None

By researching the removal of all levees in Plaquemines Parish the upper limit of what could be achieved by creating Spillways becomes visible. Figure 47 shows the locations of the areas where the levees have been removed. This spillway configuration will be referred to as “Plaquemines None”. For this configuration only the levees have been removed, no further modifications to the model have been applied; the natural river banks which were formed in the past are therefore still present at a number of location close to the Mississippi River.

Figure 47. Plaquemines None. The protected areas are represented in yellow. The levees have been removed around the red areas.

5.4.2 Plaquemines CDP

With this configuration the most densely inhabited areas of Plaquemines Parish are protected. The villages (CDPs) are located in the southern part of the Parish (see section 5.1). These Census Designated Places will remain to be protected in this spillway configuration, 71% of the inhabitants will have protection from levees. Also an important industrial complex which is located close to Ironton will be surrounded by levees. Hereto new levees have been created in the model, for these levees the same levee height has been used as the Mississippi river levees.

Approximately 50% of the total levee system in Plaquemines Parish has been removed; Figure 48 shows these locations. Because a large part of the levees in the north-western part of Plaquemines Parish is removed, the winds in the northwest quadrant of storm 120 and 27 should allow the surge to propagate across the river.

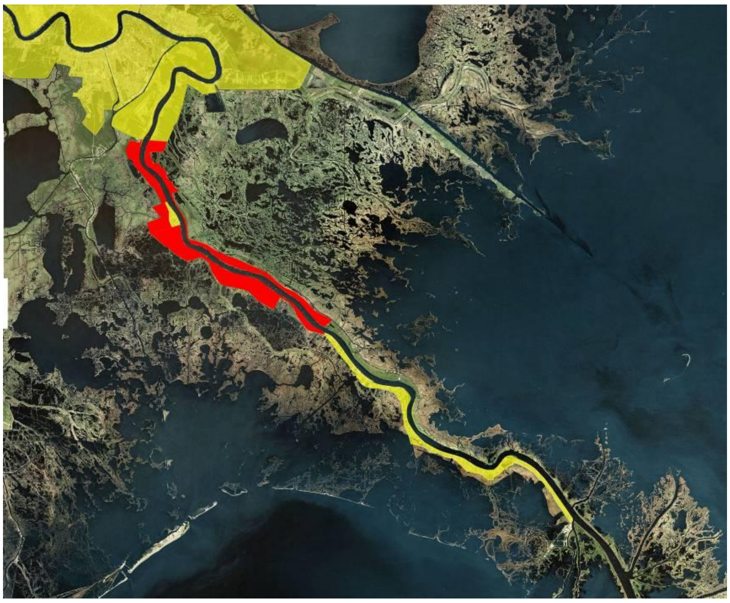


Figure 48. Plaquemines CDP. The protected areas are represented in yellow. The levees have been removed around the red areas.

5.4.3 Plaquemines Minimum

In order to influence as little of the area as possible a spillway alignment has been chosen where a relatively short length of the levees is altered. A total of five short spillways have been defined; four of these spillways are located in such a way that Western and North-western directed flows are allowed to propagate across the river.

These are located at (From north to south):

- North of Alliance on both sides of the river (+/- 2 km in length);
- At Harlem on both sides of the river (+/- 2 km in length);
- North of Port Sulphur at Soloca, only on the west side of the river (+/- 3 km);
- Empire; levees at both sides of the river have been removed at this location (+/- 3 km).

The fifth spillway of approximately 1.6 km in length between Boothville-Venice and Buras-Triumph is aimed at reducing high water levels in the inner bend which are produced by flows in northern direction in the southeast quadrant of the storm.

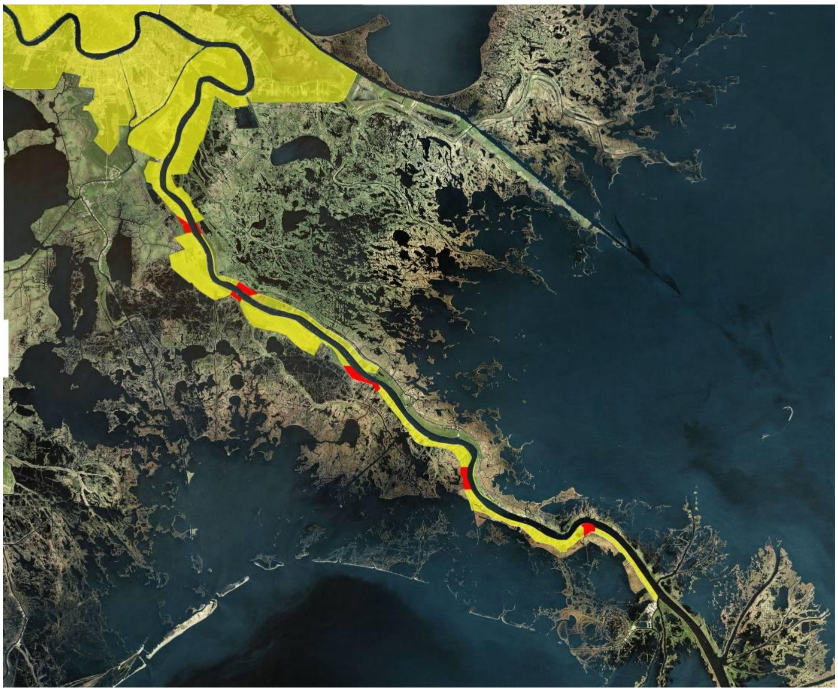


Figure 49. Plaquemines Minimum. The protected areas are represented in yellow. The levees have been removed around the red areas.

5.4.4 LACPR Spillways

Previously two levee alignments had been examined for the Louisiana Coastal Protection and Restoration (LACPR) Program (de Jong, 2007). One of these alignments was Plaquemines None, the other alignment consisted of three spillways which were located at Buras-Triumph, at Port Sulphur, and at Willis point. This study concluded that the hydraulic effectiveness of the selected configuration was not optimal and suggested that the addition of a fourth spillway between Nero and Ironton could increase the effectiveness of the spillways.

This recommendation is with some modifications included as a fourth spillway configuration within this study, and will be referred to as the LACPR spillways. Figure 50 shows the location of the spillways for this levee alignment.

The following parts of the levee system have been removed (from north to south):

- The levees near Willis Point, between Aliance and Belle Chase on both sides of the river (+/- 11 km in length);
- The levees between Ironton and Nero on both sides of the river (+/- 2 km in length);
- The levees at Port Sulphur on the Westside of the Mississippi river (+/- 7 km in length);
- The levees at Buras-Triumph, west of Boothville-Venice on the Westside of the Mississippi river (+/- 2 km in length);

In contrast to the LACPR study, no modifications have been applied to the bathymetry at the locations of the spillways.

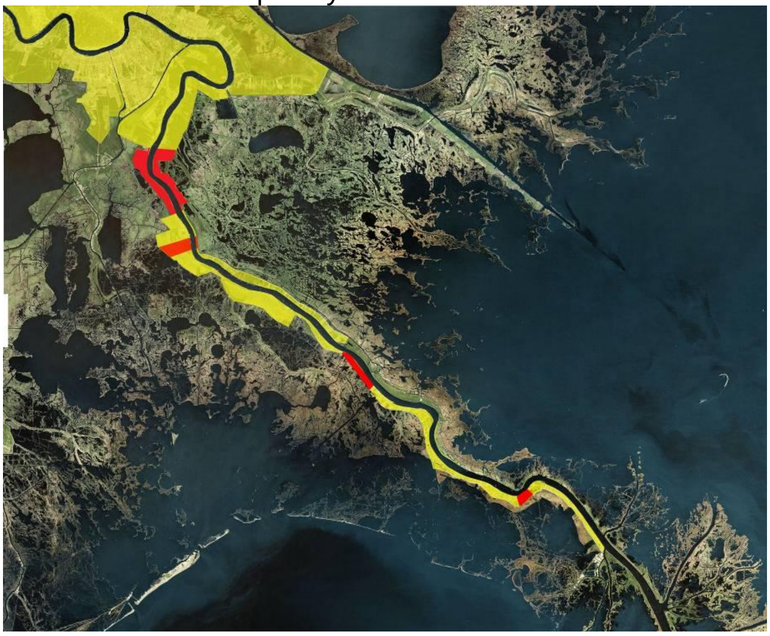


Figure 50. LACPR Spillways, the protected areas are represented in yellow. The levees have been removed around the red areas.

5.4.5 Lowered LACPR Spillways

In order to improve the hydraulic connectivity between the east and west sides of the Mississippi river it is also possible to lower the bottom level of the spillways. Some natural river banks still exist alongside the Mississippi River, these river banks could also block the flow during a hurricane and lead to a build-up of surge. Especially in the northern part of Plaquemines Parish these river banks exist.

In order to investigate the influence of the elevation of the spillways another scenario has been defined which has the same spillway locations as the previous levee configuration (section 5.5.4). Only this time the natural river banks have been removed at the spillway locations. In order to do this the bathymetry within the model has been adjusted to the same level as the surrounding bottom elevations. At each of the spillway locations the bottom has been flattened. For the southernmost two spillways little modifications were done to the bathymetry because the natural river banks at these locations were very low or did not exist.

5.5 Hydrodynamic effects of different spillway configurations

Each of the spillway configurations has been modelled with ADCIRC for the three selected storms. This section will discuss the maximum water levels and the differences with the base case for each spillway configuration. Within this section only pictures are presented of the combined maximum water levels of the three selected storms. The annexes contain maximum water level and maximum water level differences for the separate storms. A map of the most important locations can be found in Annex L.

5.5.1 Plaquemines None

Figure 51 shows the combination of the maximum water levels for Plaquemines None. For each location the combined maximum water level of all three storms is plotted. So the figure is the result of three model simulations. Figure 52 shows the computed surge level differences between the maximum surge of Plaquemines None and the maximum surge levels for the original levee configuration for the three storms combined.

Figures of the maximum water levels of each separate storm have been included in annex I.2 , Figures of the differences between Plaquemines None and the base case for each storm are presented in annex J.1. Table 11 displays the maximum surge levels for Plaquemines None and the maximum water level differences between Plaquemines None and the base case.

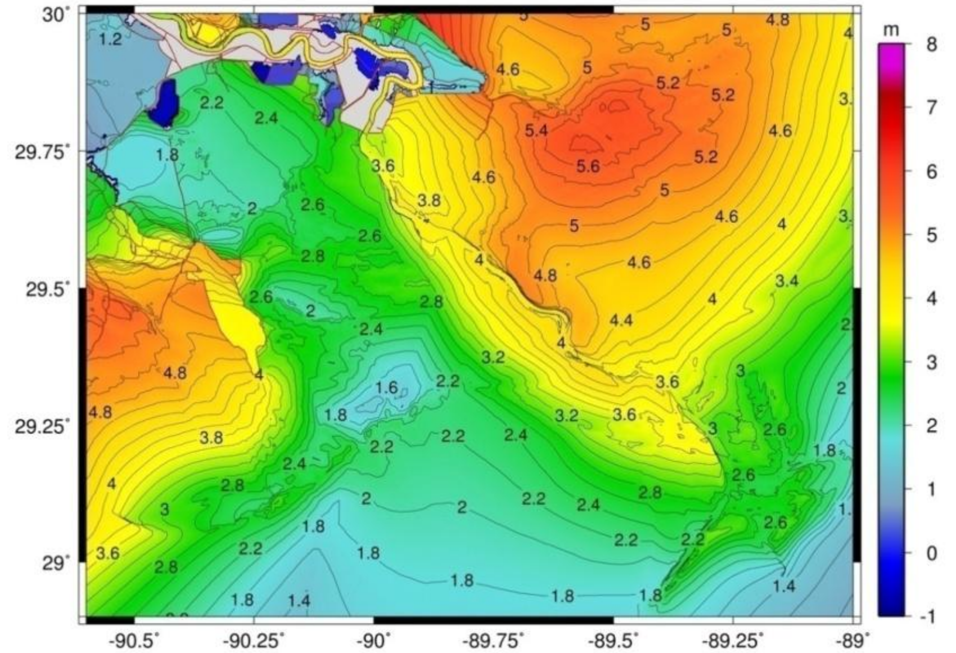


Figure 51. Composition of maximum water levels for the storms 27,69 and 120 for Plaquemines None

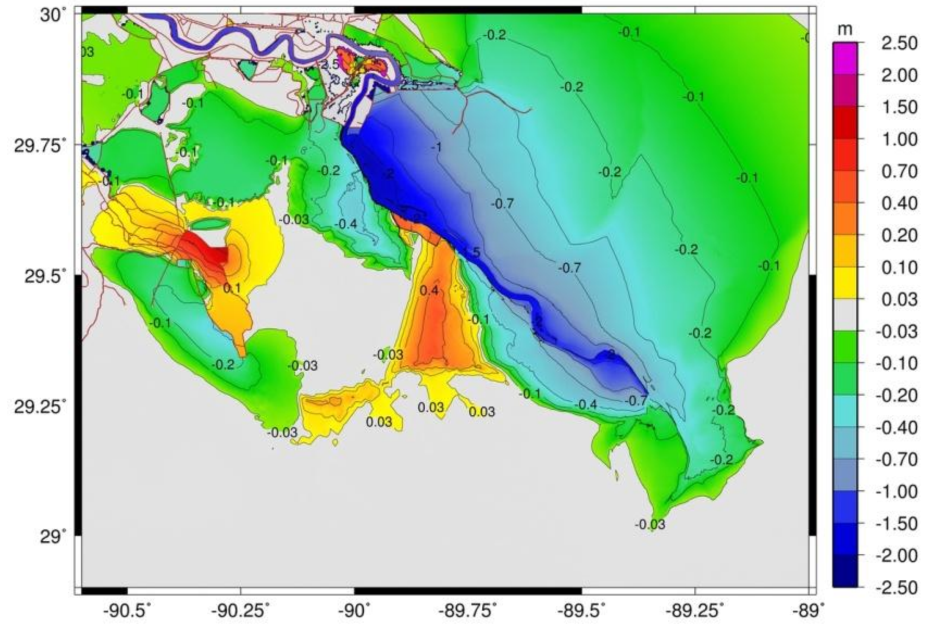


Figure 52. Maximum water Level differences between Plaquemines none and the original levee alignment for the three storms. Negative values indicate a surge reduction, positive values indicate an increase in maximum water levels.

Table 11. Maximum surge levels for Plaquemines None and the surge level differences with the base case.

		Maximum Surge Levels Plaquemines None (m)			Surge Level differences with current levee alignment(m)			Maximum Surge Levels and differences for a combination of three storms (m)		
Area	**Location**	Storm 27	Storm 69	Storm 120	Storm 27	Storm 69	Storm 120	Plaquemines None	Base Case	Surge level differences
	New Orleans (Mississippi River)	3,6	3,4	2,7	-1,2	0,8	-1,7	3,6	4,8	-1,2
	Jefferson Parish South	2,5	2,9	1,4	1,3	-0,2	0,7	2,9	3,1	-0,2
	Lafourche East	1,4	3,6	1,0	0,0	0,4	0,0	3,6	3,2	0,4
St Bernard	St Bernard Parish East	5,0	1,8	4,8	-0,1	0,0	0,0	5,0	5,1	-0,1
	St Bernard Parish South	5,3	4,0	3,0	-0,5	-0,1	-0,8	5,3	5,8	-0,5
	Braithwaite	4,0	4,3	1,7	-1,2	-0,1	-0,7	4,3	5,2	-0,9
	Belle Chase East	2,9	2,9	2,3	-2,3	-0,7	-0,8	2,9	5,2	-2,3
Plaquemines Parish West	Willis Point West	2,5	2,9	1,4	1,4	-0,2	0,6	2,9	3,1	-0,2
	Nero West	3,5	2,8	3,0	0,9	-0,8	1,7	3,5	3,6	0,0
	Port Sulphur West	4,1	2,5	3,6	-0,5	-1,0	1,5	4,1	4,6	-0,5
	Empire West	4,3	2,2	3,6	-0,8	-0,3	0,3	4,3	5,1	-0,8
	Boothville-Venice West	2,6	1,6	1,8	-2,7	-0,5	-3,0	2,6	5,3	-2,7
Plaquemines Parish East	Willis Point East	3,4	3,0	2,2	-2,0	-0,4	-1,4	3,4	5,3	-2,0
	Nero East	4,0	2,1	3,9	-1,8	0,4	-1,8	4,0	5,9	-1,8
	Port Sulphur East	4,1	2,3	4,0	-1,8	0,6	-1,9	4,1	5,9	-1,8
	Empire (Mississippi River)	4,1	1,8	4,3	-1,6	0,5	-1,6	4,3	5,9	-1,6
	Boothville-Venice (Mississippi River)	3,2	1,0	3,6	-0,5	0,2	-0,5	3,6	4,2	-0,5

By analysing the figures and table above as well as the figures displayed in the annex, the following can be concluded:

- For most locations a water level reduction is computed. The removal of the levees has resulted in a reduction of surge east of Plaquemines Parish ranging from 0.5 to 2.0 meter.

- Local increases in surge elevation can be seen at various locations along the west side of Plaquemines Parish for storm 120 and 27. Those locations are shielded from the storm with the current existing levee configuration and therefore have low water levels in the base case. For storm 69 the water level increases east of Plaquemines parish because of the same reason.
- On the Mississippi river the maximum water level reduces with 1.2 meter. For storm 69 the water level however increases at this location with 0,8 meter; the removal of the levees now allows surge to propagate upriver during this storm. Since the storm surge on the Mississippi river is much higher for storm 27 the increase in water level at this location for storm 69 does not influence the maximum combined water levels.
- South of Jefferson Parish the maximum water level reduces slightly, about 20 cm. During storm 69 the flow is partly diverted away from this area in eastward direction across and into the Mississippi river. At the same location the maximum surges increase during storm 120 and storm 27.
- East of St. Bernard the maximum water level changes are minimal. Only for storm 27 a small reduction of 10 cm is computed.
- The water levels are reduced for all storms at Braithwaite. Storm 27 does not longer produce the highest water levels at this location. The large reduction of 1.2 meter for this storm has resulted in the fact that storm 69 is now dominant for this location (see also Figure 123 in Annex K.1).
- At the Eastside of Lafourche Parish the removal of all levees result in an increase in the maximum surge levels by 0.4 m. This is caused by a change in water levels of storm 69. For storms 120 and 27 there is no change at this location. Figure 52 shows that the increase by 40 cm causes the levees at this location to overtop, therefore creating larger water level differences within the ring levee of Lafourche Parish.

5.5.2 Plaquemines CDP

Figure 53 shows the combination of the maximum water levels for Plaquemines CDP. Figure 54 shows the computed surge level differences between the maximum surge of Plaquemines CDP and the original levee configuration for a combination of three storms.

Figures of the maximum water levels of each separate storm have been included in annex I.3, Figures of the differences between Plaquemines CDP and the base case for each storm are presented in annex J.2. Table 12 displays the maximum surge levels for Plaquemines CDP and the maximum water level differences between Plaquemines CDP and the base case.

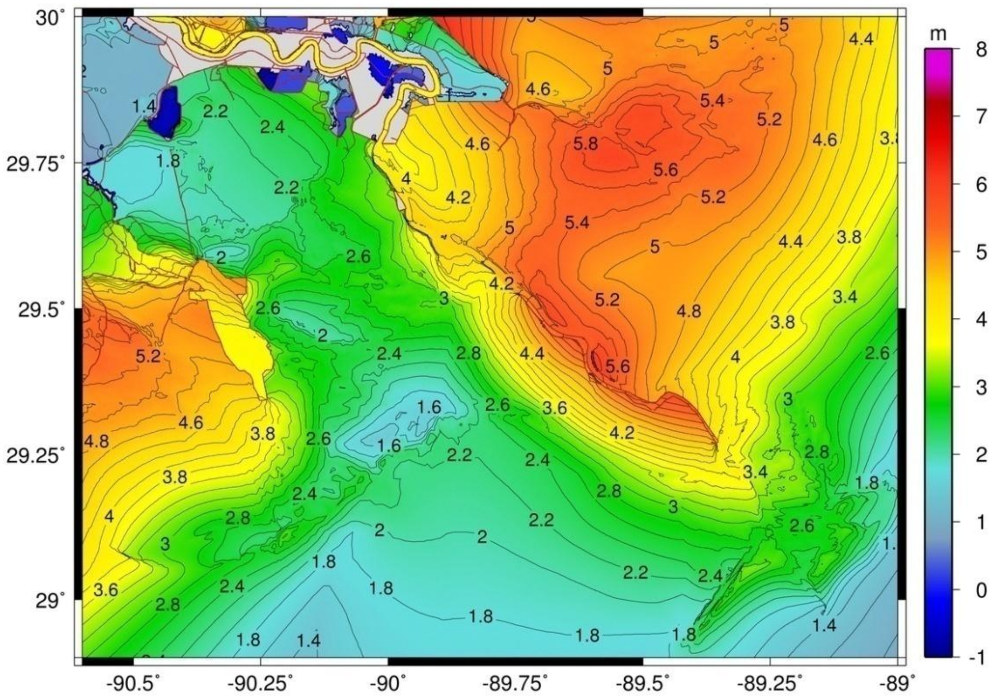


Figure 53. Composition of maximum water levels for the storms 27,69 and 120 for Plaquemines CDP

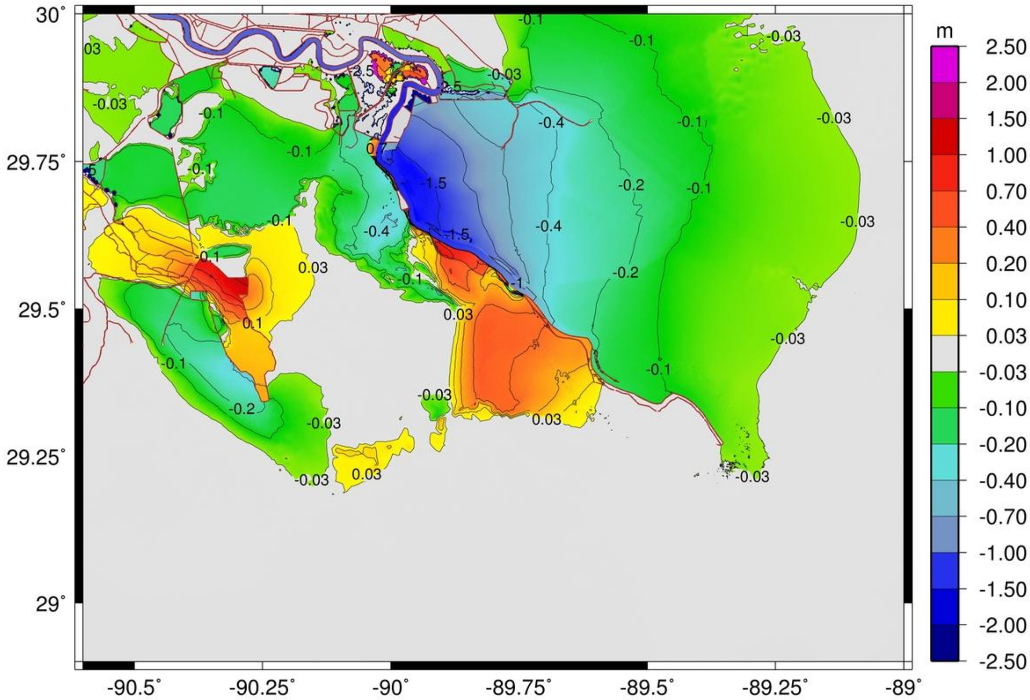


Figure 54. Maximum water Level differences between Plaquemines CDP and the base case for a combination of three storms. Negative values indicate a surge reduction, positive values indicate an increase in maximum water levels.

Table 12. Maximum surge levels for Plaquemines CDP and the surge level differences with the base case

		Maximum Surge Levels Plaquemines CDP (m)			Surge Level differences with current levee alignment(m)			Maximum Surge Levels and differences for a combination of three storms (m)		
Area	**Location**	Storm 27	Storm 69	Storm 120	Storm 27	Storm 69	Storm 120	Plaquemines CDP	Base Case	Surge level differences
	New Orleans (Mississippi River)	3,7	3,4	2,9	-1,1	0,7	-1,4	3,7	4,8	-1,1
	Jefferson Parish South	2,5	2,9	1,5	1,3	-0,2	0,7	2,9	3,1	-0,2
	Lafourche East	1,4	3,6	1,0	0,0	0,4	0,0	3,6	3,2	0,4
St Bernard	St Bernard Parish East	5,1	1,8	4,8	0,0	0,0	0,0	5,1	5,1	0,0
	St Bernard Parish South	5,3	4,0	3,2	-0,5	-0,1	-0,6	5,3	5,8	-0,5
	Braithwaite	4,2	4,3	1,8	-0,9	-0,1	-0,7	4,3	5,2	-0,9
	Belle Chase East	3,8	3,3	2,0	-1,4	-0,2	-1,0	3,8	5,2	-1,4
Plaquemines Parish West	Willis Point West	5,2	3,5	4,9	4,0	0,4	4,1	5,2	3,1	2,1
	Nero West	3,9	2,8	3,5	1,2	-0,8	2,3	3,9	3,6	0,3
	Port Sulphur West	5,0	3,3	3,2	0,4	-0,3	1,1	5,0	4,6	0,4
	Empire West	5,2	2,7	3,5	0,2	0,3	0,2	5,2	5,1	0,2
	Boothville-Venice West	5,3	2,0	4,8	0,0	0,0	0,0	5,3	5,3	0,0
Plaquemines Parish East	Willis Point East	3,8	3,0	2,8	-1,6	-0,4	-0,8	3,8	5,3	-1,6
	Nero East	4,5	2,0	4,3	-1,4	0,4	-1,3	4,5	5,9	-1,4
	Port Sulphur East	5,1	2,2	5,2	-0,8	0,5	-0,7	5,2	5,9	-0,7
	Empire (Mississippi River)	5,4	1,7	5,7	-0,2	0,3	-0,2	5,7	5,9	-0,2
	Boothville-Venice (Mississippi River)	3,7	0,9	4,1	-0,1	0,1	0,0	4,1	4,2	0,0

By analysing the figures and table above as well as the figures displayed in the annex, the following can be concluded:

- Water levels near the western levees of Plaquemines Parish, south of Empire are not influenced by the removal of the levees in the northern part of Plaquemines.
- Water levels near the western levees of Plaquemines Parish, north of Empire, but south of Ironton show an increase of the maximum water levels of up to 40 cm. This can be attributed by the huge volume of water which is pushed across the Mississippi during storm 120 and storm 27. Figure 124 in annex K.2 shows that for this particular area storm 27 becomes dominant; storm 69 produced the highest water levels for these locations in the base case.
- The increased water levels west of the Mississippi have resulted in the overtopping of the western levees. This can be attributed to the fact that the western levees have a lower elevation than the eastern levees. Without elevating the western levees, inundation in the ring levees around Empire and Port sulphur would be more common.
- Water levels decrease up to 1.6 m at the eastside of Plaquemines, close to Ironton, Nero and Willis Point
- On the Mississippi river the maximum water level reduces with 1.1 meter. Like Plaquemines None, storm 69 increases water levels at this location by 0.8 meter.
- An increase in the maximum surge levels of 40 cm at the Eastside of Lafourche Parish causes the levees to overtop in Lafourche during storm 69.
- Close to St. Bernard Parish and Braithwaite reductions of 50 to 140 cm are calculated.

5.5.3 Plaquemines Minimum

Figure 55 shows the combination of the maximum water levels for Plaquemines Minimum. Figure 56 shows the computed surge level differences between the maximum surge of Plaquemines Minimum and the original levee configuration.

Figures of the maximum water levels of each separate storm have been included in annex I.4, Figures of the differences between Plaquemines Minimum and the base case for each storm are presented in annex J.3.
Table 13 displays the maximum surge levels for Plaquemines Minimum and the maximum water level differences between Plaquemines Minimum and the base case.

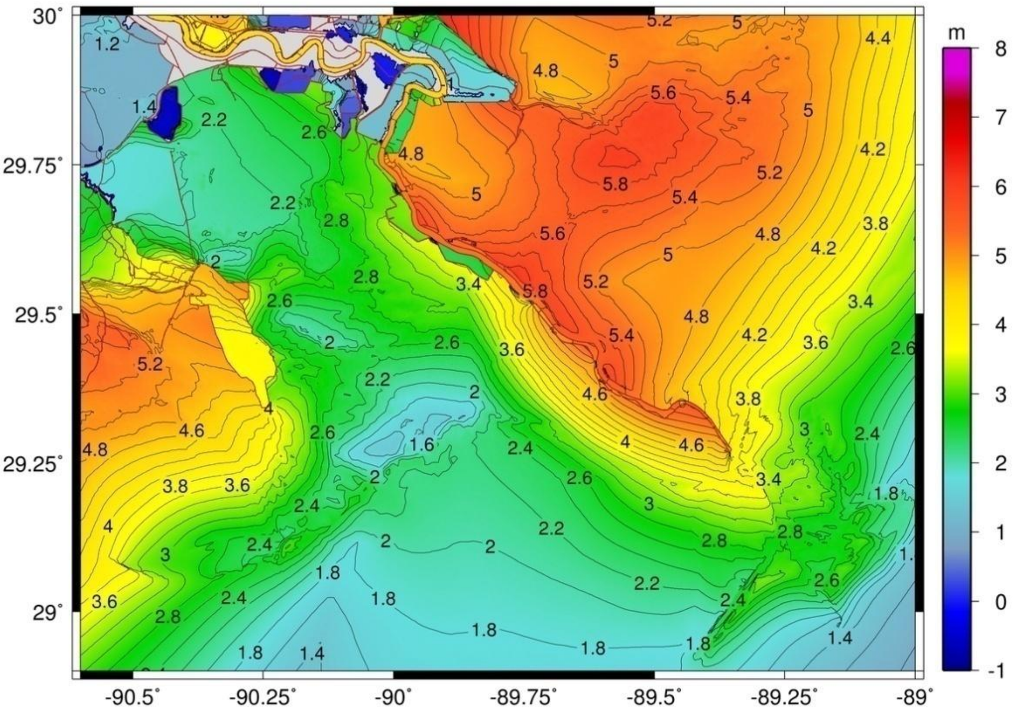


Figure 55. Composition of maximum water levels for the storms 27,69 and 120 for Plaquemines Minimum

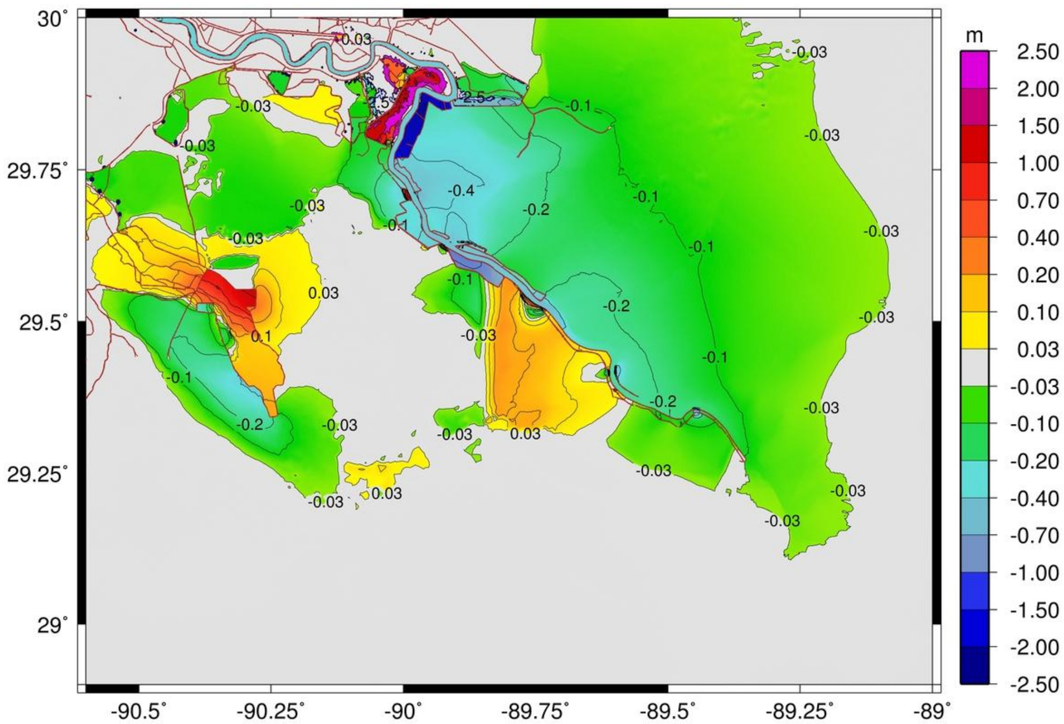


Figure 56. Maximum water level differences between Plaquemines Minimum and the base case for a combination of three storms. Negative values indicate a surge reduction, positive values indicate an increase in maximum water levels.

Table 13. Maximum surge levels for Plaquemines Minimum and the surge level differences with the base case

		Maximum Surge Levels Plaquemines Minimum (m)			Surge Level differences with current levee alignment(m)			Maximum Surge Levels and differences for a combination of three storms (m)		
Area	**Location**	Storm 27	Storm 69	Storm 120	Storm 27	Storm 69	Storm 120	Plaquemines Minimum	Base Case	Surge level differences
	New Orleans (Mississippi River)	4,3	3,0	3,7	-0,5	0,3	-0,6	4,3	4,8	-0,5
	Jefferson Parish South	1,6	3,0	0,9	0,4	-0,1	0,2	3,0	3,1	-0,1
	Lafourche East	1,4	3,6	1,0	0,0	0,4	0,0	3,6	3,2	0,4
St Bernard	St Bernard Parish East	5,1	1,8	4,8	0,0	0,0	0,0	5,1	5,1	0,0
	St Bernard Parish South	5,6	4,1	3,6	-0,2	0,0	-0,3	5,6	5,8	-0,2
	Braithwaite	4,9	4,3	1,9	-0,3	-0,1	-0,5	4,9	5,2	-0,3
	Belle Chase East	4,8	3,4	2,6	-0,4	-0,1	-0,5	4,8	5,2	-0,4
Plaquemines Parish West	Willis Point West	5,3	2,1	4,7	4,1	-1,0	3,8	5,3	3,1	2,2
	Nero West	3,1	3,5	2,1	0,5	0,0	0,9	3,5	3,6	0,0
	Port Sulphur West	4,7	3,2	3,4	0,1	-0,3	1,3	4,7	4,6	0,1
	Empire West	4,6	2,8	4,7	-0,5	0,4	1,4	4,7	5,1	-0,4
	Boothville-Venice West	5,2	1,9	4,8	-0,1	-0,1	0,0	5,2	5,3	-0,1
Plaquemines Parish East	Willis Point East	4,9	3,2	3,1	-0,5	-0,2	-0,5	4,9	5,3	-0,5
	Nero East	5,4	1,7	5,3	-0,5	0,1	-0,3	5,4	5,9	-0,5
	Port Sulphur East	5,3	2,0	5,3	-0,6	0,3	-0,6	5,3	5,9	-0,6
	Empire (Mississippi River)	5,4	1,6	5,7	-0,3	0,2	-0,2	5,7	5,9	-0,2
	Boothville-Venice (Mississippi River)	3,7	0,9	4,1	-0,1	0,1	-0,1	4,1	4,2	-0,1

By analysing the figures and table above as well as the figures displayed in the annex, the following can be concluded:

- Surge levels are reduced for most locations east of Plaquemines Parish, ranging from 10 to 60 cm.
- Water levels near the western levees of Plaquemines Parish, south of Empire are barely influenced by the spillway located in the River bend at that location. The capacity of the spillway seems too small to effectively reduce the water levels at Boothville-Venice when winds in the southeast quadrant of the storm push the water against the levee.
- The spillway located at Empire reduces the water lever east of this location (on the Mississippi River) by approximately 20 cm. At other locations on the Mississippi River close to the southern spillways similar reductions are computed.
- Further upstream the Mississippi river the reductions increase towards 0.5 meter at New Orleans.
- West of Plaquemines, between Empire and Pointe de la Hache the maximum surge levels becomes higher, the spillways located at Port Sulphur and Empire are responsible for these changes. This could form a problem for the western levees in this area because those levees are relatively low and could be overtopped.
- The two spillways located at Alliance and Harlem reduce the water levels east and west of Plaquemines Parish by approximately 60 cm.

5.5.4 LACPR Spillways

Figure 57 shows the combination of the maximum water levels for the LACPR spillways. Figure 58 shows the computed surge level differences between the maximum surge of the LACPR Spillways and the original levee configuration.

Figures of the maximum water levels of each separate storm have been included in annex I.56, Figures of the differences between the LACPR Spillways and the base case for each storm are presented in annex J.4. Table 14 displays the maximum surge levels for the LACPR Spillways and the maximum water level differences between the LACPR Spillways and the base case.

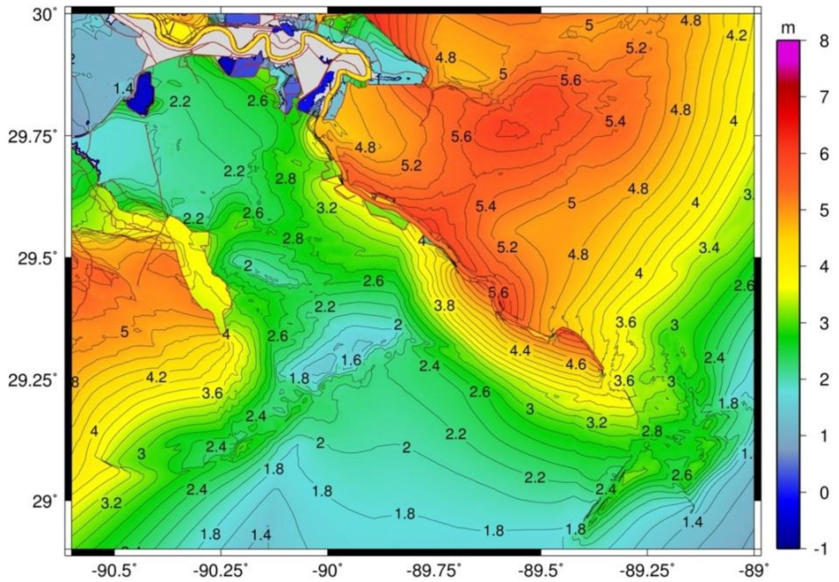


Figure 57. Composition of maximum water levels for the storms 27,69 and 120 for the LACPR Spillways

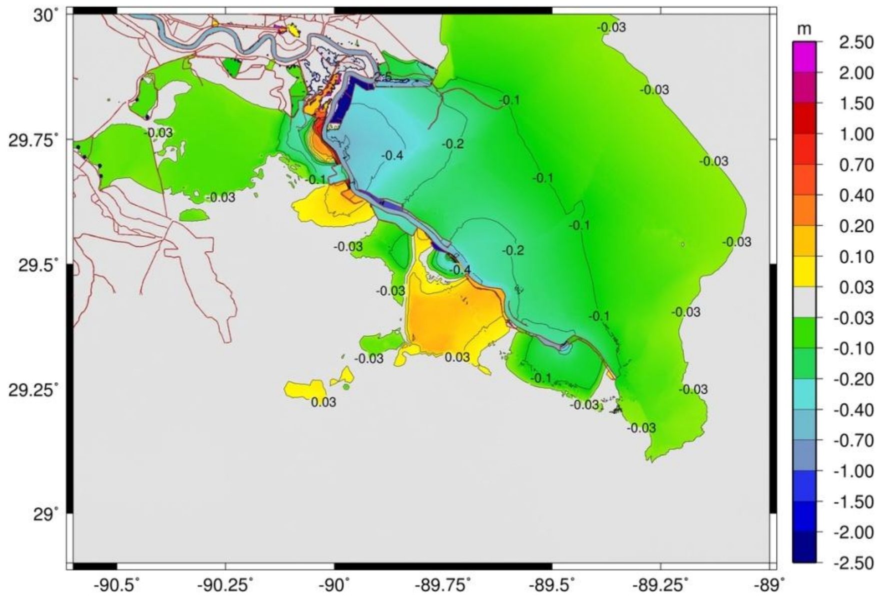


Figure 58. Maximum water level differences between the LACPR Spillways and the base case for a combination of three storms. Negative values indicate a surge reduction, positive values indicate an increase in maximum water levels.

Table 14. Maximum surge levels for the LACPR Spillways and the surge level differences with the base case.

		Maximum Surge Levels LACPR Spillways (m)			Surge Level differences with current levee alignment(m)			Maximum Surge Levels and differences for a combination of three storms (m)		
Area	Location	Storm 27	Storm 69	Storm 120	Storm 27	Storm 69	Storm 120	LACPR Spillways	Base Case	Surge level differences
	New Orleans (Mississippi River)	4,1	3,0	3,4	-0,8	0,3	-0,9	4,1	4,8	-0,8
	Jefferson Parish South	2,5	2,8	1,7	1,3	-0,3	0,9	2,8	3,1	-0,3
	Lafourche East	1,4	3,4	1,0	0,0	0,2	0,0	3,4	3,2	0,2
St Bernard	St Bernard Parish East	5,1	1,8	4,8	0,0	0,0	0,0	5,1	5,1	0,0
	St Bernard Parish South	5,6	4,0	3,6	-0,2	-0,1	-0,2	5,6	5,8	-0,2
	Braithwaite	4,8	4,3	2,0	-0,4	-0,1	-0,5	4,8	5,2	-0,4
	Belle Chase East	4,6	3,3	2,9	-0,6	-0,2	-0,2	4,6	5,2	-0,6
Plaquemines Parish West	Willis Point West	4,4	2,6	3,8	3,3	-0,5	3,0	4,4	3,1	1,4
	Nero West	3,0	3,6	1,9	0,4	0,0	0,6	3,6	3,6	0,0
	Port Sulphur West	4,4	2,9	4,4	-0,2	-0,7	2,3	4,4	4,6	-0,2
	Empire West	5,2	2,7	3,5	0,1	0,3	0,2	5,2	5,1	0,1
	Boothville-Venice West	5,2	1,9	4,8	-0,1	-0,1	0,0	5,2	5,3	-0,1
Plaquemines Parish East	Willis Point East	4,7	3,1	3,5	-0,6	-0,4	-0,1	4,7	5,3	-0,6
	Nero East	5,6	1,7	5,5	-0,3	0,0	-0,1	5,6	5,9	-0,3
	Port Sulphur East	5,3	2,1	5,0	-0,6	0,4	-0,9	5,3	5,9	-0,6
	Empire (Mississippi River)	5,3	1,6	5,6	-0,3	0,2	-0,3	5,6	5,9	-0,3
	Boothville-Venice (Mississippi River)	3,6	0,9	4,1	-0,1	0,1	-0,1	4,1	4,2	-0,1

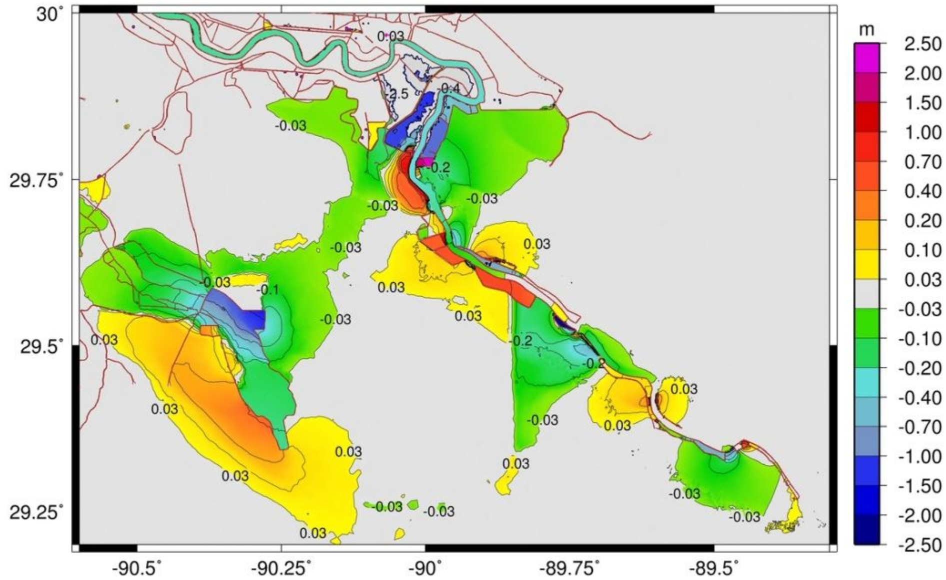


Figure 59. Maximum water level differences between the LACPR Spillways and Plaquemines Minimum for a combination of three storms. Negative values indicate a lower water level for the LACPR spillways, positive values indicate lower water levels for Plaquemines Minimum

By analyzing the figures and table above as well as the figures displayed in the annex, the following can be concluded:

- Surge levels are reduced for most locations east of Plaquemines Parish, ranging from 10 to 60 cm.
- West of Plaquemines, close to the spillway locations the surge levels increase up to 20 cm.
- Local differences exist between the maximum water levels of Plaquemines Minimum and the LACPR spillways due to the different locations of the

spillways. This can be seen in Figure 59. The LACPR spillways produce lower water levels close to Port Sulphur and Buras-Triumph while higher water levels are computed close to Nero and Empire.

- The LACPR spillways reduce water levels further at locations near Jefferson, St. Bernard and on the Mississippi river compared to Plaquemines Minimum. This can be attributed to the larger length of the LACPR spillway at Willis Point.

5.5.5 Lowered LACPR Spillways

Figure 62 shows the combination of the maximum water levels for the lowered LACPR spillways. Figure 128 shows the computed surge level differences between the maximum surge of the lowered LACPR Spillways and the original levee configuration.

Figures of the maximum water levels of each separate storm have been included in annex I.66, Figures of the differences between the lowered LACPR Spillways and the base case for each storm are presented in annex J.5.

		Maximum Surge Levels Lowered LACPR Spillways (m)			Surge Level differences with current levee alignment(m)			Maximum Surge Levels and differences for a combination of three storms (m)		
Area	Location	Storm 27	Storm 69	Storm 120	Storm 27	Storm 69	Storm 120	Lowered LACPR Spillways	Base Case	Surge level differences
	New Orleans (Mississippi River)	3,9	2,8	3,3	-0,9	0,2	-1,0	3,9	4,8	-0,9
	Jefferson Parish South	2,7	2,7	1,8	1,5	-0,4	1,0	2,7	3,1	-0,4
	Lafourche East	1,4	3,4	1,0	0,0	0,2	0,0	3,4	3,2	0,2
St Bernard	St Bernard Parish East	5,1	1,8	4,8	0,0	0,0	0,0	5,1	5,1	0,0
St Bernard	St Bernard Parish South	5,6	4,0	3,6	-0,2	-0,1	-0,2	5,6	5,8	-0,2
St Bernard	Braithwaite	4,8	4,2	1,9	-0,4	-0,2	-0,5	4,8	5,2	-0,4
St Bernard	Belle Chase East	4,5	3,2	2,7	-0,6	-0,3	-0,3	4,5	5,2	-0,6
Plaquemines Parish West	Willis Point West	4,3	2,7	3,7	3,1	-0,4	2,9	4,3	3,1	1,2
Plaquemines Parish West	Nero West	3,1	3,6	2,0	0,4	0,0	0,8	3,6	3,6	0,0
Plaquemines Parish West	Port Sulphur West	4,4	2,9	4,4	-0,2	-0,7	2,3	4,4	4,6	-0,2
Plaquemines Parish West	Empire West	5,1	2,4	3,5	0,0	-0,1	0,2	5,1	5,1	0,0
Plaquemines Parish West	Boothville-Venice West	5,2	1,9	4,8	-0,1	-0,1	0,0	5,2	5,3	-0,1
Plaquemines Parish East	Willis Point East	4,5	2,7	3,4	-0,8	-0,7	-0,2	4,5	5,3	-0,8
Plaquemines Parish East	Nero East	5,5	1,6	5,4	-0,4	0,0	-0,2	5,5	5,9	-0,4
Plaquemines Parish East	Port Sulphur East	5,1	2,0	5,1	-0,8	0,3	-0,8	5,1	5,9	-0,8
Plaquemines Parish East	Empire (Mississippi River)	5,0	1,5	5,4	-0,6	0,1	-0,5	5,4	5,9	-0,5
Plaquemines Parish East	Boothville-Venice (Mississippi River)	3,6	0,9	4,1	-0,1	0,1	-0,1	4,1	4,2	-0,1

displays the maximum surge levels for the Lowered LACPR Spillways and the maximum water level differences between the Lowered LACPR Spillways and the base case.

Finally the differences between the LACPR spillways and the Lowered LACPR spillways can be seen in Figure 62.

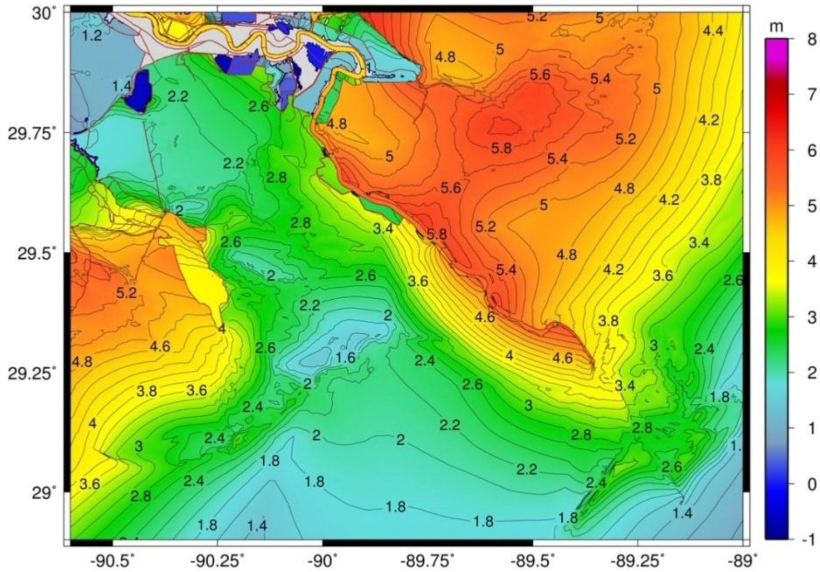


Figure 60. Composition of maximum water levels for the lowered LACPR spillways. Negative values indicate a surge reduction, positive values indicate an increase in maximum water levels.

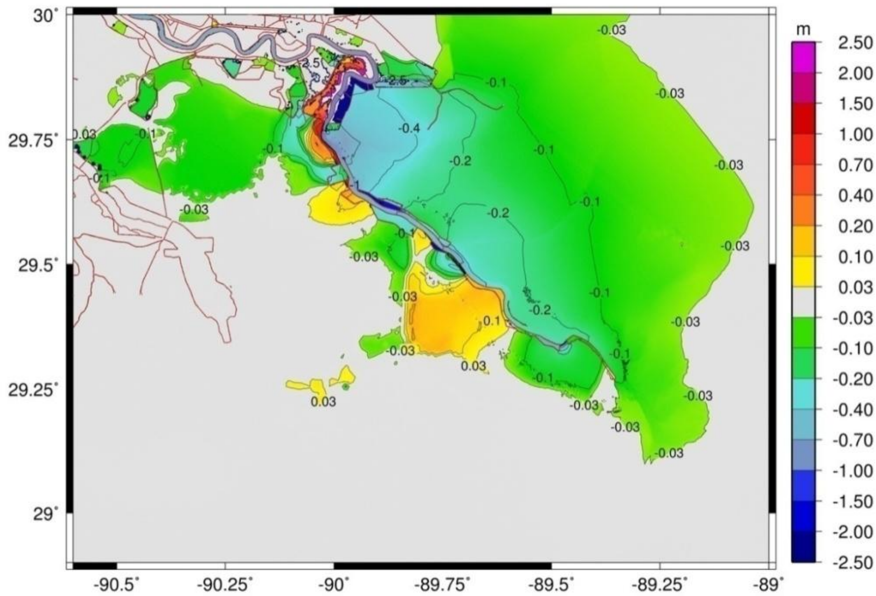


Figure 61. Maximum water level differences between the Lowered LACPR Spillways and the base case for a combination of three storms. Negative values indicate a surge reduction, positive values indicate an increase in maximum water levels.

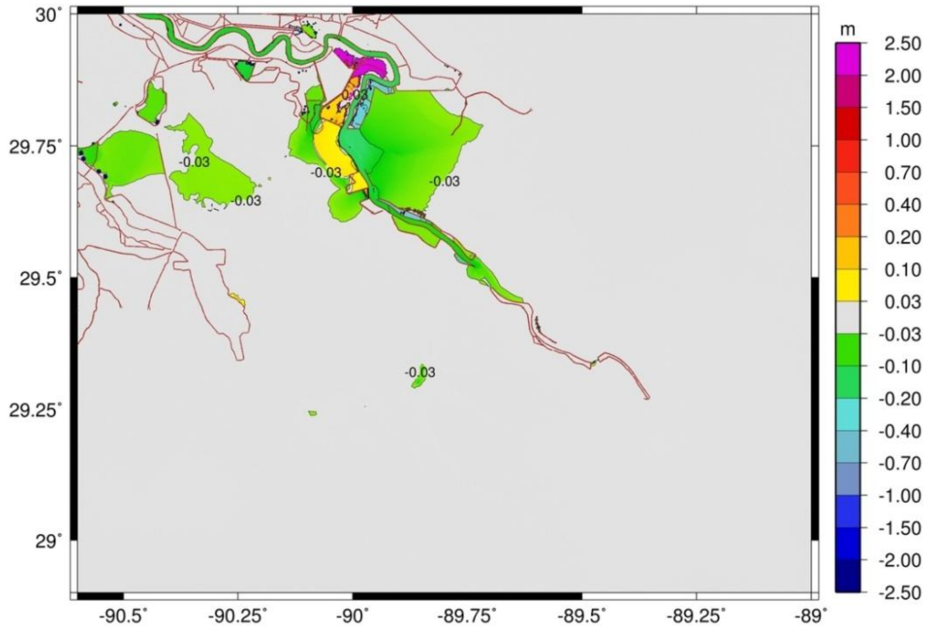


Figure 62. Differences between the lowered LACPR Spillways and the LACPR Spillways. Negative values indicate a reduction of the water level due to the removal of the natural river banks.

Table 15. Maximum surge levels for the Lowered LACPR Spillways and the surge level differences with the base case.

		Maximum Surge Levels Lowered LACPR Spillways (m)			Surge Level differences with current levee alignment(m)			Maximum Surge Levels and differences for a combination of three storms (m)		
Area	**Location**	Storm 27	Storm 69	Storm 120	Storm 27	Storm 69	Storm 120	Lowered LACPR Spillways	Base Case	Surge level differences
	New Orleans (Mississippi River)	3,9	2,8	3,3	-0,9	0,2	-1,0	3,9	4,8	-0,9
	Jefferson Parish South	2,7	2,7	1,8	1,5	-0,4	1,0	2,7	3,1	-0,4
	Lafourche East	1,4	3,4	1,0	0,0	0,2	0,0	3,4	3,2	0,2
St Bernard	St Bernard Parish East	5,1	1,8	4,8	0,0	0,0	0,0	5,1	5,1	0,0
	St Bernard Parish South	5,6	4,0	3,6	-0,2	-0,1	-0,2	5,6	5,8	-0,2
	Braithwaite	4,8	4,2	1,9	-0,4	-0,2	-0,5	4,8	5,2	-0,4
	Belle Chase East	4,5	3,2	2,7	-0,6	-0,3	-0,3	4,5	5,2	-0,6
Plaquemines Parish West	Willis Point West	4,3	2,7	3,7	3,1	-0,4	2,9	4,3	3,1	1,2
	Nero West	3,1	3,6	2,0	0,4	0,0	0,8	3,6	3,6	0,0
	Port Sulphur West	4,4	2,9	4,4	-0,2	-0,7	2,3	4,4	4,6	-0,2
	Empire West	5,1	2,4	3,5	0,0	-0,1	0,2	5,1	5,1	0,0
	Boothville-Venice West	5,2	1,9	4,8	-0,1	-0,1	0,0	5,2	5,3	-0,1
Plaquemines Parish East	Willis Point East	4,5	2,7	3,4	-0,8	-0,7	-0,2	4,5	5,3	-0,8
	Nero East	5,5	1,6	5,4	-0,4	0,0	-0,2	5,5	5,9	-0,4
	Port Sulphur East	5,1	2,0	5,1	-0,8	0,3	-0,8	5,1	5,9	-0,8
	Empire (Mississippi River)	5,0	1,5	5,4	-0,6	0,1	-0,5	5,4	5,9	-0,5
	Boothville-Venice (Mississippi River)	3,6	0,9	4,1	-0,1	0,1	-0,1	4,1	4,2	-0,1

By analyzing the figures and table above as well as the figures displayed in the annex, the following can be concluded:

- Figure 62 shows that the removal of the natural river banks does not have much influence on water levels south of Nero and in areas further away from the northern spillways. This was expected because few changes to the bathymetry were applied at the two southern Spillways.

- South of St. Bernard and East of Belle Chase the lowering of the river banks cause an additional surge reduction of 3 to 10 cm.
- At the location of the spillway the maximum water level for the lowered Plaquemines Spillways is raised by approximately 3 to 10 cm compared to the original spillways.
- The water level can be reduced an additional 10 cm at the Mississippi River at New Orleans by removing the natural river banks at the location of the spillways.

5.6 Conclusions

In this section the following research question will be answered:

What are the quantitative effects of the selected spillway configurations on the maximum storm surge levels during hurricanes near Orleans, St. Bernard, Lafourche, Jefferson and Plaquemines Parish?

Table 16 Overview of the maximum surge levels and surge reductions at different locations within the study area.

		Maximum Surge Levels (m)						Surge Level Increase (m)				
Area	Location	Current Levees	Plaqumines None	Plaquemines CDP	Plaquemin Minimum	LACPR Spillways	Lowered LACPR spillways	Plaquemines None vs. Current Levees	Plaquemines CDP vs. Current Levees	Plaquemines Minimum vs. Current Levees	LACPR Spillways. Vs. Current Levees	Lowered LACPR spillways vs. Current Levees
	New Orleans (Mississippi River)	4,8	3,6	3,7	4,3	4,1	3,9	-1,2	-1,1	-0,5	-0,8	-0,9
	Jefferson Parish South	3,1	2,9	2,9	3,0	2,8	2,7	-0,2	-0,2	-0,1	-0,3	-0,4
	Lafourche East	3,2	3,6	3,6	3,6	3,4	3,4	0,4	0,4	0,4	0,2	0,2
St Bernard	St Bernard Parish East	5,1	5,0	5,1	5,1	5,1	5,1	-0,1	0,0	0,0	0,0	0,0
	St Bernard Parish South	5,8	5,3	5,3	5,6	5,6	5,6	-0,5	-0,5	-0,2	-0,2	-0,2
	Braithwaite	5,2	4,3	4,3	4,9	4,8	4,8	-0,9	-0,9	-0,3	-0,4	-0,4
	Belle Chase East	5,2	2,9	3,8	4,8	4,6	4,5	-2,3	-1,4	-0,4	-0,6	-0,6
Plaquemines Parish West	Willis Point West	3,1	2,9	5,2	5,3	4,4	4,3	-0,2	2,1	2,2	1,4	1,2
	Nero West	3,6	3,5	3,9	3,5	3,6	3,6	0,0	0,3	0,0	0,0	0,0
	Port Sulphur West	4,6	4,1	5,0	4,7	4,4	4,4	-0,5	0,4	0,1	-0,2	-0,2
	Empire West	5,1	4,3	5,2	4,7	5,2	5,1	-0,8	0,2	-0,4	0,1	0,0
	Boothville-Venice West	5,3	2,6	5,3	5,2	5,2	5,2	-2,7	0,0	-0,1	-0,1	-0,1
Plaquemines Parish East	Willis Point East	5,3	3,4	3,8	4,9	4,7	4,5	-2,0	-1,6	-0,5	-0,6	-0,8
	Nero East	5,9	4,0	4,5	5,4	5,6	5,5	-1,8	-1,4	-0,5	-0,3	-0,4
	Port Sulphur East	5,9	4,1	5,2	5,3	5,3	5,1	-1,8	-0,7	-0,6	-0,6	-0,8
	Empire (Mississippi River)	5,9	4,3	5,7	5,7	5,6	5,4	-1,6	-0,2	-0,2	-0,3	-0,5
	Boothville-Venice (Mississippi River)	4,2	3,6	4,1	4,1	4,1	4,1	-0,5	0,0	-0,1	-0,1	-0,1

Different spillway configurations have different effects for each of the areas of interest. Therefore conclusions will be drawn for each location separately. An overview of the surge reductions is shown in Table 16.

5.6.1 New Orleans Parish

The following can be concluded about the quantitative effects of spillways on the maximum water levels near Orleans Parish.

- All spillway configurations reduce the combined maximum surge levels at the Mississippi River near New Orleans.
- The surge is reduced for storm 27 and 120 because less water is forced upriver when spillways are modelled. For storm 69 the opposite is true, surge is allowed to propagate upriver and this causes an increase of the storm surge on the Mississippi river. The storm surge during storm 69 is however still lower than the storm surge of storm 27 at the same location.
- The removal of all levees (Plaquemines None) can reduce the combined maximum storm surge with 1.2 meter and is therefore most effective of all studied levee configurations. Surge levels are reduced 1.1 meter for Plaquemines CDP, 0.8 meter for the LACPR spillways and 0.5 meter for Plaquemines Minimum. This indicates that the length of the spillways in the Northern part of Plaquemines Parish is very important for the surge reduction near New Orleans. This was also expected because the winds in the northwest

quadrant of the storm are directed towards the southwest, perpendicular to the Mississippi River which allows the surge to propagate from west to east, across the river.
- The maximum water levels can be further reduced by removing the natural river banks, thereby effectively lowering the bottom elevation at the location of the spillways. Model results show that the maximum water level at New Orleans can be reduced by an additional 10 cm.

5.6.2 St. Bernard Parish

The following can be said about the quantitative effects of spillways on the maximum water levels near St. Bernard Parish.

- East of St. Bernard water levels are not influenced by the spillways. Only when all levees are removed a small difference of 10 cm can be seen.
- At the other locations south of St. Bernard Parish (Braithwaite, St. Bernard South and Belle Chase East) spillways do have an effect on the maximum surge levels. Reductions are largest for Plaquemines None (0.5 – 2 m), followed by Plaquemines CDP (0.5 – 1.4 m), the LACPR spillways (0.2 - 0.6 m), and Plaquemines minimum (0.2 – 0.4 m). The length of the spillways in the northern part of Plaquemines Parish seems to be very important as well for surge reductions near St. Bernard Parish.
- Lowering the LACPR spillways has a small effect on the water levels in St. Bernard Parish, the water levels were reduced an additional 3 to 10 cm due to the removal of the natural river banks.

5.6.3 Jefferson Parish

The following can be said about the quantitative effects of spillways on the maximum water levels near Jefferson Parish.

- Water levels south of Jefferson Parish are reduced for all spillway configurations. Depending on the spillway configuration these reductions are 10 to 40 cm.
- Storm 69 produces the highest water levels at these locations. During this storm the spillways in the northern part of Plaquemines Parish allow the surge to propagate across and into the Mississippi river, thereby reducing the maximum water levels at Jefferson Parish.
- Water levels at Jefferson Parish do increase for storm 27 and storm 120 but the water level for storm 69 remains higher, therefore the combined maximum surge still reduces. The increases in maximum surge levels for storm 27 and storm 120 are 0.7 to 1.5 meter, depending on the storm and the spillway scenario. For Plaquemines Minimum the increases of the maximum surge levels for storm 27 and 120 are much smaller, 0.2 to 0.4 meter; this can be explained by the fact that the northern spillway is located father away from Jefferson Parish for Plaquemines Minimum, compared to the other levee alignments.

5.6.4 Lafourche Parish

Water levels at the eastern side of Lafourche Parish increase for all levee configurations. An increase of the flow in western direction during storm 69 is responsible for this. The raised maximum water level at Lafourche Parish causes the levees to be overtopped, thereby resulting in higher flood levels within the ring levee of Lafourche Parish.

5.6.5 Plaquemines Parish

The following can be said about the quantitative effects of spillways on the maximum water levels near Plaquemines Parish.

- Storm 27 and 120 tend to reduce water levels east of Plaquemines Parish and increase water levels west of Plaquemines Parish. Storm 69 reduces water levels west of Plaquemines Parish and increases water levels east of Plaquemines Parish.
- East of Plaquemines Parish the storms 120 and 27 remain dominant, so for a situation with spillways the increased water level due to storm 69 is still lower than the water level at these locations for storm 120 and 27. This effectively means that the combined maximum water levels reduce east of Plaquemines Parish. These reductions are highest for Plaquemines None (1.3 -2.2 m); the quantitative effects of the other spillway scenarios are very diverse (see Table 16). The reductions of the maximum water levels are local and dependant on the location of the spillways.
- West of Plaquemines Parish the water levels are reduced for most locations. Locally the spillways tend to funnel the water during storm 27 and 120 and therefore high surge levels are produce close to the spillways. At some of the locations near the western levees of Plaquemines Parish storm 27 becomes dominant and storm 69 does not longer produce the highest water levels. This results in the fact that the combined maximum water levels can increase close to a spillway close to the western levees.
- Since levees at the west side of Plaquemines Parish are very low compared to the eastern levees, an increase in maximum water levels at the western side can cause the levees to overtop, resulting in a larger inundations of Plaquemines Parish compared to a scenario without spillways.
- The most southern spillway in Plaquemines Minimum and in the LACPR spillways scenario is able to reduce water levels at the western levees close to Boothville-Venice by approximately 10 cm. The capacity of the spillway at this location seems not sufficient to decrease water levels within the entire river bend significantly.

5.7 Discussion

Within the LACPR report a recommendation was made to investigate the influence of small ring levees around the townships in Plaquemines Parish. The townships are however not defined by law and a visit to the region itself has revealed that it is difficult to indicate borders between the settlements. Houses and industry are scattered throughout the region. To protect a large part of the inhabitants of Plaquemines, while maximizing the length of the spillways, the Plaquemines CDP configuration has been included in this study; this configuration does not consist of a number of small ring levees, but has one large ring levee.

In order to save costs a lowering of the 1:100 year design level is desired. Because of the small number of storms which have been used for this study and because the influence of wind waves on surge is not included it is not possible to determine if the 1:100 year water levels can be reduced.

For this study the combined maximum water levels of three storms give an indication of the maximum storm surge for a particular area, these maximum water levels will in some cases not be representative for the 1:100 year water level. This can be explained with the following example (see Table 17):

For Plaquemines CDP, at the location south of Jefferson Parish the maximum surge level of storm 69 is the highest of all storms. By creating the spillways the water level for this storm will be reduced from 3.1m to 2.9m. For storm 27 the surge at this location increases from 1.2 to 2.5 meter (1.3 meter difference). For storm 120 the surge increases from 0.8 to 1.5 meter (0.7 meter difference). Because the maximum combined surge level is 3.1 meter for the original levee configuration and the maximum water level of Plaquemines CDP is 2.9 meter the selected methodology will present a surge reduction of 0.2 meter. The 1:100 year water levels are however more likely to be raised for this area because the increase for storm 120 and 27 is larger than the decrease for storm 69, also the chance that a storm with the properties of storm 120 or storm 27 will hit the Louisiana coast is greater because most storms in the gulf of Mexico travel to the north or with an angle to the northeast. Storm 69 has an angle toward the northwest. Therefore the effect on the maximum combined water levels does not have to represent the effect on the 1:100 year water levels.

Table 17. Example of maximum water level calculation

	Maximum water level at Jefferson Parish (m)		
Storm	Base Case	Plaquemines CDP	Water Level Differences (m)
27	1.2	2.5	+1.3
69	3.1	2.9	-0.2
120	0.8	1.5	+0.7
Combined	3.1	2.9	-0.2

6 CONCLUSION

The objective of this study to gain insight in the influence of multiple spillway alignments along the lower Mississippi river on the capability to reduce storm surge during hurricanes, by adapting the ADCIRC model to improve the balance between model speed and model accuracy.

In order to present the conclusions of this study four questions will be answered in this chapter. These questions have been defined previously in section 1.5

1. *How can the ADCIRC model be adapted in order to gain a good balance between model accuracy and model speed considering the fact that multiple levee configurations need be studied within a limited amount of time?*

To perform storm surge simulations for multiple levee configurations within a limited amount of time a new modeling strategy has been chosen and a new grid has been created. In this way the model is expected to produce accurate results while keeping calculation times within limits. The IHNC grid has been used as a basis for a new grid.

The grid resolution near the Bird-foot delta and the corresponding bathymetry and topography has been improved in order to increase the accuracy of the model near Plaquemines Parish. The benefit of using the modified IHNC grid compared to the widely used SL15 grid is that it does not have as many nodes and is therefore faster.

The modelling methodology has been reduced to two steps; a river spin-up run (4.8 wall clock hours) and a 7 day hurricane run (16.8 wall clock hours). Hereto a time step of 2 seconds will be used in contrast to most other studies which use a time step of 1 second. The effects of tides and short-crested wind waves will not be modelled in order to save time. Neglecting the effects of waves is considered acceptable because this study will focus on differences between water levels and not on absolute water levels.

2. *How does the adapted model perform with respect to the Katrina measurements and the other ADCIRC models?*

For locations in Louisiana and Mississippi a regression analysis shows that the modified IHNC model performs better than the S08 model. The modified IHNC model has an r^2 value of 0.914 while the s08 model has a regression coefficient of 0.803. The regression coefficient of the original IHNC model is somewhat higher (0.927). These differences between the Modified and Original IHNC grid can be explained by the fact that some large errors occur. The Sl15 model shows the same error at one of these locations.

Both for the IHNC grid and the modified IHNC grid the errors at the Empire Locks are larger than for the SL15 model. In both cases an overestimation of the surge is calculated. This might be explained by the coarsened grid within the area west and southwest of Plaquemines Parish for both the IHNC and the modified IHNC grid. The enhancements in the Bird-foot delta which have been applied by modifying the IHNC model contribute to a somewhat smaller error (1 m) at the Empire Locks compared to the error of the original IHNC grid (1.5 m).

The modification of the IHNC grid resulted in a decrease of water levels northwest of the bird foot delta. A local error at the location of Poydras is only 3 cm for the modified IHNC grid while it was 80 cm for the original IHNC grid. This provides an indication that the modification has a positive effect on the accuracy of the model results east of Plaquemines Parish because surge levels are reduced within this area.

The amount of available data is however too small to be able to statistically prove that the modified IHNC grid provides better results than the original IHNC grid for Plaquemines Parish and the surrounding area.

3. *Which storms should be modeled in order to give an indicative overview of potential effects of spillways on the maximum surge levels near Orleans, St. Bernard, Jefferson and Plaquemines Parish?*

It is not possible to use a storm set which can be used to statistically represent the variability of storms in the Gulf of Mexico due to time constraints. To get an indicative overview of the effects of spillways on the maximum surge levels in the areas of interest storms have been selected which are likely to have a major impact on the 1:100 year water levels.

To be able to capture the most important processes storms have been selected which capture a range in water levels at each of the focus areas, these are: Plaquemines Parish, Jefferson Parish, St Bernard and the Mississippi River. The storms will differ from each other in terms of track and landfall location. This choice was made because these parameters capture most of the differences between the storm surge levels. In order to reduce the number of degrees of freedom the storms have approximately the same strength, this means that they have a similar central pressure, radius to maximum winds and forward speed.

These considerations have resulted in the selection of storms 27, 69 and 120 out of a storm set of 152.

4. *Which factors are important for determining spillway configurations and what are the quantitative effects of the selected spillway configurations on the maximum storm surge levels during hurricanes near Orleans, St. Bernard, Lafourche, Jefferson and Plaquemines Parish?*

Both the land use within Plaquemines Parish as well as the hydrodynamic behaviour of the storm surge have been analysed; these factors have been used to determine the location of spillways for 5 different spillway scenarios. These five scenarios are:

- Plaquemines None, in this scenario all levees South of Belle Chase have been removed to indicate the maximum possible effect of spillways.
- Plaquemines CDP, in this scenario the most important residential and industrial areas remain protected while 50% of the levees are removed.
- Plaquemines Minimum, in this scenario 5 different spillways have been selected with a total length of approximately 12 km. These spillways have been selected in such a way that flows caused by western and north-western directed wind are allowed to propagate across the river, while a relatively short length of the spillways is maintained.
- LACPR spillways, this scenario has been recommended by a previous study that was part of the LACPR project. The scenario consists of 4 separate spillways with a total length of approximately 22 km.

- Lowered LACPR spillways, this scenario was chosen to identify the importance of the natural river banks of the Mississippi river with respect to the effectiveness of spillways. This scenario is identical to the LACPR spillways scenario except for the fact that the natural river banks have been removed in the model as well.

The ADCIRC model results show that the quantitative effects of the different levee alignments are different between the different areas of interest. The most important effects are summarized below.

All spillway configurations reduce the maximum surge levels at the Mississippi River near New Orleans. The removal of all levees (Plaquemines None) can reduce the combined maximum storm surge with 1.2 meter and is therefore the most effective of all studied levee configurations. Model results show that the length of the spillways in the northern part of Plaquemines Parish is very important for the surge reduction near New Orleans on the Mississippi River, this is most likely caused by the fact that the wind direction for two of the selected storms was directed toward the south west at this location, which allowed the surge to propagate across to the Mississippi river. The maximum water levels can be reduced further by approximately 10 cm at the Mississippi river by removing the natural river banks at the spillway location.

East of St. Bernard water levels are not influenced by the spillways. South of St. Bernard Parish spillways do have an effect on the maximum surge levels. Reductions are largest for Plaquemines None (0.5 – 2 m), followed by Plaquemines CDP (0.5 – 1.4 m), the LACPR spillways (0.2 - 0.6 m), and Plaquemines minimum (0.2 – 0.4 m). Also for the area south of St. Bernard Parish the length of the spillway in the Northern Part of Plaquemines Parish appears to be very important.

Water levels at the eastern side of Lafourche Parish increase for all levee configurations. The raised maximum water level at Lafourche Parish cause the levees to be overtopped, thereby resulting in higher flood levels within the ring levee of Lafourche Parish than in a situation without spillways..

Water levels south of Jefferson Parish are reduced for storm 69. Storm 120 and storm 27 raise the water levels at this location for most selected configurations. The combined maximum surge levels reduce at this location, the effect of the spillways on the 1:100 year water levels remains however unclear.

Near Plaquemines Parish the effect of spillways on storm surge east and west of the levee system is different. The maximum water levels reduce east of Plaquemines Parish for all spillway scenarios but not for all storms. The combined maximum water level does however decrease east of Plaquemines Parish. The amount of surge reduction appears to be highly dependable on the length and location of the spillway.

West of Plaquemines Parish the water levels are reduced for most locations. Locally the spillways tend to funnel the water, therefore high surge levels are produced close to the spillways. Levees at the west side of Plaquemines Parish are very low compared to the eastern levees, an increase in maximum water levels at the western side can cause the levees to overtop, resulting in a larger inundation of the protected areas of Plaquemines Parish compared to a scenario without spillways.

The capacity of the most southern spillway in three of the selected scenarios seems not sufficient to decrease water levels within the river bend close to BoothVille-Venice significantly. The effect of this spillway is only local.

7 RECOMMENDATIONS

Relatively little surge measurements are available for the area close to Plaquemines Parish; therefore the validation of computer models is difficult. During Katrina some of the measurement equipment failed. It is recommended to install equipment which can withstand a hurricane and which can monitor the storm surge elevation in time, at various locations near the Bird-Foot delta and on the Mississippi river.

It is recommended to perform simulations with more hypothetical storms in order to be able to calculate the 1:100 year and 1:50 year water level for the selected spillway configurations.

Some of the levees in Plaquemines Parish are in private control; research should be carried out on the question if privately owned levees are desirable with respect to the flood protection of Plaquemines Parish against storm surge.

In order to be able to determine if spillways are ‘desired’ not only the impact on the maximum storm surge levels is of importance. It is recommended to perform an Environmental Impact Assessment or a Cost Benefit analysis in which other factors like shipping, salt intrusion in the delta, flood protection against high river discharge and the economic development of the region are also included.

Spillways will most likely affect the sedimentation in the region because sediments could be deposited again in the deltaic plain. It is recommended to perform research in order to study the effect that the spillways will have on the erosion or rehabilitation of the wetlands near New Orleans.

Just before the hurricane season in 2008, the Mississippi discharges were very high. It is unclear if high river discharges are likely to coincide with hurricane events and what the effects on storm surge will be. It is recommended to perform a study on this subject as well.

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INDEX OF APPENDICES

Annex A
Vertical Datum

A VERTICAL DATUMS

Several Vertical Datums are commonly used to describe topographic and water level elevations. In this annex a description will be given of the most important vertical datums.

In the United States water level measurements and bathymetric measurements are often referenced to a tidal datum whereas topographic data is referenced to a geodetic datum. To be able to compare different elevations, it is best to use only one vertical datum for all data, therefore throughout this study, al elevations are referenced to the NAVD88 (2004.65) datum.

A.1 Geodetic datums

Land elevations are generally referenced to geodetic datums. Today the North American Vertical Datum of 1988 (**NAVD88**) is used in Louisiana and Mississippi. This datum has an ellipsoid surface and is fixed on the Mean Sea level at a location in Canada. The NAVD88 datum is relatively new and some data is still only available for the older **NGVD29** vertical datum.

The NAVD88 has recently been updated in order to correct initial errors and to encompass the subsidence which is taking place in southern Louisiana. Measurement which took place in the past decades with reference to the NAVD88 datum appeared to be erroneous because of this. This updated datum is called **NAVD88 (2004.65)** and this datum will be used throughout this report for elevations.

A.2 Tidal Datums

Tidal datums are used to identify water levels. (Luther et al., 2007). Along multiple gauges near the US coast measurements are continuously being performed, this data is used to calculate tidal elevations at different locations along the coast. In the U.S., water level observations, tide predictions and bathymetric measurements are referenced to the Mean Lower Low Water (MLLW). MLLW is the average of all lower water levels during each lunar day over a 19-year period. This 19 year period is called National Tidal Datum Epoch. Table 18 shows the most important vertical datums which are currently in use, Figure 63 presents the definitions of these datums.

The tidal range near the US coast varies considerably, and therefore the distance between the MLLW level compared to an ellipsoid like the NAVD88 (2004.65) can be significant and this difference will vary locally. Although tidal datums are useful for navigation purposed this type of data should not be used for calculation storm surge (Westerink et al., 2008a).

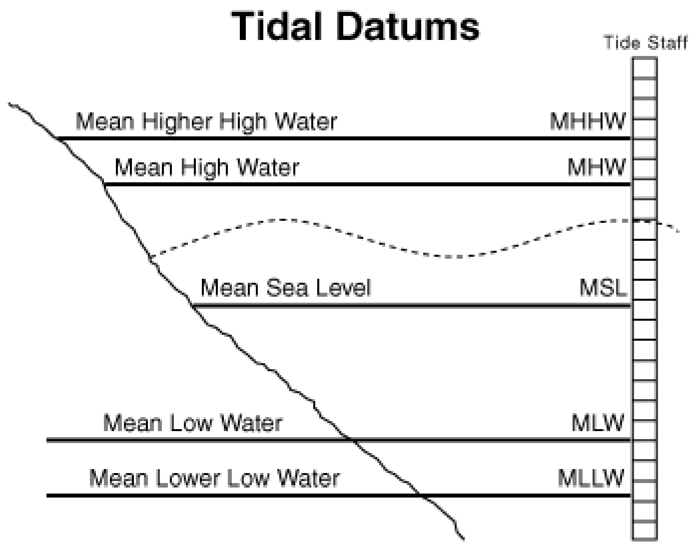


Figure 63. Tidal Datums

Table 18. Tidal water level definitions (NOAA, 2000)

MHHW Mean Higher High Water	The average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch.
MHW Mean High Water	The average of all the high water heights observed over the National Tidal Datum Epoch.
MSL Mean Sea Level	The arithmetic mean of hourly heights observed over the National Tidal Datum Epoch.
MLW Mean Low Water	The average of all the low water heights observed over the National Tidal Datum Epoch.
MLLW Mean Lower Low Water	The average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch.
National Tidal Datum Epoch	The specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums.

Annex B
Storm surge theory

B STORM SURGE THEORY

B.1 Surge and waves

Waves are generally defined as a disturbance of the equilibrium state in any given body of material, which propagates though that body over distances and times much larger than the characteristic wave-lengths and periods of the disturbances (Holthuijsen, 2007). Many different types of waves can be distinguished in terms of their period or wave length. The longest waves are trans-tidal waves, which are generated by low frequency fluctuations in the Earth's crust and atmosphere. Tides are shorter waves and they are generated by the celestial bodies of which the moon and the sun are the most important ones. Their periods range from a few hours to little over one day and their wavelengths vary between a few hundred to a few thousand kilometers. Waves which can be seen at most beaches are predominantly wind-generated waves. These waves have periods between 30 and ¼ seconds; the restoring force of all of these waves is gravity. For smaller waves shorter than ¼ seconds the surface tension dominates the restoring force. These waves are called capillary waves. (Brown et al., 1999).
The wave period and length of surge waves are generally shorter than tides, but longer than wind generated waves. Storm surge is the abnormally high water level during a storm, and has a period and length roughly the same as those of the generating storm (Holthuijsen, 2007). An overview of the properties in terms of energy and wave frequencies for different types of waves is shown in Figure 64.

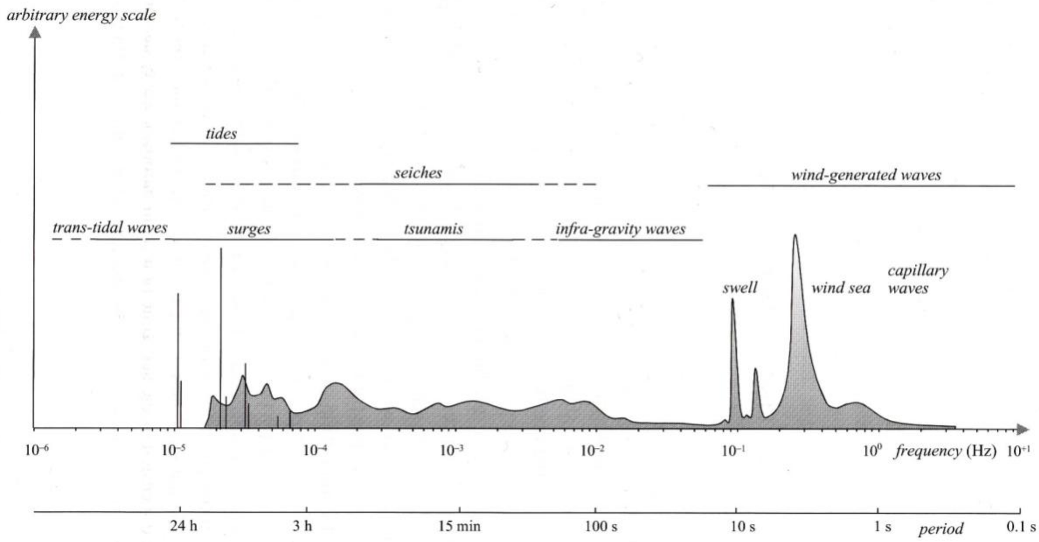


Figure 64. Frequencies and periods for various types of waves (Holthuijsen, 2007)

B.2 Storm surge formative processes

This section will elucidate the important processes for the formation of storm surge. In order of descending importance the main contributors to determine storm water levels in Louisiana are (IPET, 2007):

- Wind
- Geographic/topographic controls
- Breaking wind waves
- The Mississippi river discharge
- The atmospheric pressure within a hurricane
- The astronomical tides
- Precipitation.

The most important process to determine the storm surge is the wind. Wind produces a shear stress on the water surface that pushes the water forward. Changes in water level due to wind occur primarily in shallow water because the effect of the wind on surge is largest with smaller water depths. Like the interaction between wind and waves, the relationship between surge and wind is highly nonlinear. The shear stress that is responsible for the storm surge generation is related to the wind speed to a second or third power. The intensity of a hurricane in terms of hurricane categories (e.g. Saffir-Simpson) has therefore an enormous influence on the water levels near the coast. Current meteorological descriptions like the Saffir-Simpson scale alone are however not sufficient to predict the severity of a storm surge (IPET, 2007).

As the wind moves the water toward the coast, the surge will encounter variations within the bathymetry and the obstruction by the coast will force the surge to become higher. The local geography is therefore a major factor which determines storm surge levels. In broad, shallow continental shelf regions the potential for high storm surge elevations is great; also levees or other topographic controls can catch the water which is pushed towards it. Due to the fact that hurricanes in the Gulf of Mexico rotate counter clockwise the winds near the coast force the surge to propagate from the east in western direction. The levees along the Mississippi river delta will as a result start to act as a topographic control themselves. For southeast Louisiana the combined effect of geographic/topographic controls together with the wind exceed the combined effect of all other factors.(IPET, 2007) The storm surge contribution due to wind and geographic/topographic controls exceeded 5m at some places in Louisiana during Katrina.

Wind waves transport energy and momentum; the momentum will generate a stress, variations of these stresses act as a force on the water, just like gravity. This transport of wave-induced momentum is called radiation stress (Holthuijsen, 2007), in oceanic waters the difference in radiation stresses are generally very small so the forces resulting from these differences in horizontal momentum are also very small. When wind waves enter shallow water the wave height and direction can change according to the bathymetry. Waves will start to break when they are approximately 0,6 to 0,65 times the local water depth and energy will start to dissipate. When waves break the change in radiation stress becomes larger, and this can result in a rise of the water level or the creation of water currents. The process which leads to the increasing water levels due to breaking waves is called wave-induced set-up. Shorter period wind waves therefore also contribute to the mean water level or storm surge. Computer models have indicated that the contribution of wave set-up to storm surge was approximately 60 cm during Katrina. During the beginning of the Hurricane season (early summer) the river discharges are generally higher than in later parts of the season (October and November), the discharge can have a significant effects on storm surge. According to the Interagency Performance Evaluation Task Force (IPET) the effect of the Mississippi river discharge on storm surge can be on the order of feet (IPET, 2007).

In the eye of a hurricane a very low atmospheric pressure exists compared to the surrounding environment (Malkus, 1958). This means that the weight of the storm which pushes down on the water will be lower within the eye, and therefore the water level in the eye will be higher than in the periphery of the storm, this bulge is highest in the centre of the storm (approximately 0,3-0,6 meter) and decreases to zero at the edge of the storm.

Tides also have an effect on storm water levels. When a hurricane reaches the coast during the ebb tide the water levels will be lower than when a hurricane makes landfall during high astronomical tides. The tidal range in the Gulf of Mexico ranges from 15 cm to 45 cm; this is very low compared to the Netherlands, where the tidal range is approximately 2 to 4 meters (Brown et al., 1999).

Precipitation can also increase the water level, either by falling directly on the local water bodies or by running off into water bodies from land. Because large areas of Southern Louisiana lay beneath Mean Sea Level many pumping stations help with draining water into the Gulf of Mexico or the Mississippi river. The total contribution of precipitation to storm surge levels is estimated to be about 30 cm (IPET, 2007), but often the effect of runoff is experienced after the storm surge peak has passed.

Annex C
Storm surge modelling

C STORM SURGE MODELLING

In this study a model will be used to perform storm surge calculations in southern Louisiana. In this Annex appropriate models will be discussed which can be used for this purpose.

C.1 Numerical solution methods

In general two different numerical solution methods are used by computer models. These are the Finite Difference and the Finite Element method.

The **Finite Difference** method (FD) represents the water levels at a set of discrete points for each time step. The model grid is a network of straight or curved lines with nodes at the intersections. Water currents are generally computed at the links between these nodes. Within the FD method two types of structured grids can be distinguished, a rectangular grid and a curvilinear grid. A **rectangular grid** (Figure 65b) has equal spacing between nodes. Often near the coastline greater differences in bathymetry exist and therefore the step size between nodes near the coast will need to be smaller than at deep sea to obtain accurate results; with a rectangular grid the step size is the same everywhere, and will therefore use more calculation points than would be necessary with the use of a more flexible grid. A **curvilinear grid** (Figure 65a) represents the configuration of a water body better because the grid can be fitted along boundaries and contours and because the distance between grid nodes does not have to be the same everywhere. (Anonymous, 2005).

The **Finite Element** method (FE) divides the water body into a set of triangular or polygonal elements. Almost in all cases an **unstructured grid** is used combination with the FE method (Figure 65b). The advantage of an unstructured or irregular grid is that it is possible to work with large variations in grid step size. If in a small area of the water body a high resolution grid is required, the entire domain will not be affected. The downside of using unstructured grids is that it can be very time consuming to set up such a grid, and that the FE method generally is less computationally efficient than the Finite Difference Method (Moffatt & Nickol Engineers, 2005)

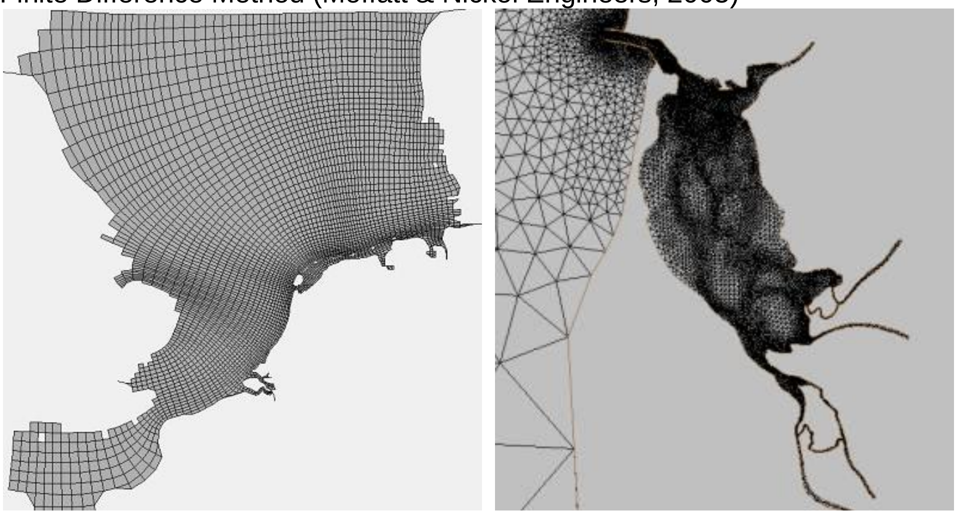


Figure 65 (a) example of a curvilinear grid from the DELFT 3D model (www.wldelft.nl,2008), (b) example of an unstructured grid from the ADCIRC model (www.nd.edu/~adcirc, 2008)

C.2 Hydrodynamic models

Several hydrodynamic models can be used to compute storm surge elevations. An overview of well known hydrodynamic models is presented in Table 19. For each model the main characteristics have been given.
The use of a Finite element model with the capability of using unstructured grids is preferred over the use of a Finite Difference model.

Table 19. Overview of the characteristics of different hydrodynamic models. (Moffatt & Nickol Engineers, 2005)

Type of Model	Characteristics of Numerical Model(s) / Specific Model	HEC-UNET, HEC-6, HEC-RAS	RMA-2, -4, -10, -11, SED-2D	MIKE-11, -21, -21, -3, -FM, -C	TRIM, UnTRIM	DELFT2D, DELFT3D	TELEMAC	CH2D, CH3D, ICM	WASP	ADCIRC	CE-QUAL-W2	GEMSS (GLLVHT)
General	Numerical Solution Method	FE	FE	FD[1]	FD	FD	FE	FD	FE	FE	FE	FD
	Numerical Grid Type	NA[2]	UN	RE[1]	RE[7]	CU	UN	CU	NA[3]	UN	RE	CU
	General Model Availability	F	$	$$	L	$$	$$	L	$	$	F	L
Hydrodynamic Model	Water Levels and Velocity	■	■	■	■	■	■	■	□[3]	■	■	■
	Wetting and Drying	■	■	■	■	■	■	■	□	■	■	■
	Evaporation and Precipitation	□	■	■	□	■	■	■	□	□	□	■
	Control Structures	■	■	■	□	◪	■	□	□	■	□	■
	Temporal Variation (Unsteady Flow)	■[4]	■	■	■	■	■	■	□	■	■	■
	Spatial Variation (2-D Modeling)	□	■	■	■	■	■	■	□	■	◪[6]	■
	1-D / 2-D Model Integration	□	◪	◪	□	□	□	□	□	□	□	◪
	Vertical Stratification (3-D Modeling)	□	■	■	■	■	■	■	□	■	◪[6]	■
Wave Model	Wind-Generated Waves	□	□	■	□	■	■	■	□	□	□	□
	Wave-Current Interactions	□	■	■	□	■	■	■	□	■	□	■
Sediment Transport Model	Cohesive Processes	■[4]	■	■	□	■	■	■	□	□	□	■
	Bed Load Transport	■	□	■	□	■	■	■	□	□	□	■
	Wind-Driven Wave Resuspension	□	■	■	□	■	■	■	□	□	□	■
	Source / Sink Terms	□	■	■	□	■	□	□	□	□	□	□
	Dynamic Bed Morphology	■	□	◪[5]	□	■	□	■	□	□	□	□
	Channel Migration	□	□	◪[5]	□	□	□	□	□	□	□	□

Key:

FE	Finite Element	FD	Finite Difference	CU	Curvilinear orthogonal
RE	Rectangular	UN	Unstructured	F	Public Domain
$	Available at low cost	$$	Relatively high cost	L	Limited availability (coop agreement, etc.)
■	Addressed	◪	Partially Addressed	□	Not Addressed

Notes:

1. Curvilinear grid for MIKE-21C, and finite element for MIKE-FM
2. Not Applicable (1-D model)
3. The WASP model can take input hydrodynamics from a number of other models
4. Unsteady flow and sediment transport are not available simultaneously
5. Channel migration is available as a specialized module, not integrated with other morphologic modules
6. CE-QUAL-W2 can be run in a 2-D or a 1+1-D mode
7. Irregularly shaped finite difference grid for UnTRIM

Four models from Table 19 are capable of using unstructured grids, these are:

- RMA Model series: The RMA model series is a set of 1D,2D and 3D models which are typically used to calculate water surface elevations and flow distribution around islands, flow patterns near bridges and river junctions or water circulation and transport over wetlands (Wagner and Mueller, 2001). The RMA models have been originally developed by the US Army Corps of Engineers (USACE).
- TELEMAC model series: The TELEMAC model was developed at the Laboratiore National d'Hydraulique in France. It is now a joint effort of several research teams in Europe. Applications of TELEMAC include flood simulations, dam breaks, and tides (Hervouet, 2000).
- ADCIRC model: ADCIRC is a surge model developed by Rick Luettich (University of North Carolina Institute of Marine Sciences) and Joannes Westerink (University of Notre Dame Department of Civil Engineering and Geological Sciences). Typical ADCIRC applications include: modelling tides and wind-driven circulation, analysis of hurricane storm surge and flooding, dredging feasibility and material disposal studies, larval transport studies, and near shore marine operations (www.sura.org, 2008).
- The Flexible Mesh (FM) versions of the MIKE 21 and MIKE 3 flow models are developed by DHI in Denmark. The mike models simulate water level variations and flows in response to a variety of forcing functions on floodplains, in lakes, estuaries and coastal areas.

For the purpose of modelling storm surge near New Orleans the most important forcing terms are: Wind, Geographic/topographic controls, Breaking wind waves, Mississippi river discharge, atmospheric pressure within a hurricane, astronomical tides and precipitation (see section B.1).

According to Table 19 all four models have approximately the same properties. With regard to hydrodynamic and wave modelling there are only a few differences between the models. ADCIRC does not incorporate wind-generated waves while TELEMAC, MIKE and RMA are able to calculate these waves. The interaction between waves and currents is however included in all three models. ADCIRC also does not include precipitation and evaporation. The influence of precipitation on storm surge is however relatively small and because rainwater runoff will not likely coincide with the peak storm surge level this will only be considered a small disadvantage.

The RMA and ADCIRC models are both used by the Army Corps of Engineers, the use of the TELEMAC model in Northern America has been limited. The mike FM models are relatively new in the market and are not widely tested. (Moffatt & Nickol Engineers, 2005). Currently most US organizations prefer the ADCIRC model over the RMA model because ADCIRC has a faster solution algorithm than RMA (MOE, 2006).

For this study the ADCIRC model has been selected. Several ADCIRC models have been applied for storm surge modelling near New Orleans in the past, these models have already been calibrated and validated and are available for use. For these reasons the ADCIRC model has been adopted to be the main modelling tool in this study.

Annex D
ADCIRC Model Governing Equations

D ADCIRC MODEL GOVERNING EQUATIONS

D.1 Governing Equations

The governing ADCIRC continuity equation in its non-conservative form and the momentum equations for a spherical coordinate system are given below.

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R\cos\phi}\left(\frac{\partial UH}{\partial \lambda} + \frac{\partial (VH\cos\phi)}{\partial \phi}\right) = 0$$

$$\frac{\partial U}{\partial t} + \frac{1}{R\cos\phi} U \frac{\partial U}{\partial \lambda} + \frac{V}{R}\frac{\partial U}{\partial \phi} - \left(\frac{\tan\phi}{R} U + f\right)$$
$$= -\frac{1}{R\cos\phi}\frac{\partial}{\partial \lambda}\left[\frac{p_z}{\rho_0} + g(\zeta - \alpha\eta)\right] + \frac{\upsilon_T}{H}\frac{\partial}{\partial \lambda}\left[\frac{\partial UH}{\partial \lambda} + \frac{\partial UH}{\partial \phi}\right] + \frac{\tau_{s\lambda}}{\rho_0 H} - \tau_* U$$

$$\frac{\partial V}{\partial t} + \frac{1}{R\cos\phi} U \frac{\partial U}{\partial \lambda} + \frac{V}{R}\frac{\partial V}{\partial \phi} - \left(\frac{\tan\phi}{R} U + f\right) U$$
$$= -\frac{1}{R}\frac{\partial}{\partial \lambda}\left[\frac{p_z}{\rho_0} + g(\zeta - \alpha\eta)\right] + \frac{\upsilon_T}{H}\frac{\partial}{\partial \phi}\left[\frac{\partial VH}{\partial \lambda} + \frac{\partial VH}{\partial \phi}\right] + \frac{\tau_{s\phi}}{\rho_0 H} - \tau_* V$$

With:

ζ = free surface elevation relative to geoid [m]
λ, ϕ = longitude, latitude [degrees]
t = time [s]
R = $\frac{\sqrt{gH}}{f}$= Rossby deformation radius [m]
g = acceleration due to gravity [m/s^2]
H = h + ζ = Water depth [m]
f = $2\Omega\sin\Phi$ = Coriolis parameter [s^{-1}]
U,V = depth averaged horizontal velocities [m/s]
h = bathymetric depth relative to geoid [m]
Ω = angular velocity of the Earth [rad/s]
p_z = atmospheric pressure at the free surface [N/m^2]
η = Newtonian equilibrium tide potential [-]
α = effective earth elasticity factor [-]
ρ_0 = reference density of water [kg/m^3]
$\tau_{s\lambda}, \tau_{s\phi}$ = applied free surface stress [N/m^2]
τ_* = $C_f \frac{\sqrt{(U^2+V^2)}}{H}$ = bottom friction term
C_f = nonlinear bottom friction coefficient
υ_T = depth average horizontal eddy viscosity coefficient

Annex E
ADCIRC Models

E ADCIRC MODELS

E.1 Adcirc grids

E.1.1 ADCIRC s08 grid

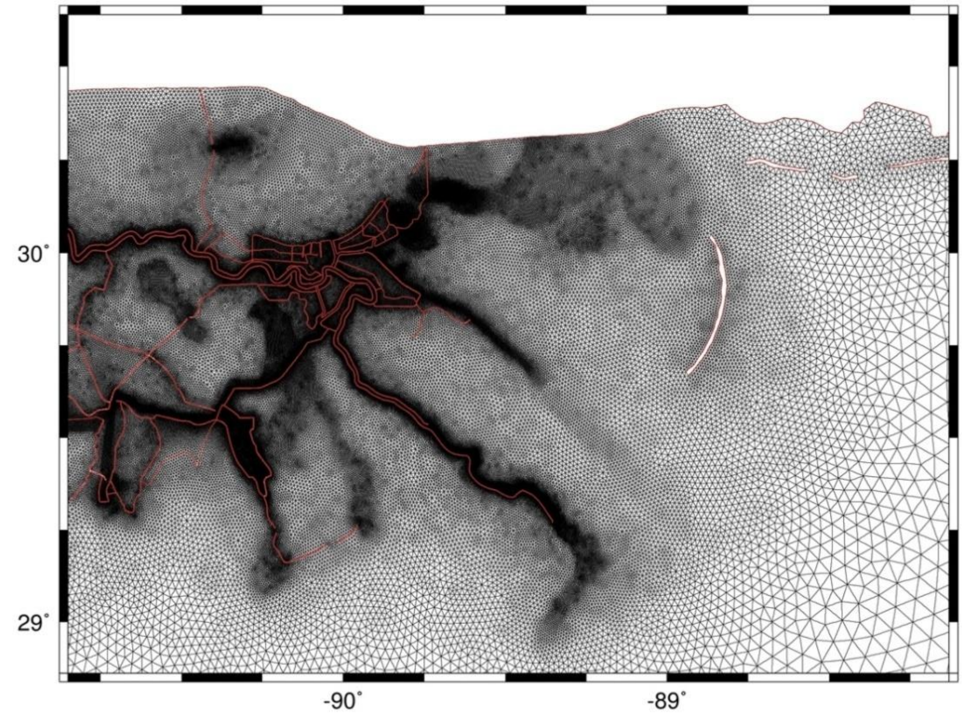


Figure 66. ADCIRC S08 Grid for south-east Louisiana

E.1.2 ADCIRC SL15 grid

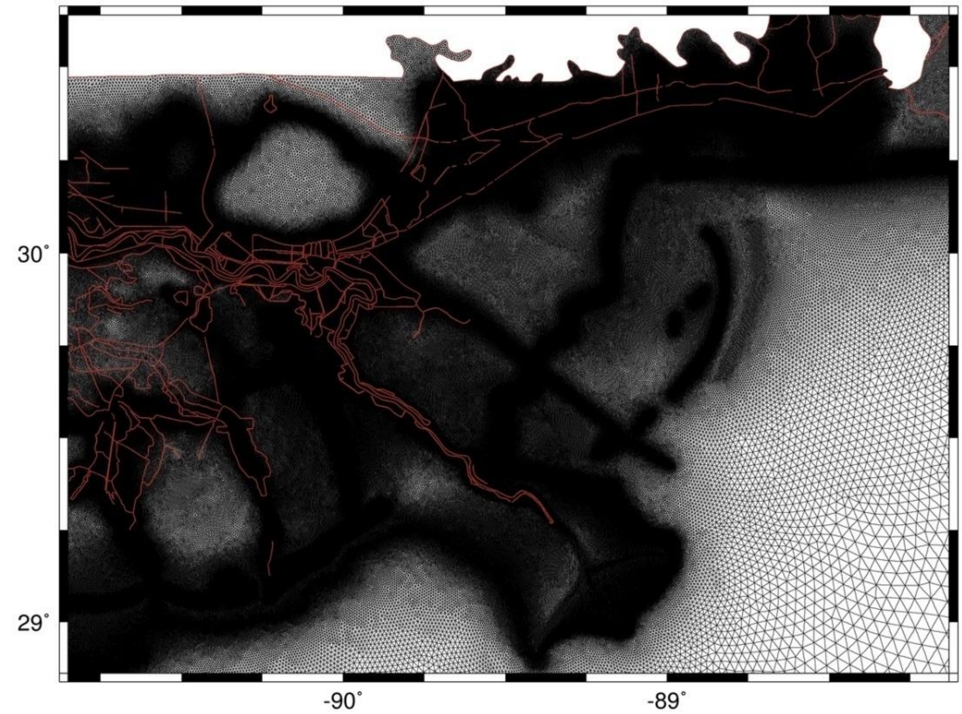


Figure 67. ADCIRC SL15 for south-east Louisiana

E.1.3 ADCIRC SL15 version 7 grid

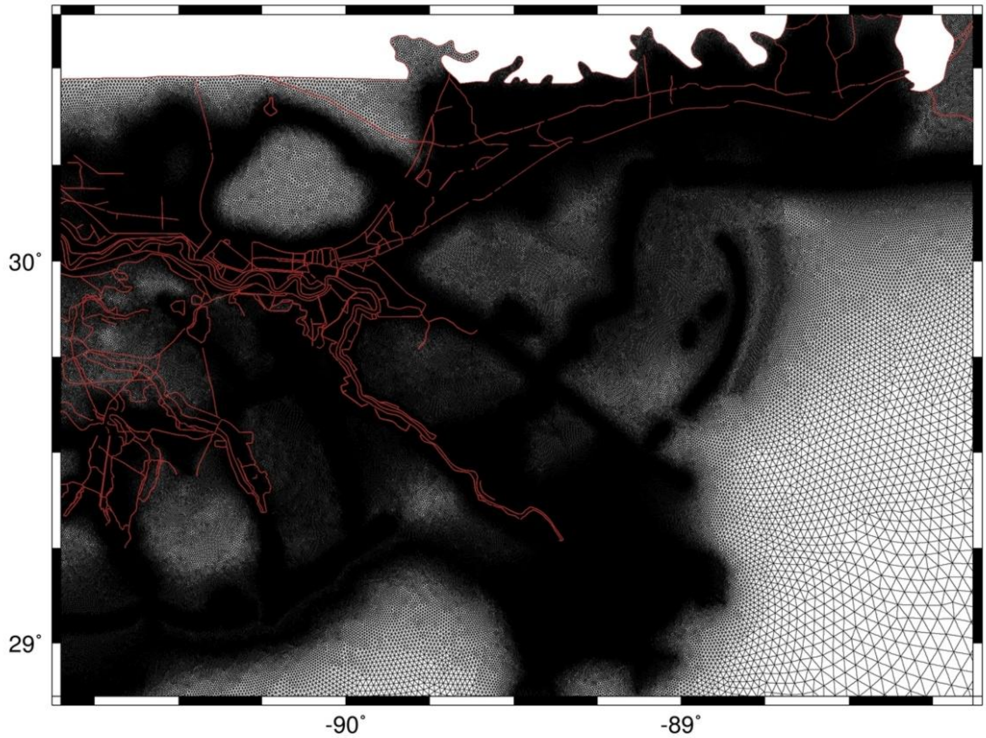


Figure 68 ADCIRC SL15 version 7 grid for south-east Louisiana

E.2 ADCIRC IHNC grid

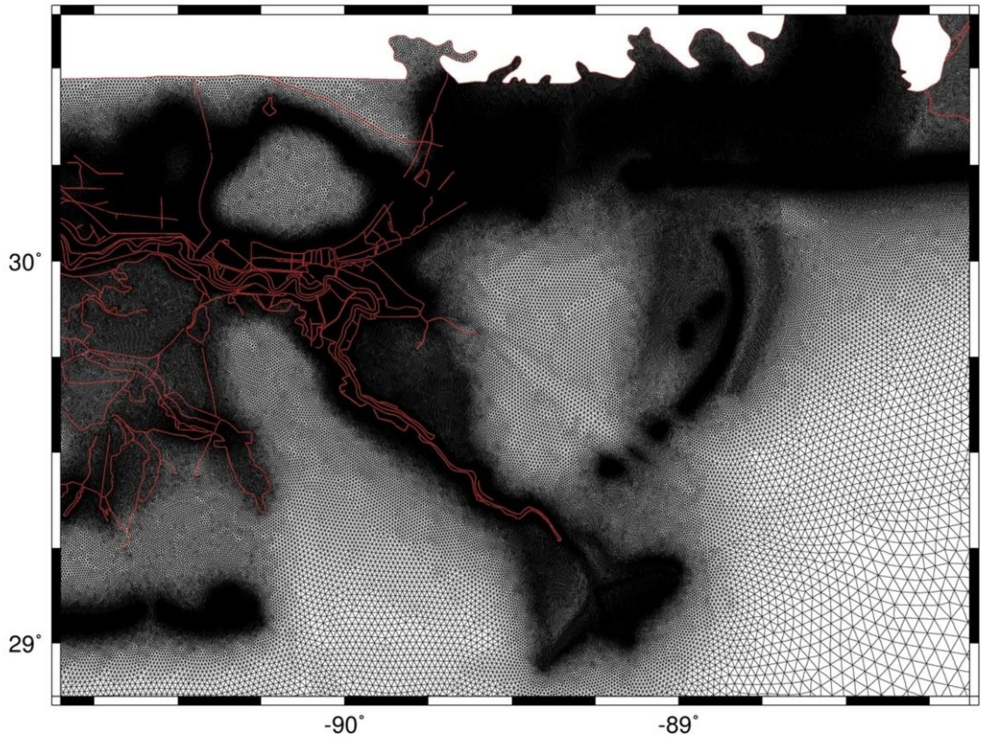


Figure 69. ADCIRC IHNC grid for south-east Louisiana

E.2.1 ADCIRC modified IHNC grid

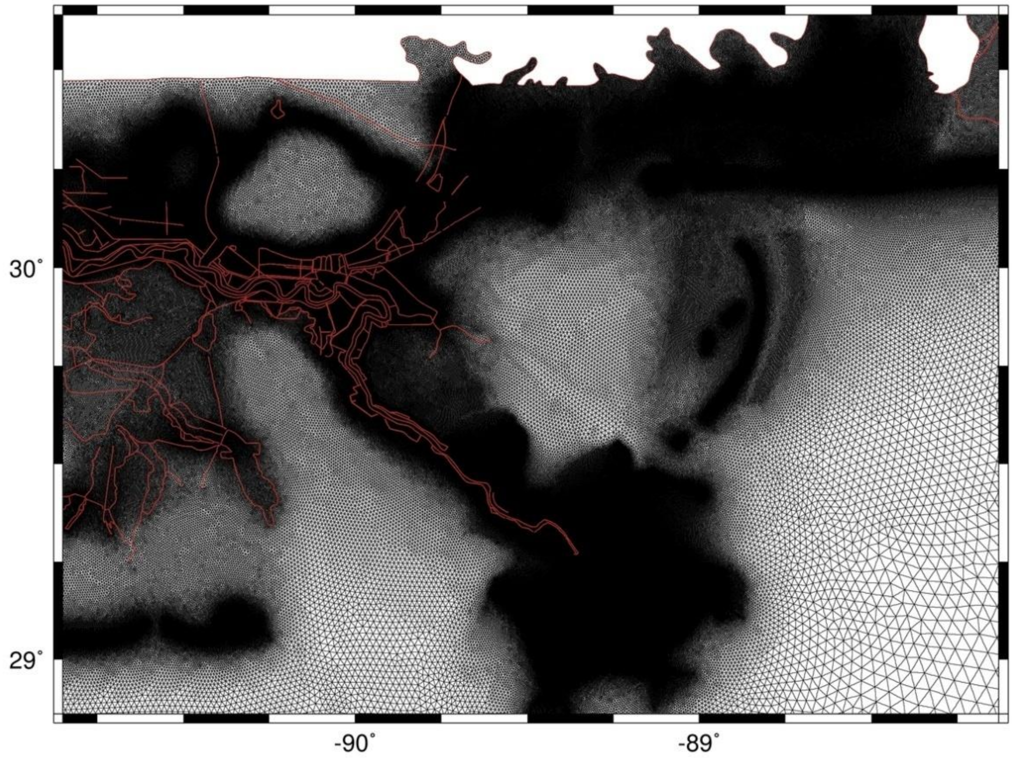


Figure 70. ADCIRC modified IHNC grid

E.3 GRID Density

E.3.1 ADCIRC S08 Grid

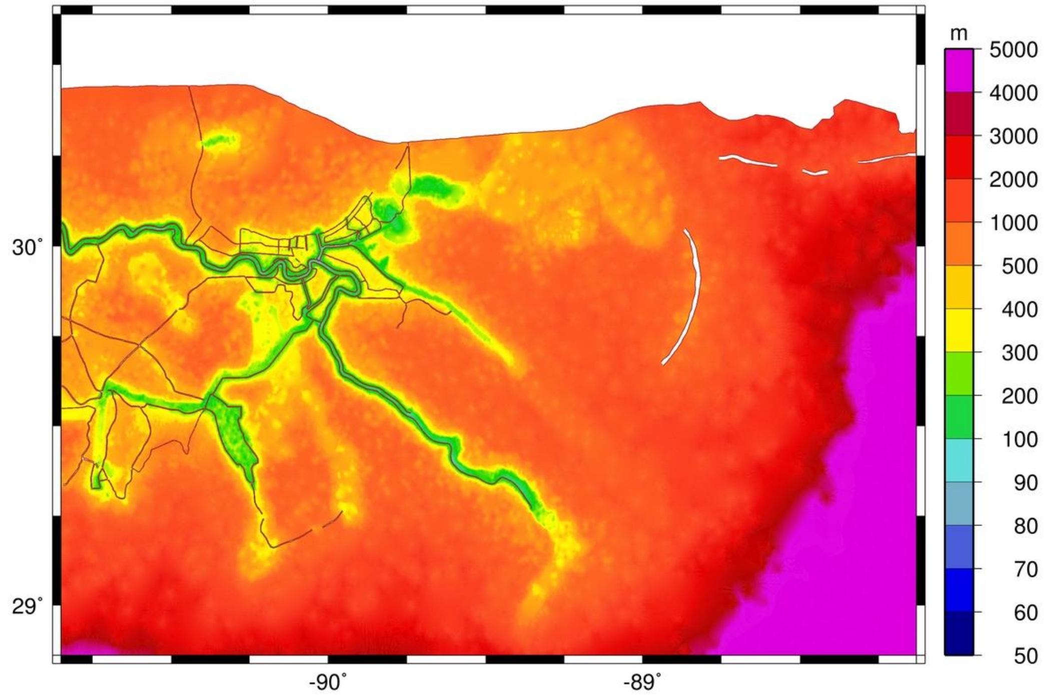


Figure 71 ADCIRC spacing between nodes of the S08 Model

E.3.2 ADCIRC SL15 grid

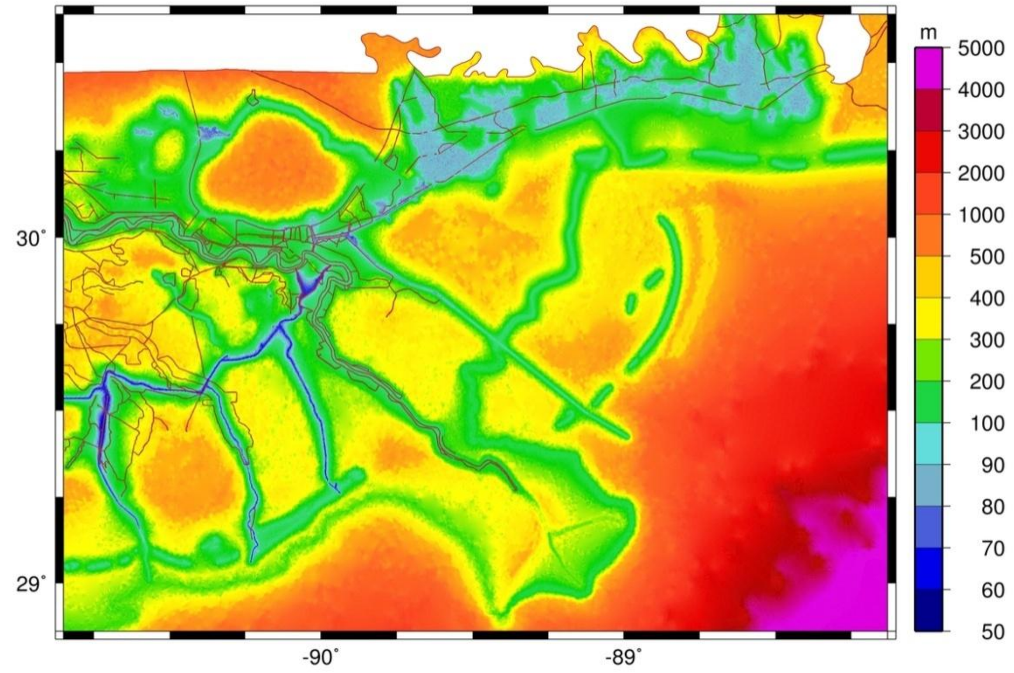


Figure 72. ADCIRC spacing between nodes of the SL15 Model

E.3.3 ADCIRC SL15 grid version 7

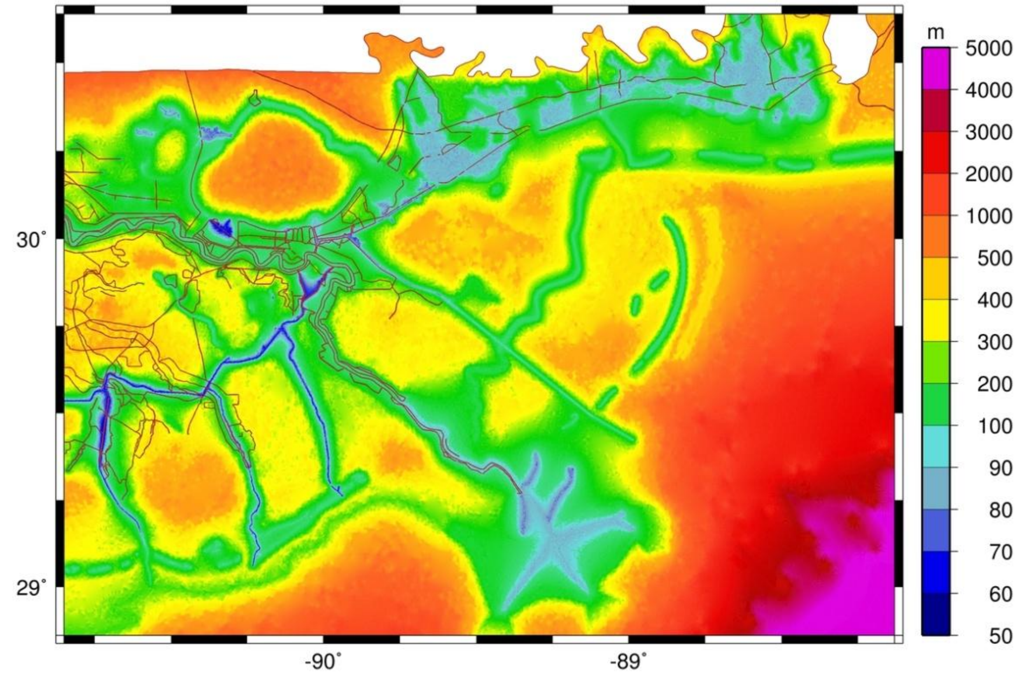


Figure 73 ADCIRC spacing between nodes of the SL15 version 7 Model

E.3.4 IHNC grid

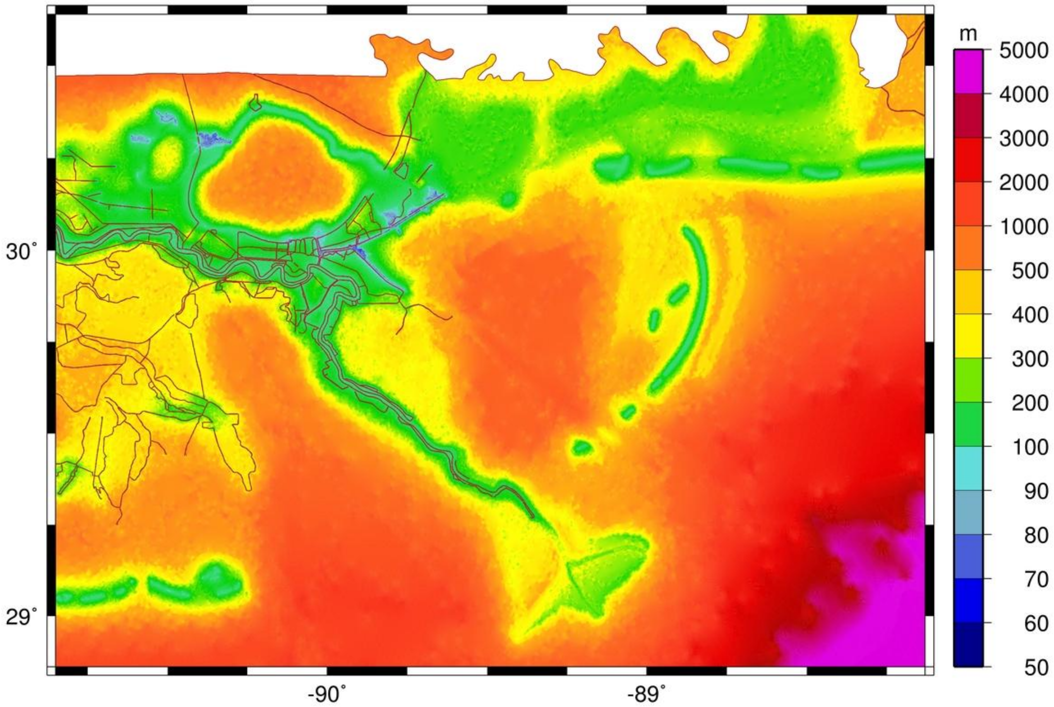
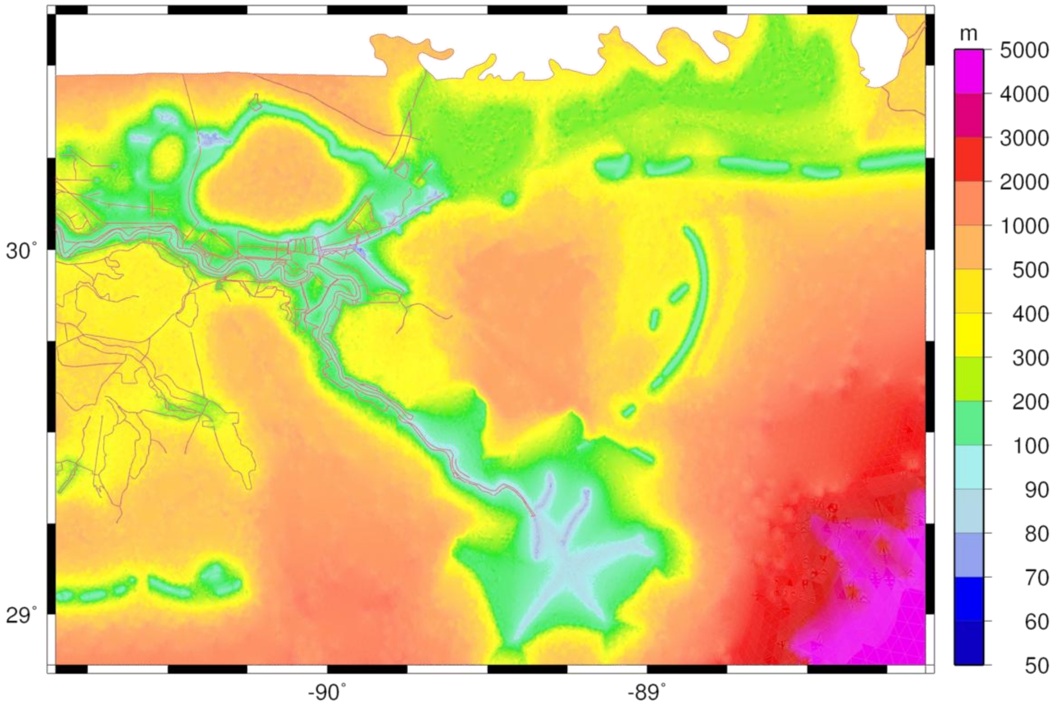


Figure 74. ADCIRC spacing between nodes of IHNC grid

E.3.5 Modified IHNC grid



Annex F
Model Performance

F MODEL PERFORMANCE

F.1 Regression lines

F.1.1 ADCIRC S08 model

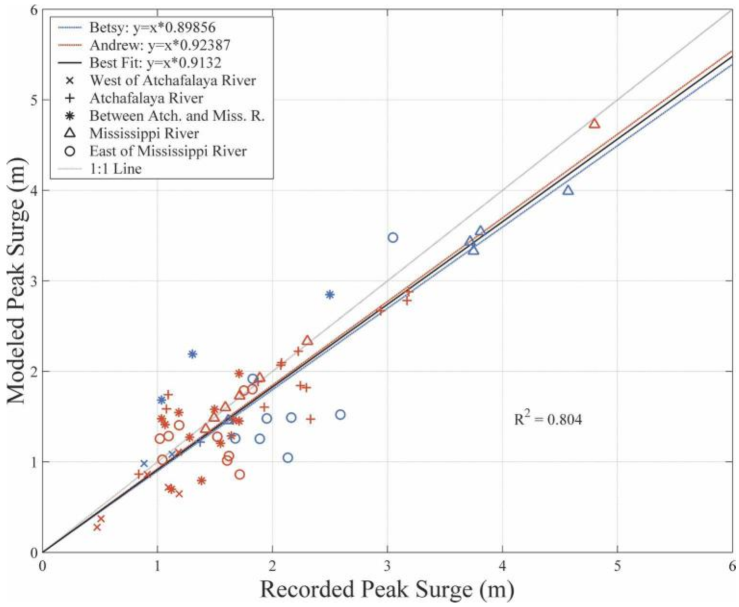


Figure 75. Comparison between model results and measured data of hurricanes Katrina and Rita .The model has a r^2 value of 0.80 (Westerink et al., 2008b)

F.1.2 ADCIRC SL15 grid

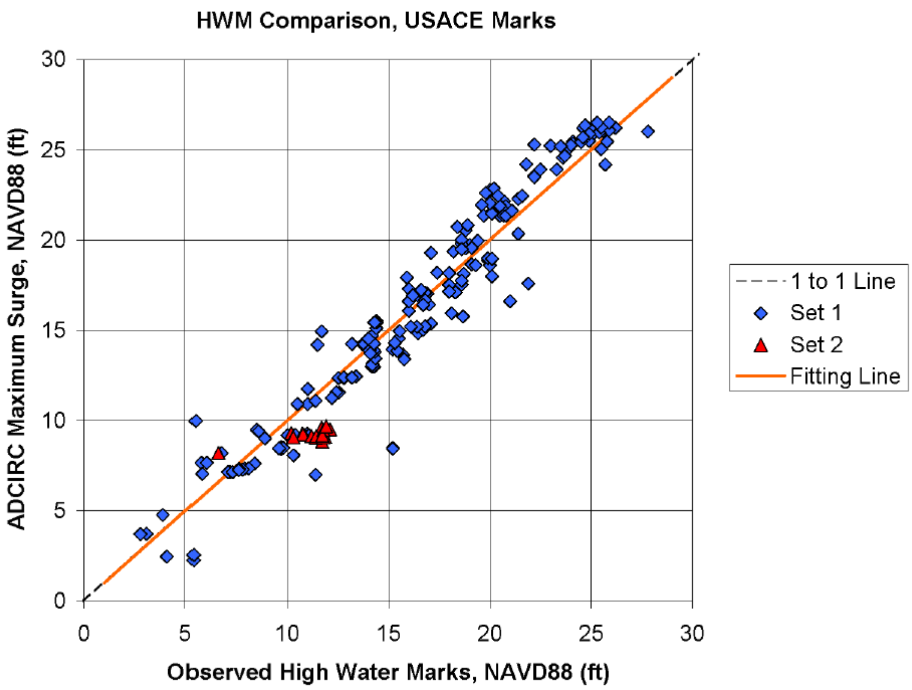
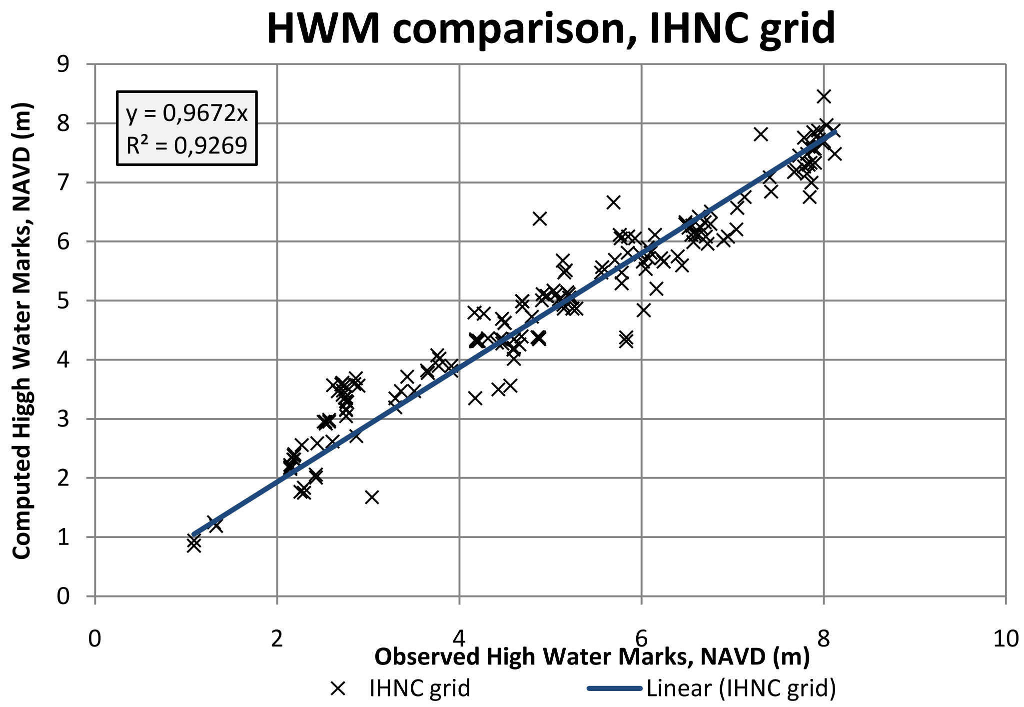
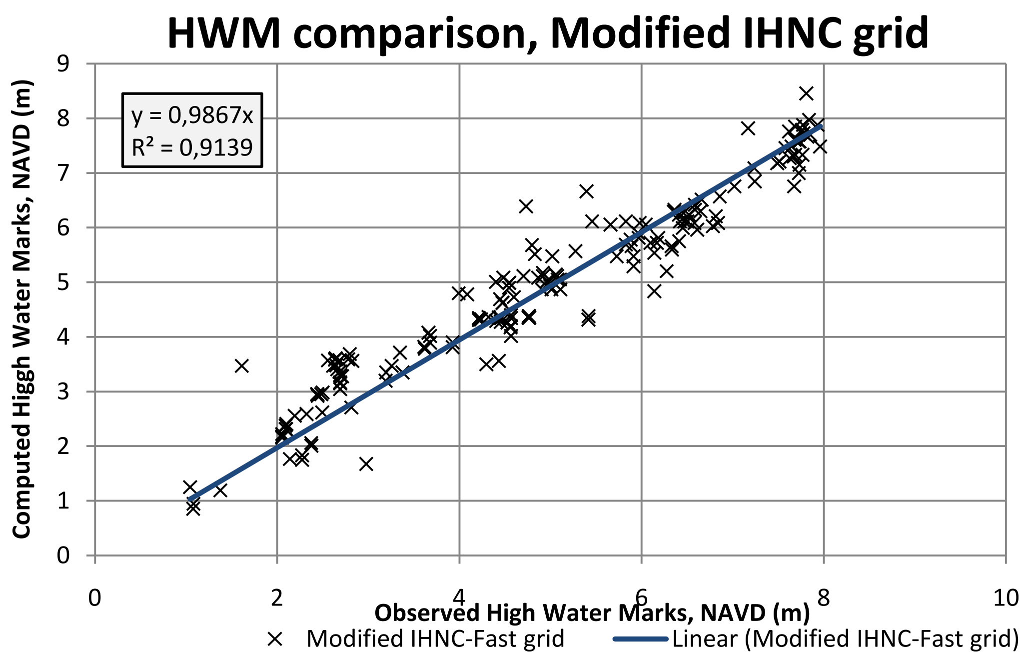


Figure 76. HWM comparison for the ADCRC SL15 model. This comparison shows a regression line with a slope of 1.0007 and an r2 value of 0.937(Westerink et al., 2008a)

F.1.3 ADCIRC IHNC grid

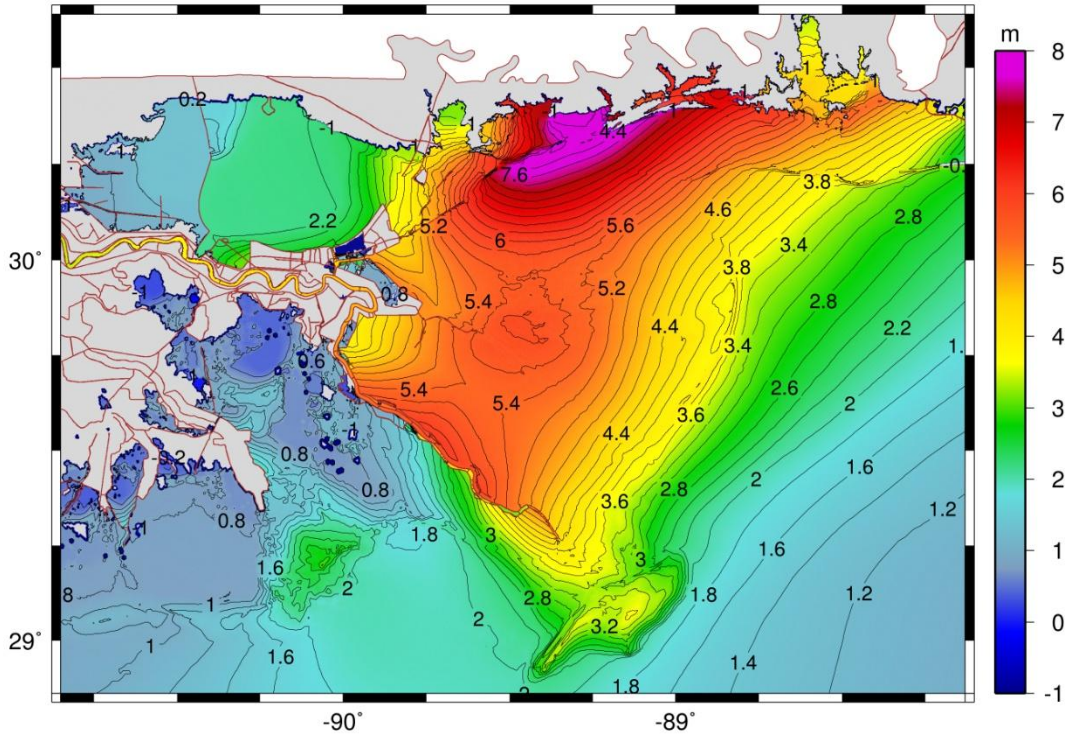


F.1.4 ADCIRC Modified IHNC grid



F.2 Maximum surge levels

F.2.1 ADCIRC IHNC grid



F.2.2 ADCIRC Modified IHNC grid

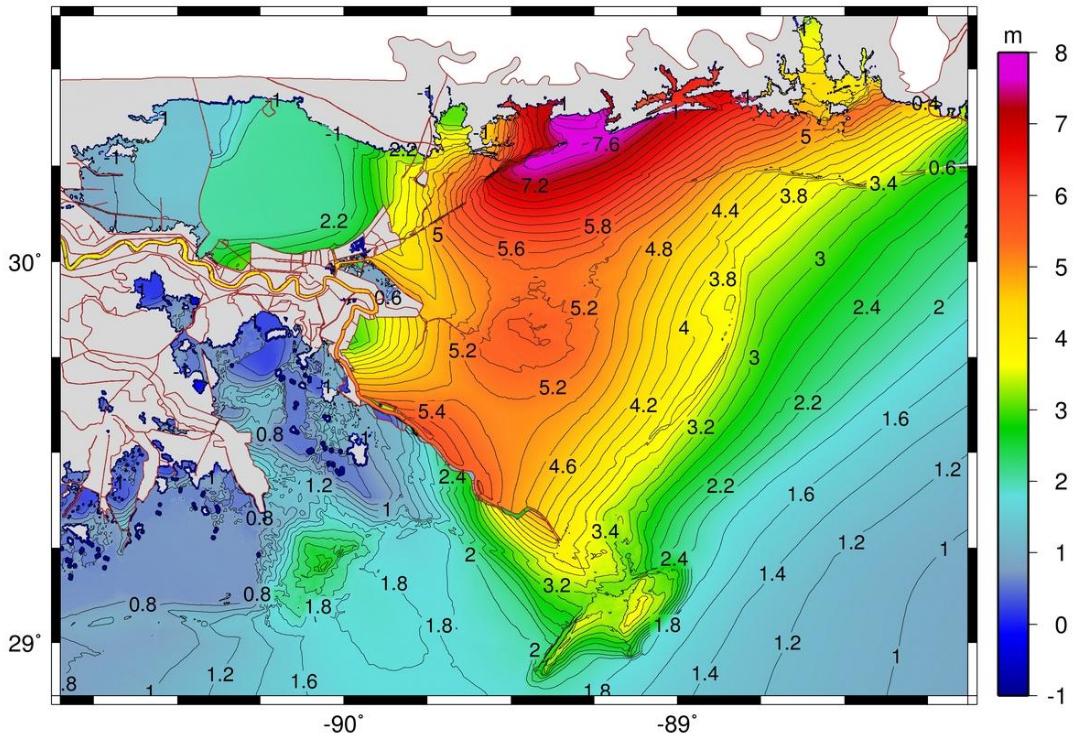


Figure 77. Maximum Surge elevation during Katrina as computed by the modified DCIRC IHNC model

Annex G
Spatial properties of the Modified INHC ADCIRC model

G SPATIAL PROPERTIES OF THE MODIFIED INHC ADCIRC MODEL

G.1 Modified IHNC grid Bathymetry

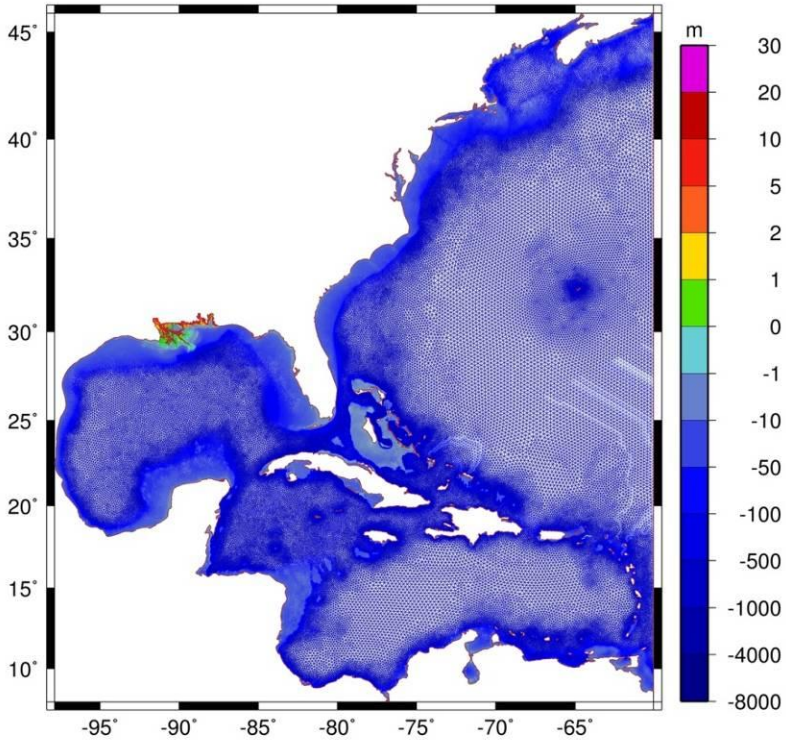


Figure 78. Bathymetry within the full domain.

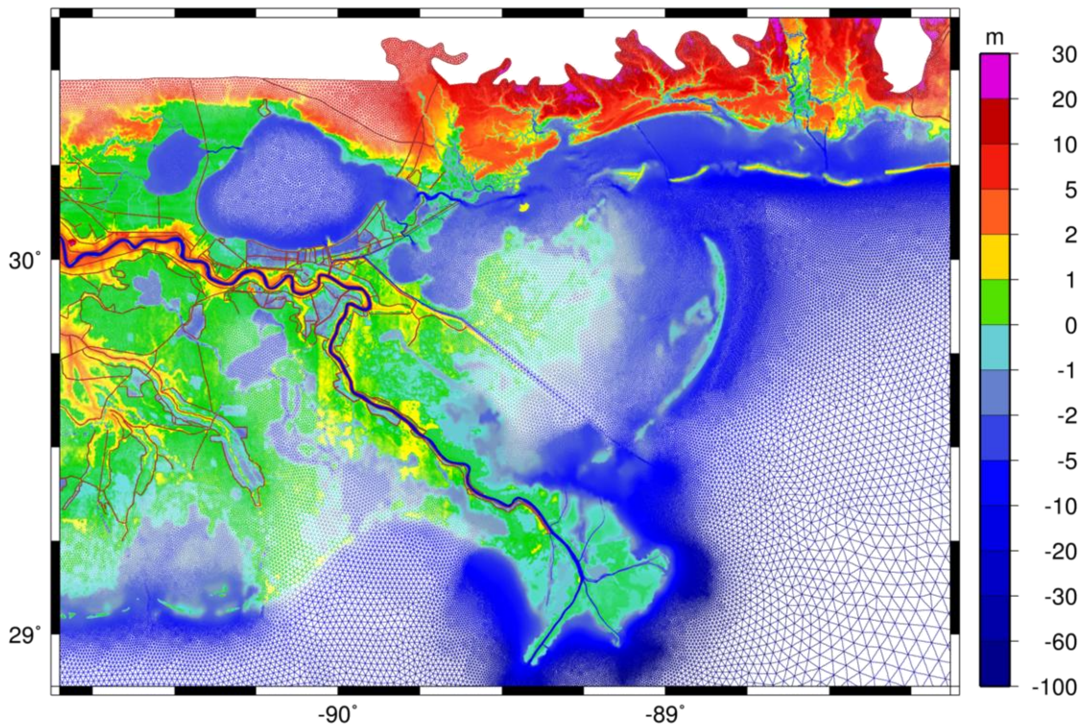


Figure 79. Bathymetry in the modified IHNC grid for South-West Louisiana.

G.2 Manning N values

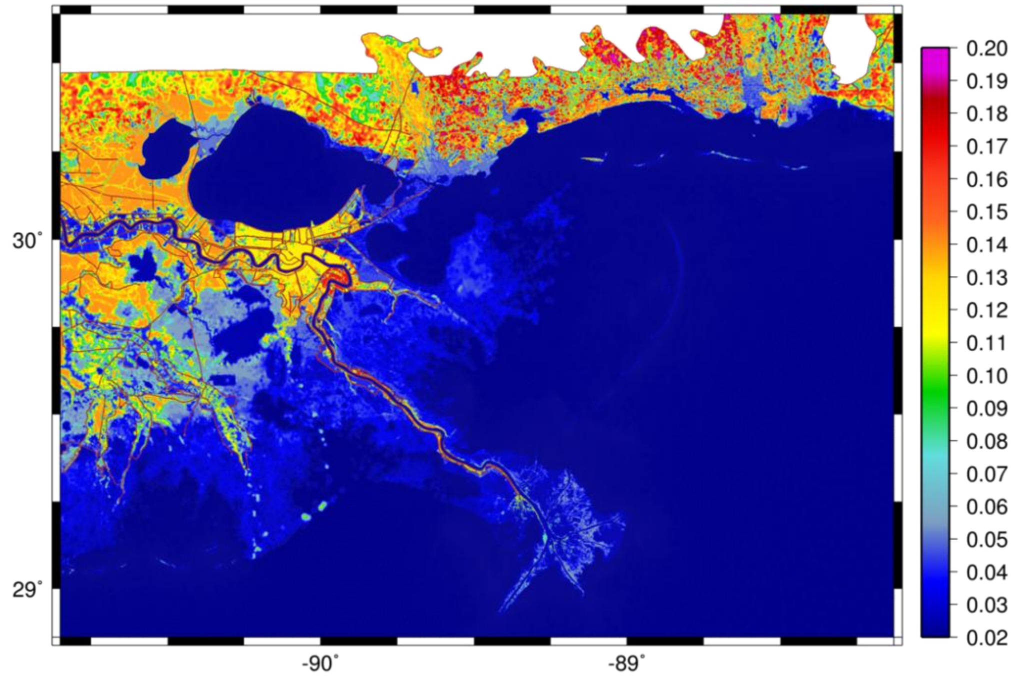


Figure 80. Manning-n roughness values in Southeast Louisiana..

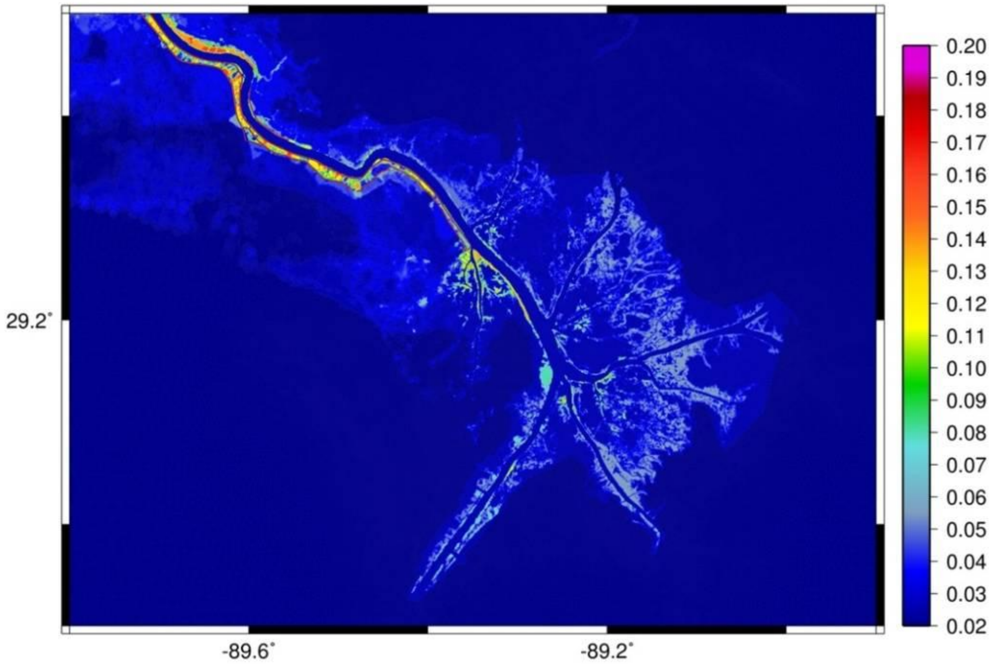


Figure 81. Detail of the Manning-n roughness values in the Mississippi delta.

Table 20. Manning n values for different land use types, (courtesy of Westerink et al. (2008a))

NLCD Class	Description	Manning-n
11	Open Water	0.020
12	Ice/Snow	0.022
21	Low Residential	0.120
22	High Residential	0.121
23	Commercial	0.050
31	Bare Rock/Sand	0.040
32	Gravel Pit	0.060
33	Transitional	0.100
41	Deciduous Forest	0.160
42	Evergreen Forest	0.180
43	Mixed Forest	0.170
51	Shrub Land	0.070
61	Orchard/Vineyard	0.100
71	Grassland	0.035
81	Pasture	0.033
82	Row Crops	0.040
83	Small Grains	0.035
84	Fallow	0.032
85	Recreational Grass	0.030
91	Woody Wetland	0.140
92	Herbaceous Wetland	0.035
95*	Cypress Forest	0.145

** Class 95 is constructed from the GAP data for Louisiana. The NLCD did not have coverage for a certain kind of wetland forest called "Cypress," so Gap data sets were merged into the NLCD and the Cypress Forest land type was imposed upon the NLCD data for the Cypress class and given a new name.

G.3 Directional Surface Roughness

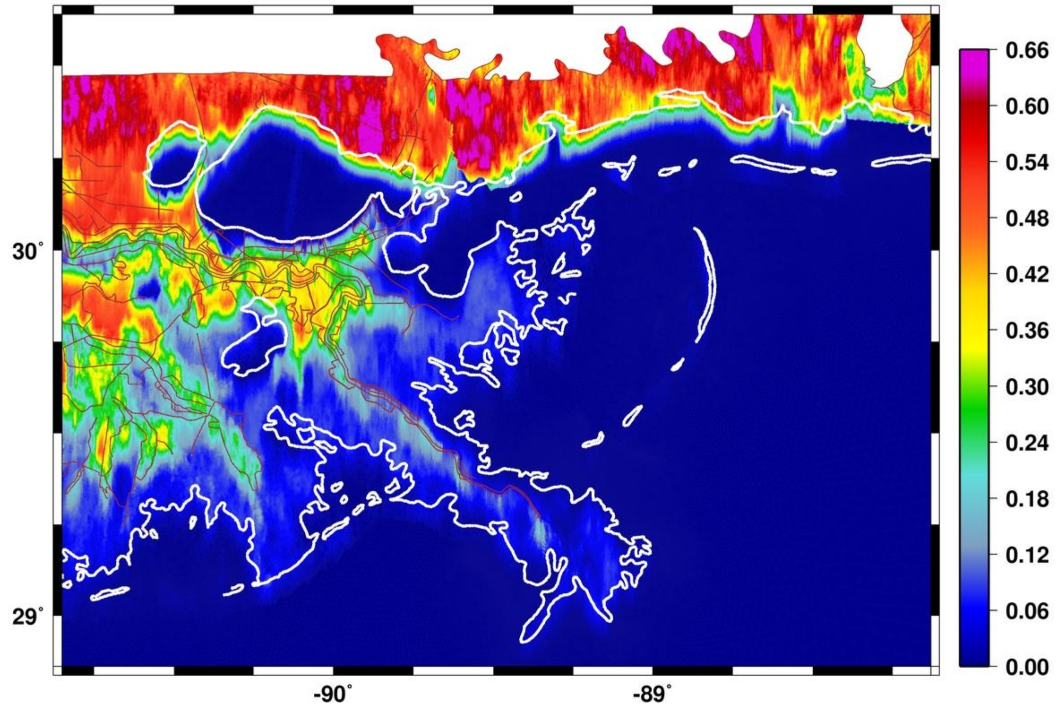


Figure 82. Directional Surface Roughness values for South-East Louisiana with the wind coming from the North. The white lines indicate the 0m NAVD line.

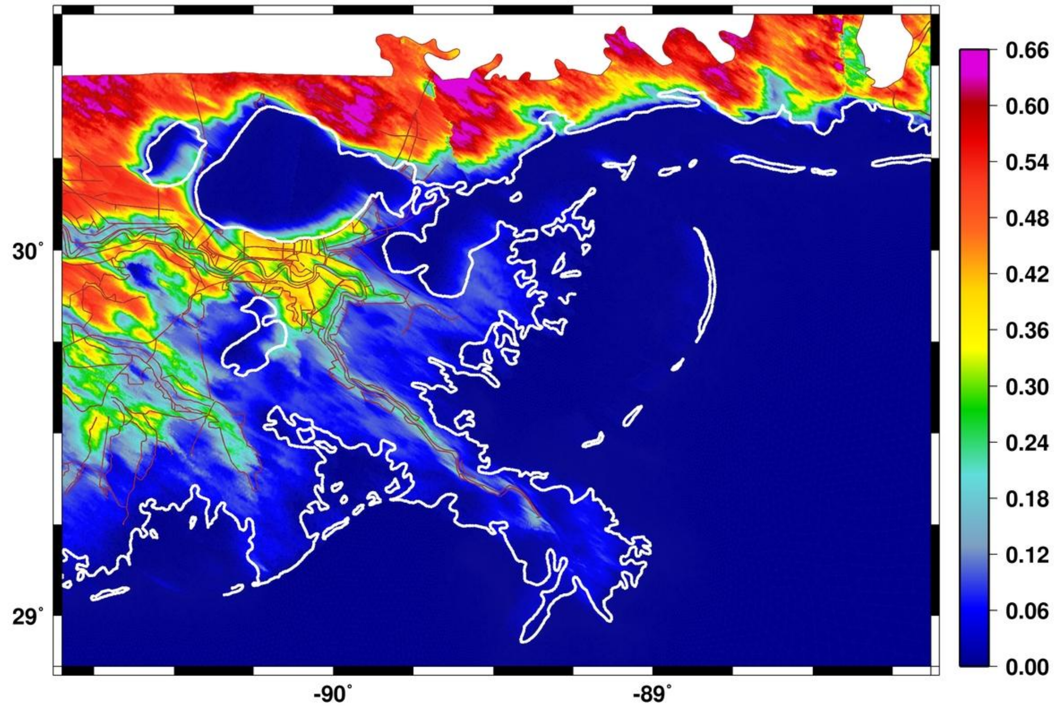
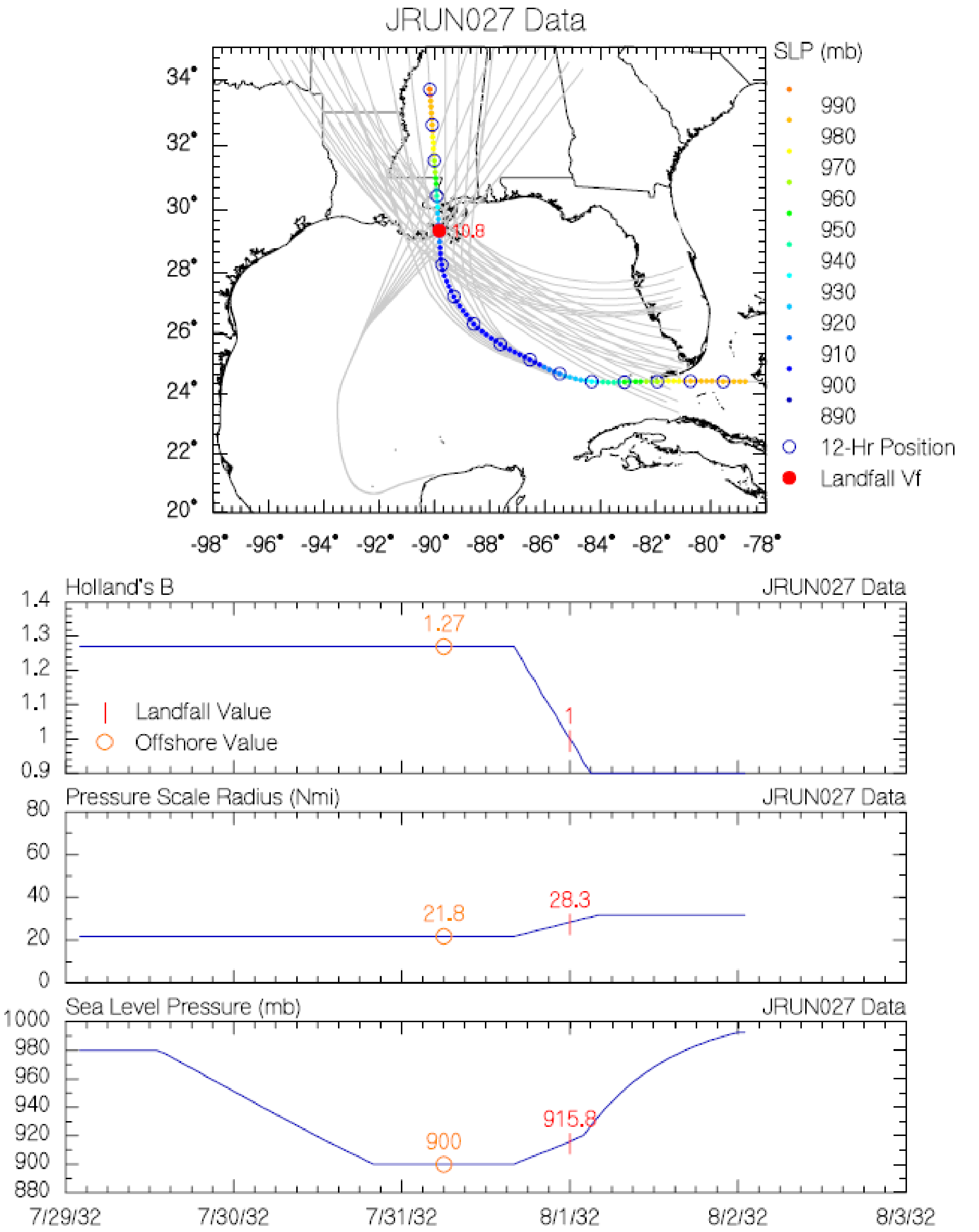


Figure 83. Directional Surface Roughness values for South-East Louisiana with South Easterly winds. The white lines indicate the 0m NAVD line.

Annex H
Hypothetical Hurricanes

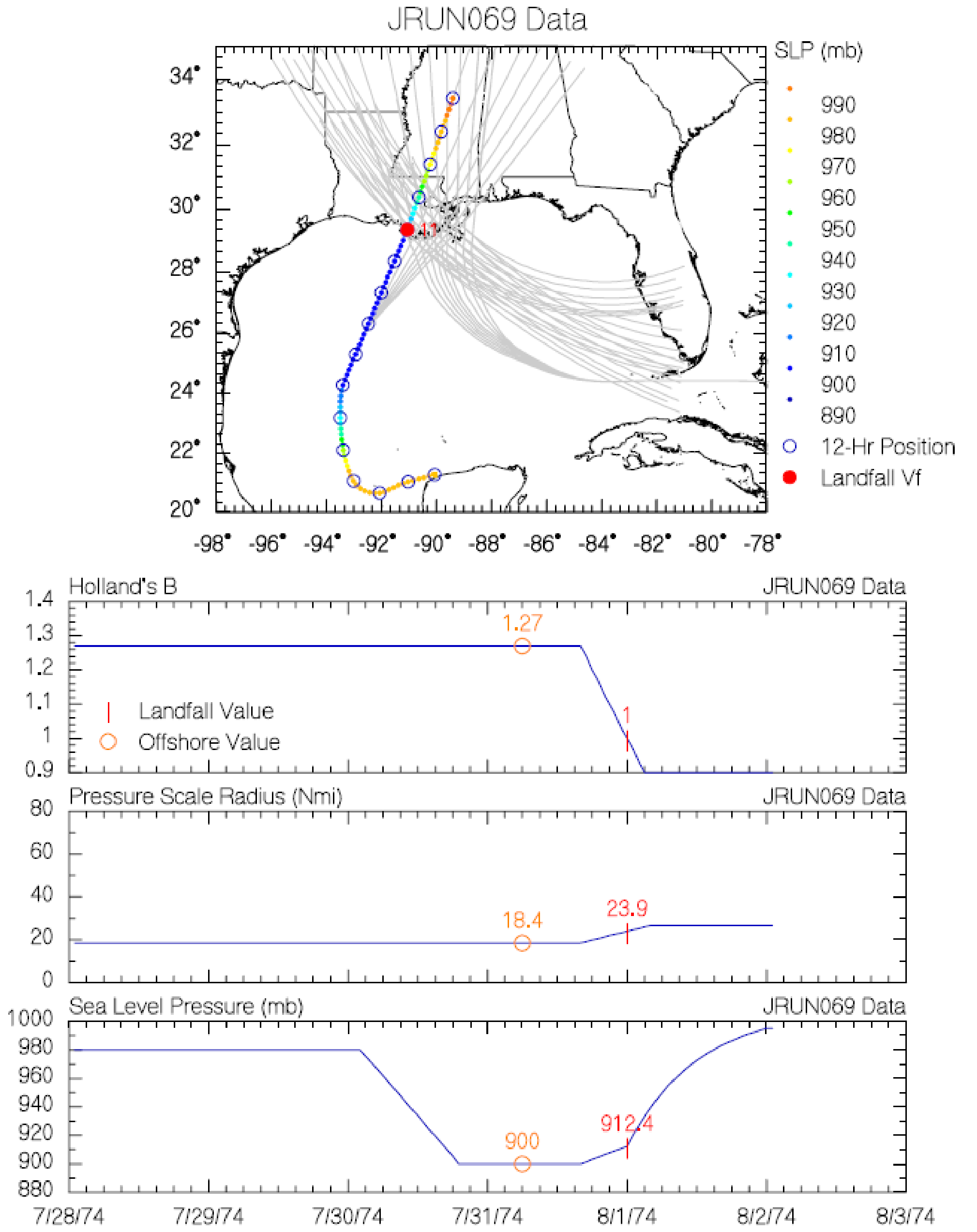
H STORM PROPERTIES

H.1 Properties of Storm 27



Printed from H:\URS\ERDCData\JRUN027.WPG (created on Dec-05-2006 01:37PM)

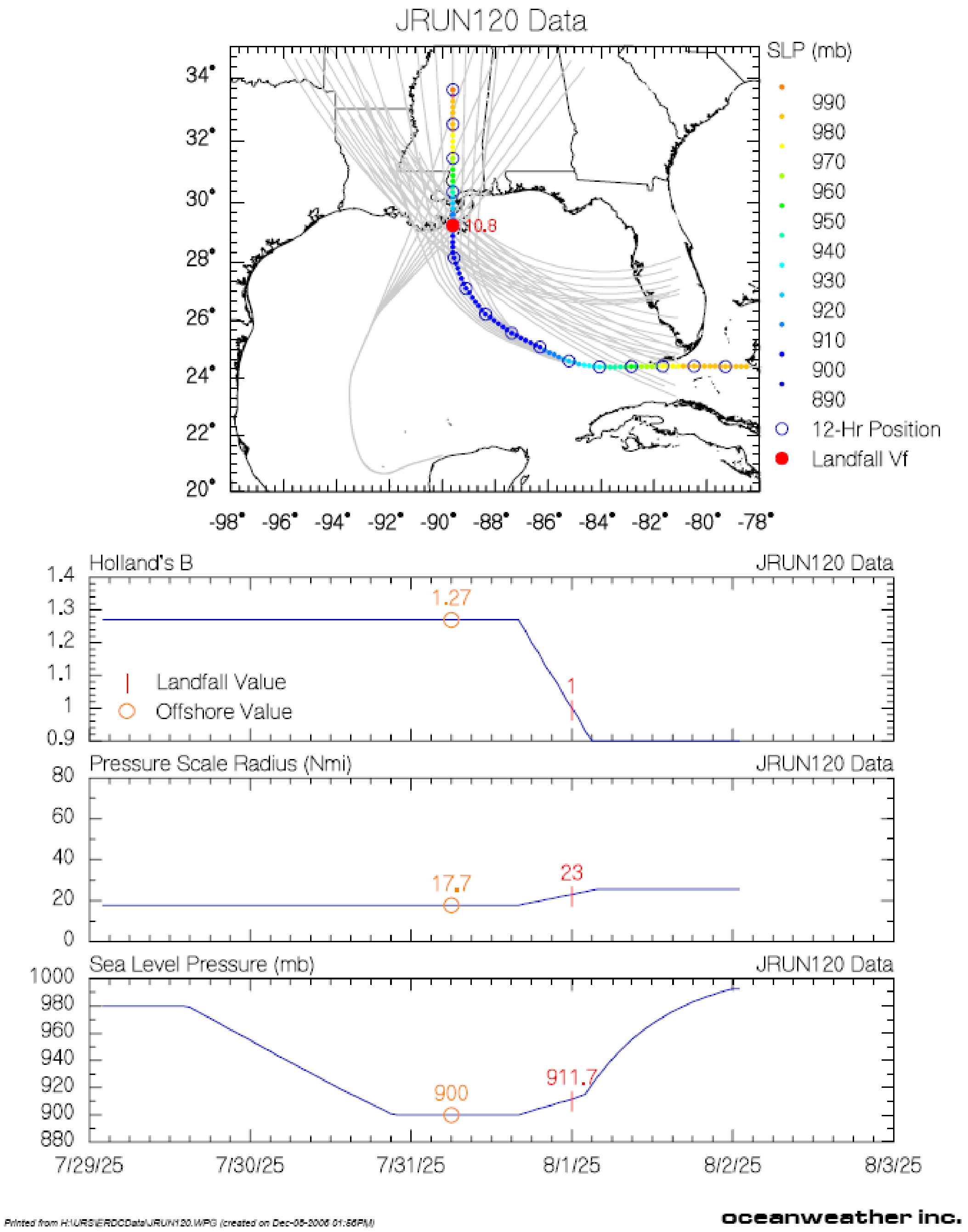
H.2 Properties of Storm 69



Printed from H:\URS\ERDCData\JRUN069.WPG (created on Dec-05-2006 01:45PM)

oceanweather inc.

H.3 Properties of Storm 120



Annex I
Maximum Water Levels

I MAXIMUM WATER LEVELS

I.1 Current levees

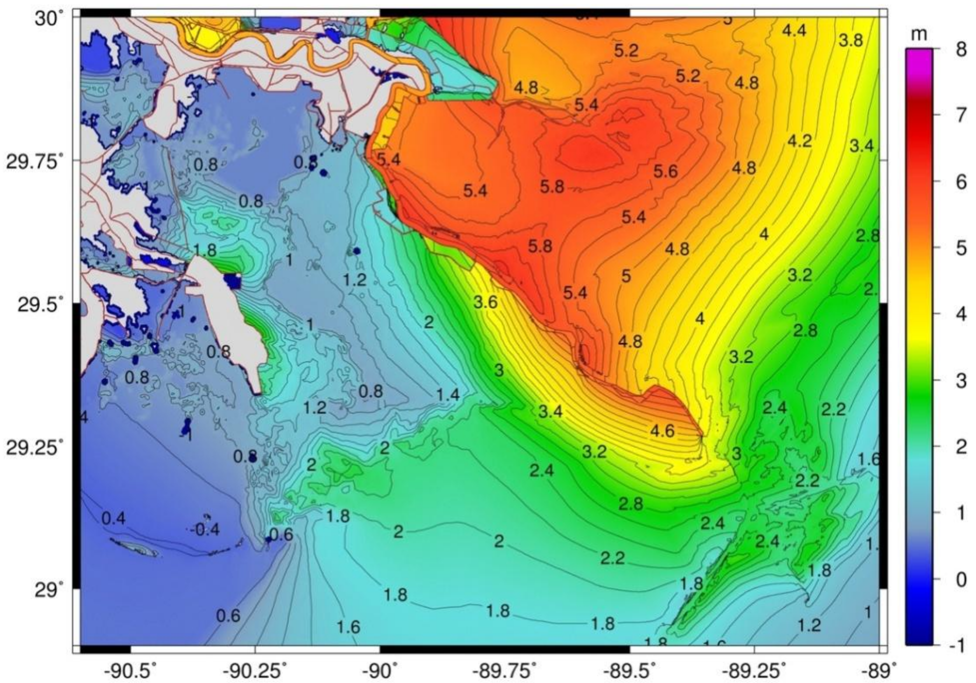


Figure 84. Maximum water levels during storm 27

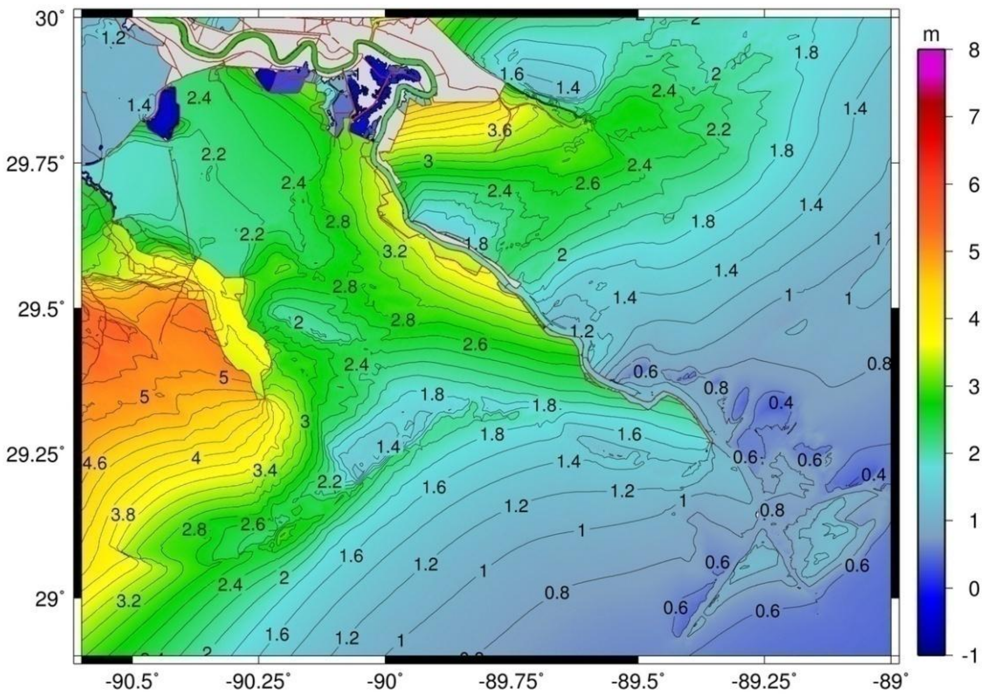


Figure 85. Maximum Water Levels during storm 69

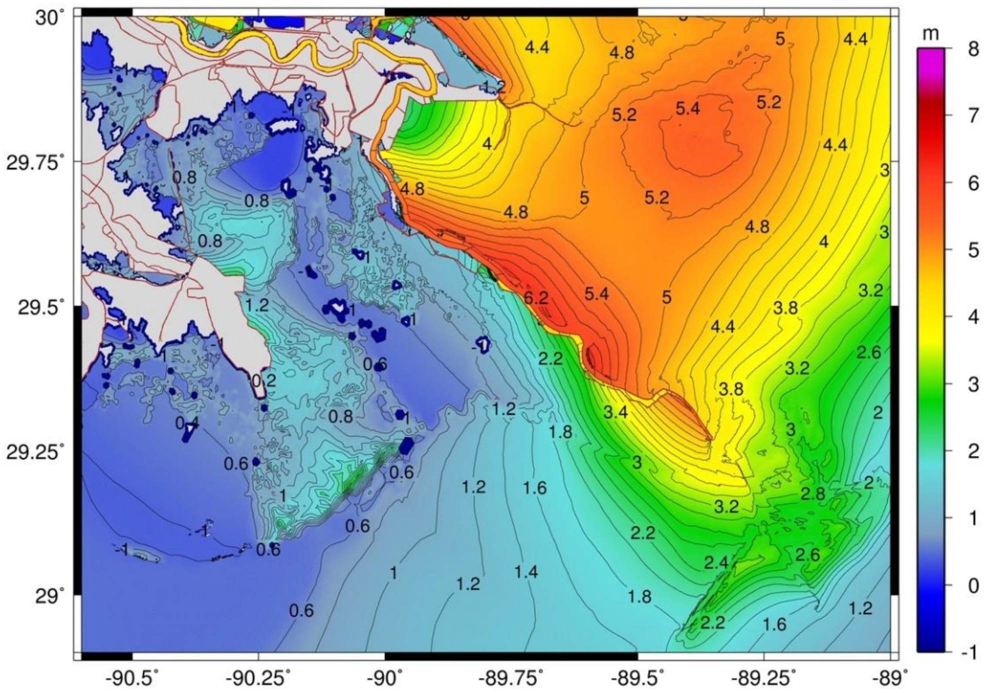


Figure 86. Maximum water levels during storm 120

I.2 Plaquemines None

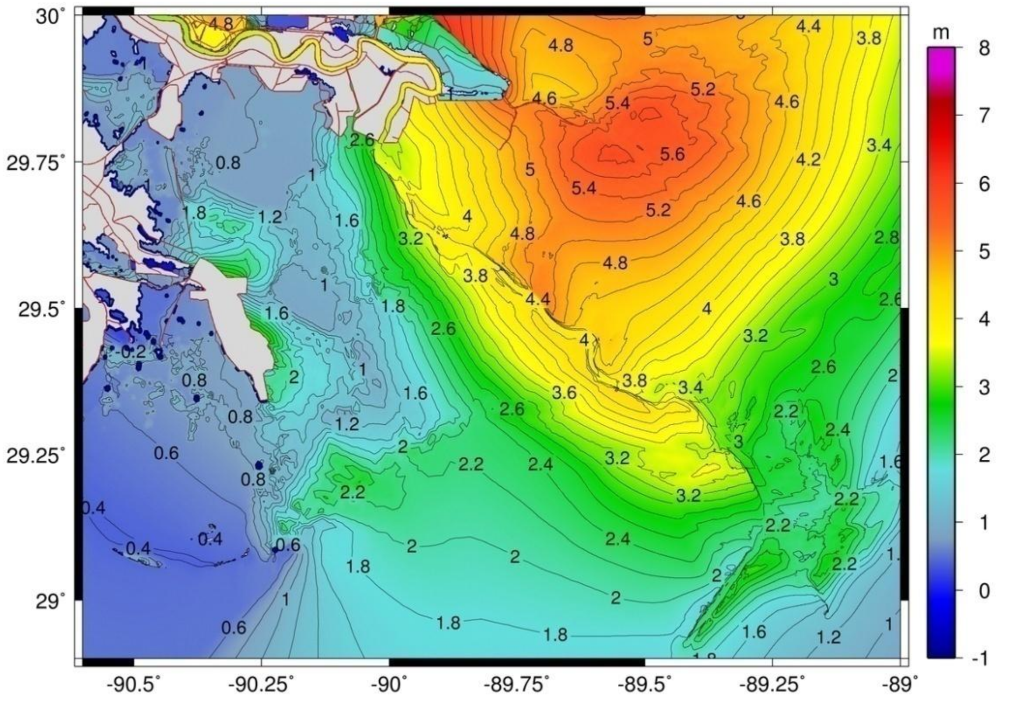


Figure 87. Maximum water levels during storm 27

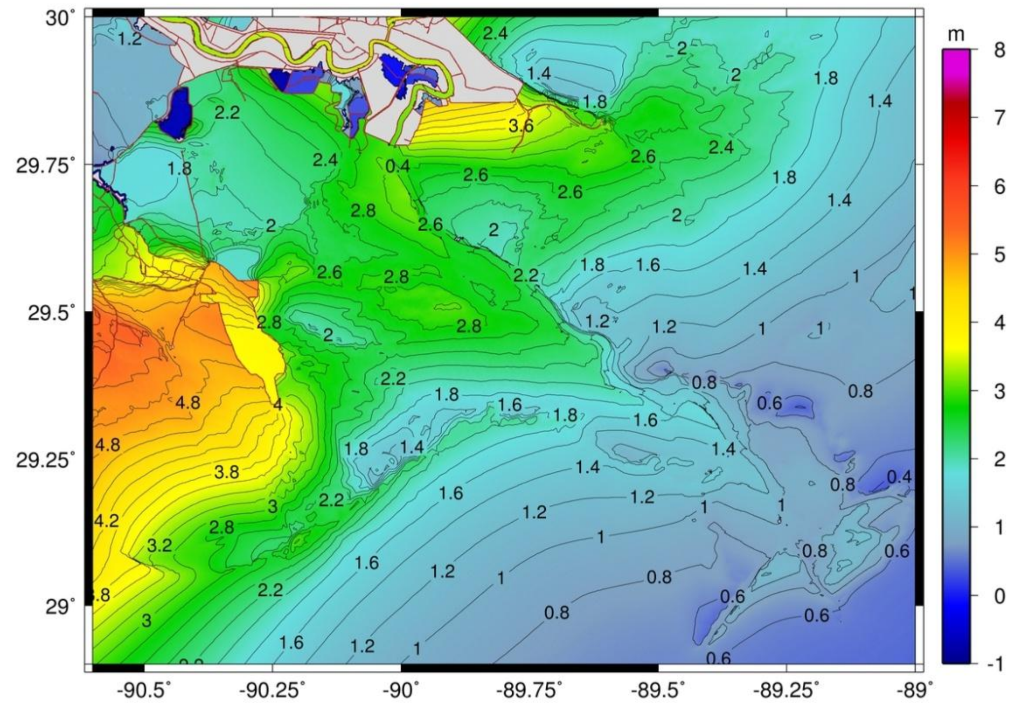


Figure 88. Maximum water levels during storm 69

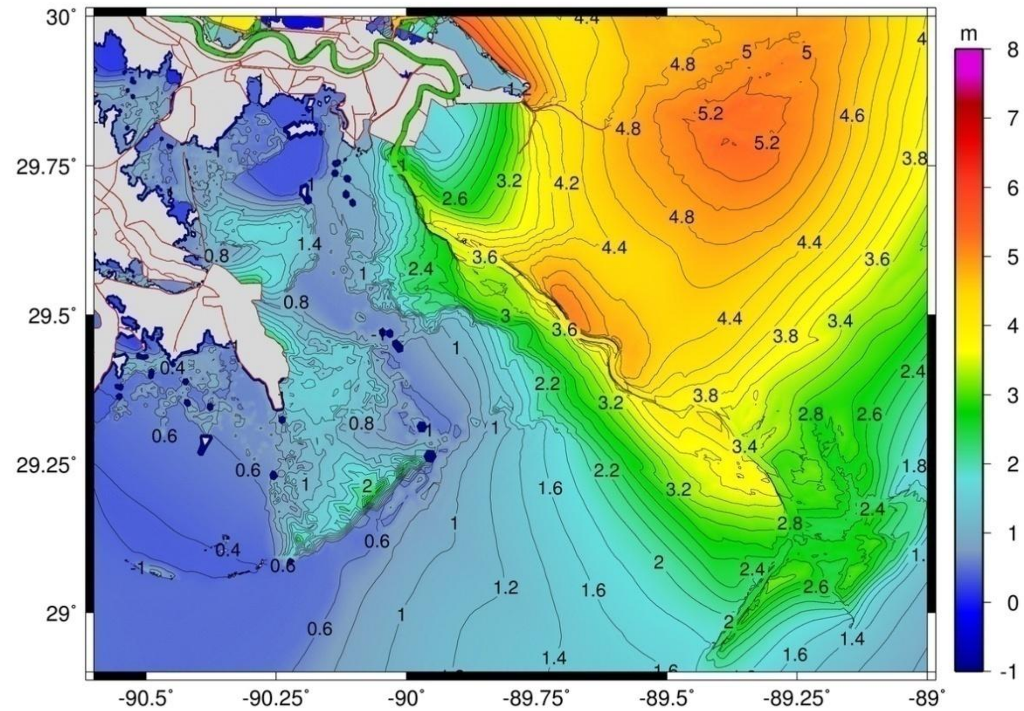


Figure 89 Maximum water levels during storm 120

I.3 Plaquemines CDP

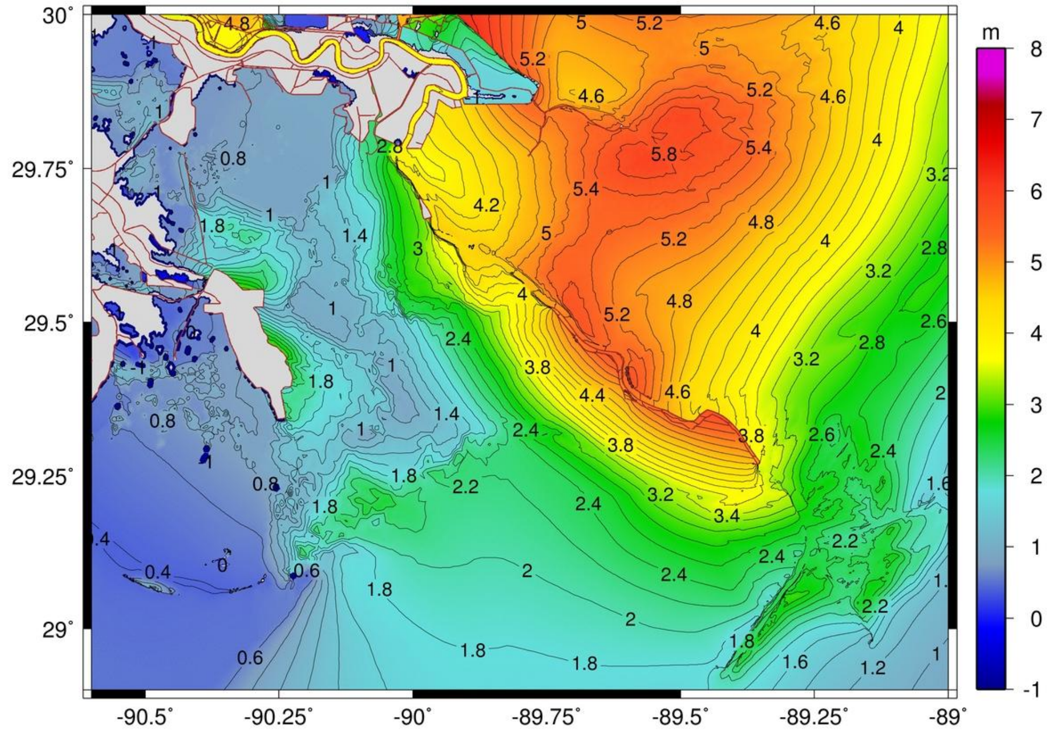


Figure 90. Maximum water levels during storm 27

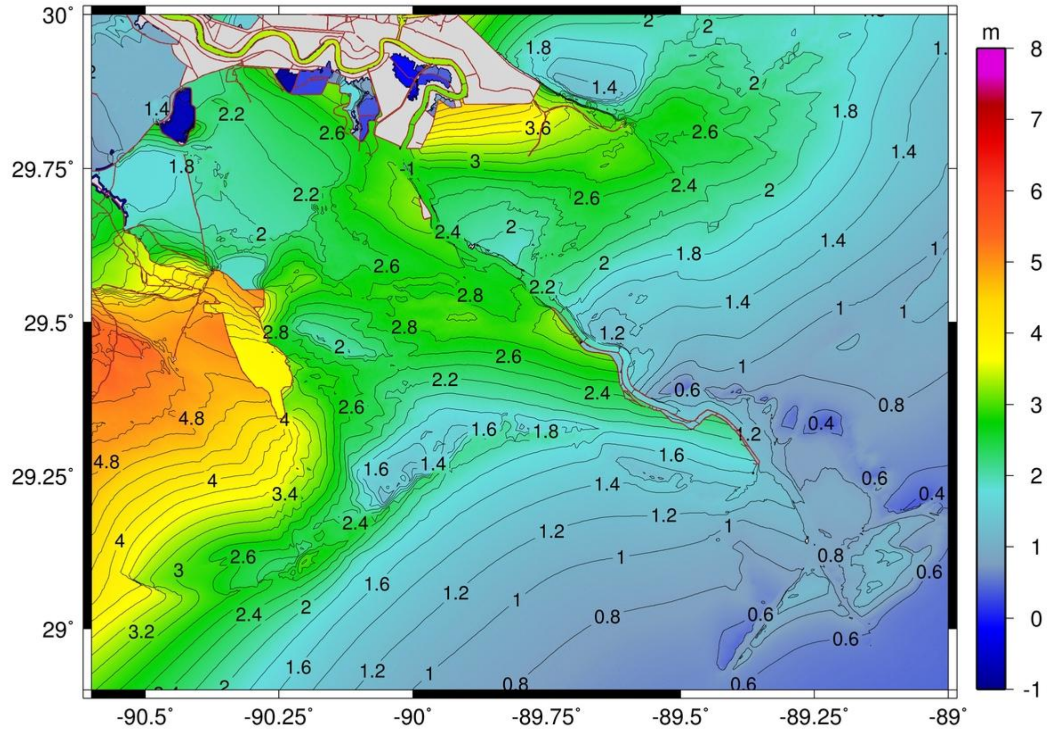


Figure 91. Maximum water levels during storm 69

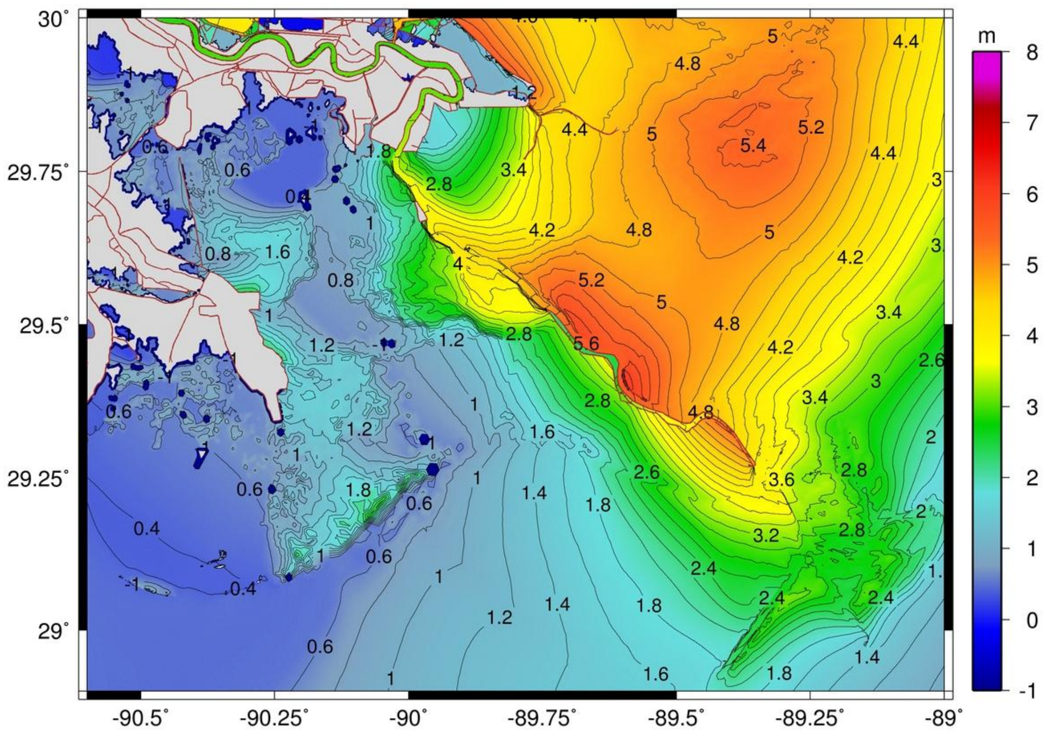


Figure 92. Maximum water levels during storm 120

I.4 Plaquemines Minimum

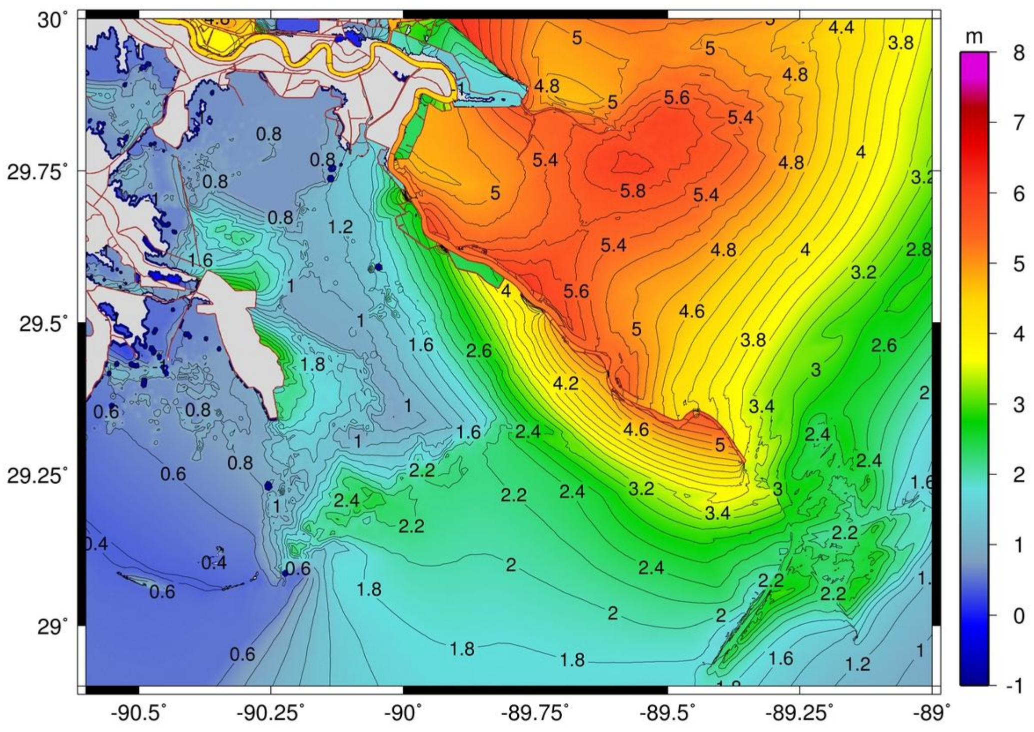


Figure 93. Maximum water levels during storm 27

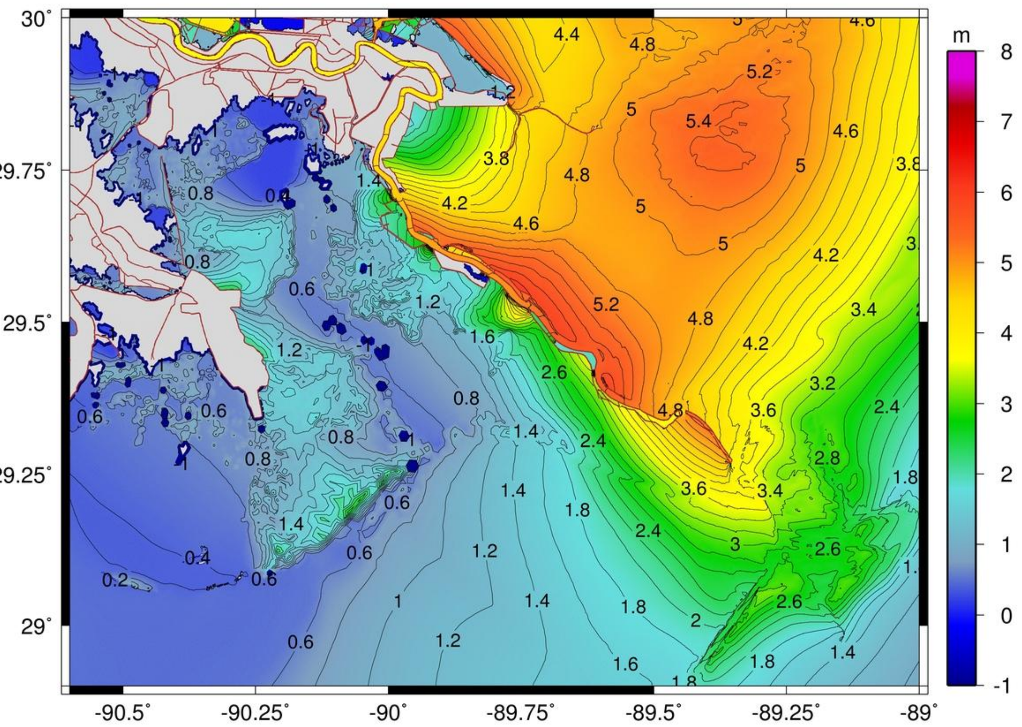


Figure 94. Maximum water levels during storm 69

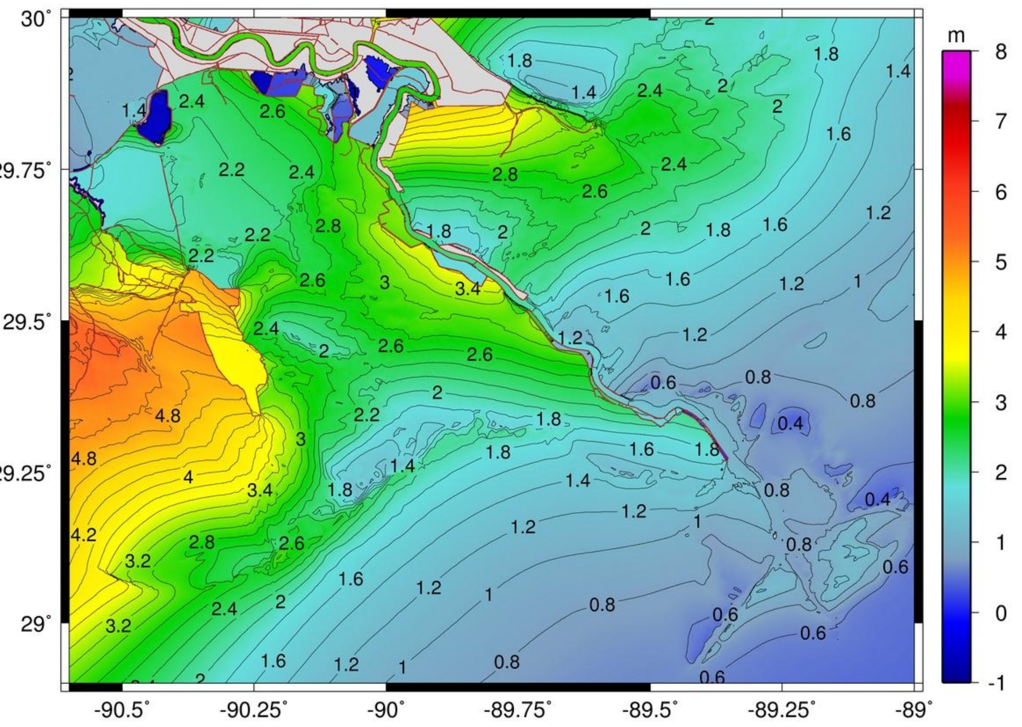


Figure 95. Maximum water levels during storm 120

I.5 LACPR Spillways

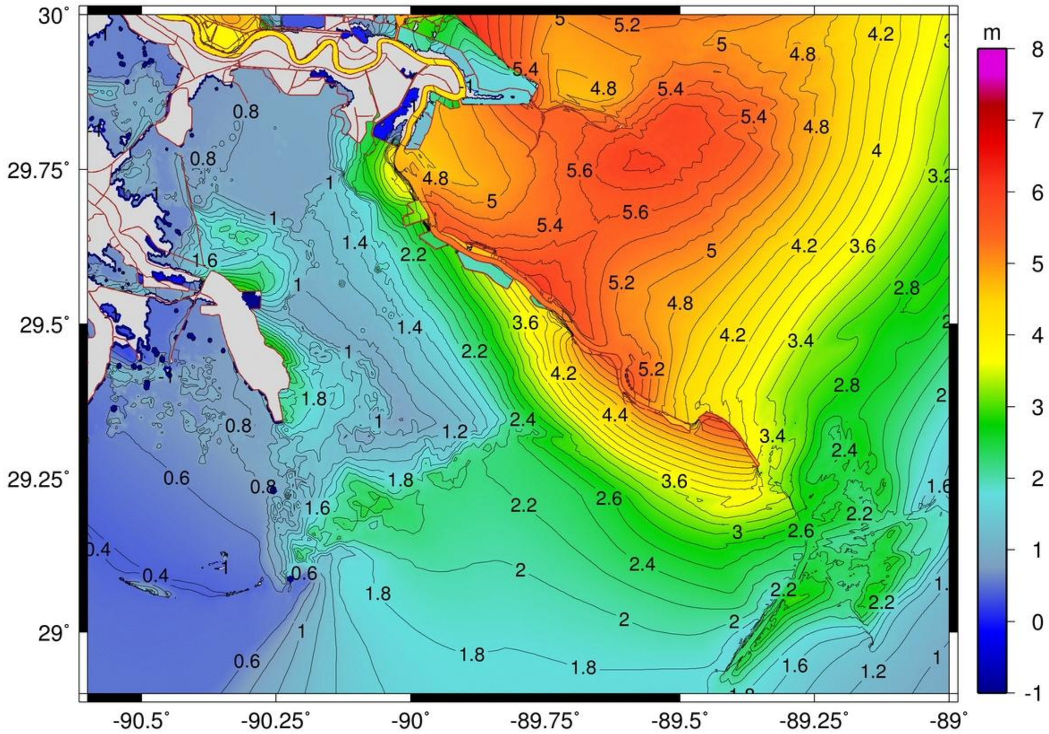


Figure 96. Maximum water levels during storm 27

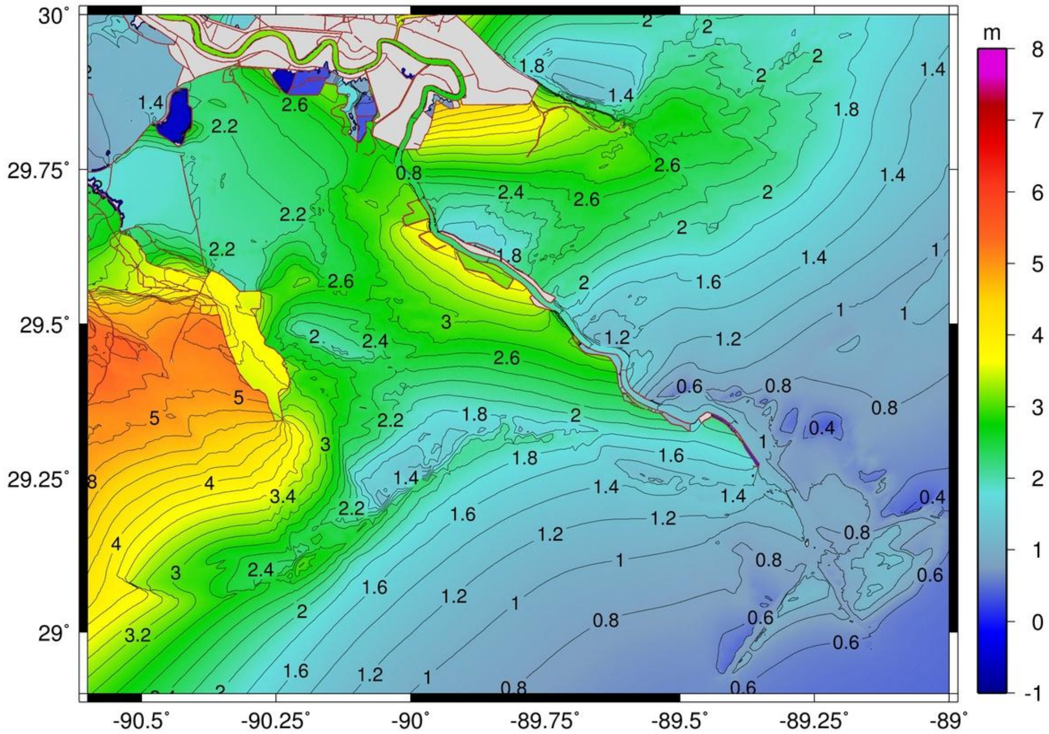


Figure 97. Maximum water levels during storm 69

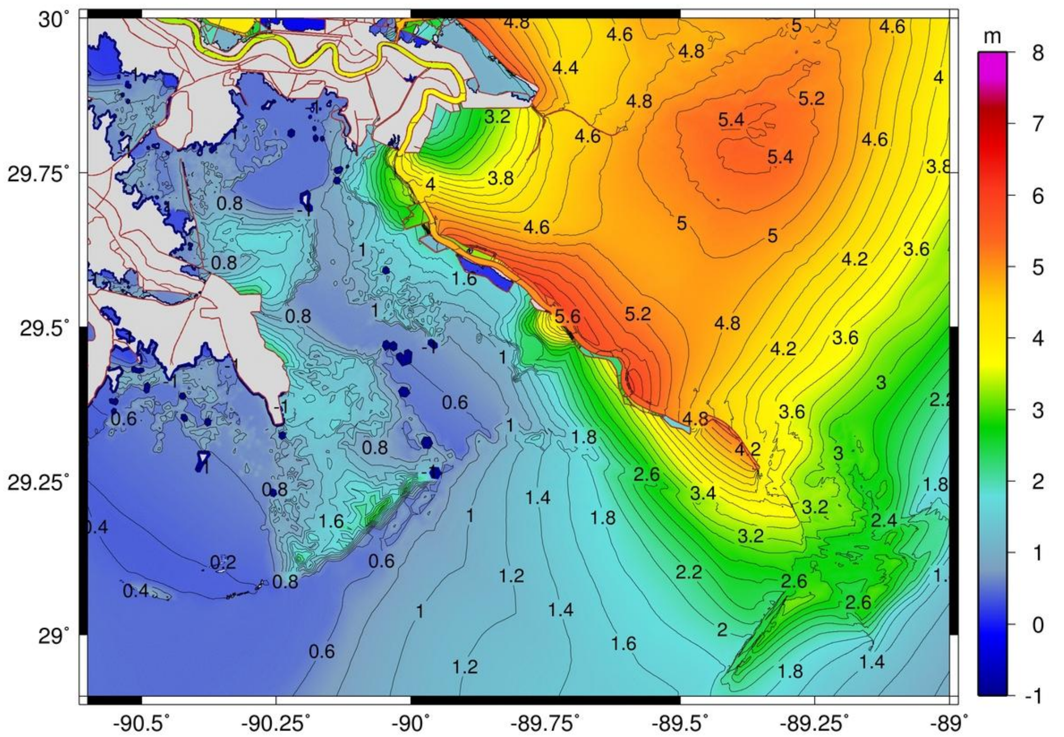


Figure 98. Maximum water levels during storm 120

I.6 Lowered LACPR Spillways

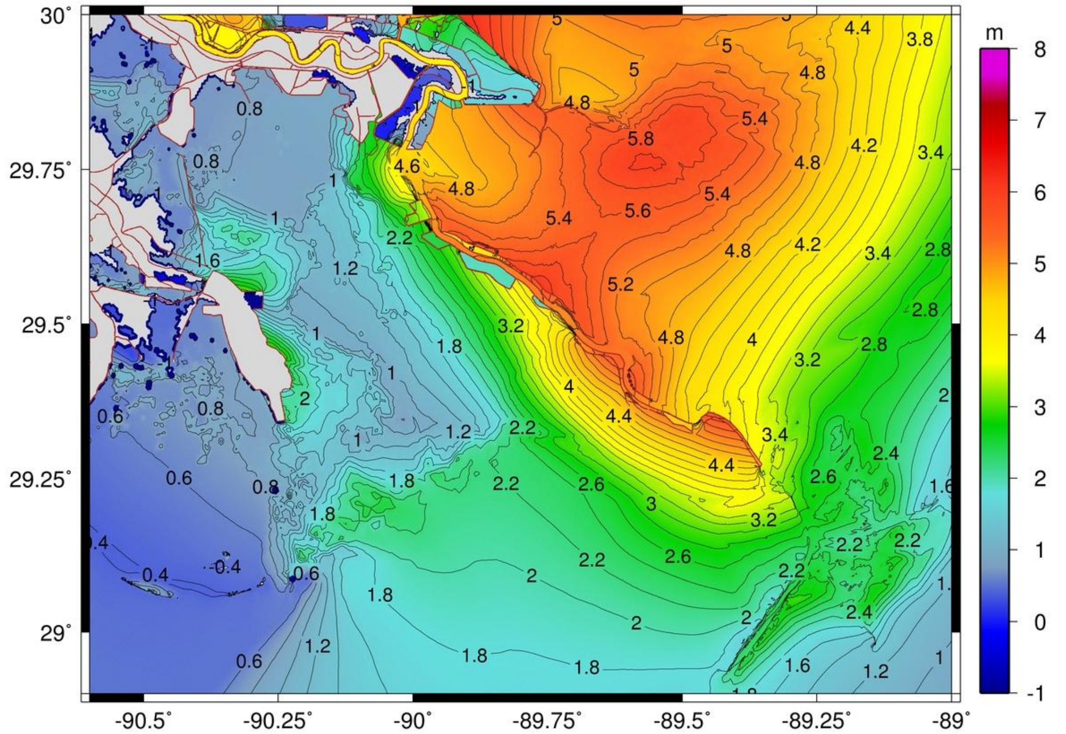


Figure 99. Maximum water levels during storm 27

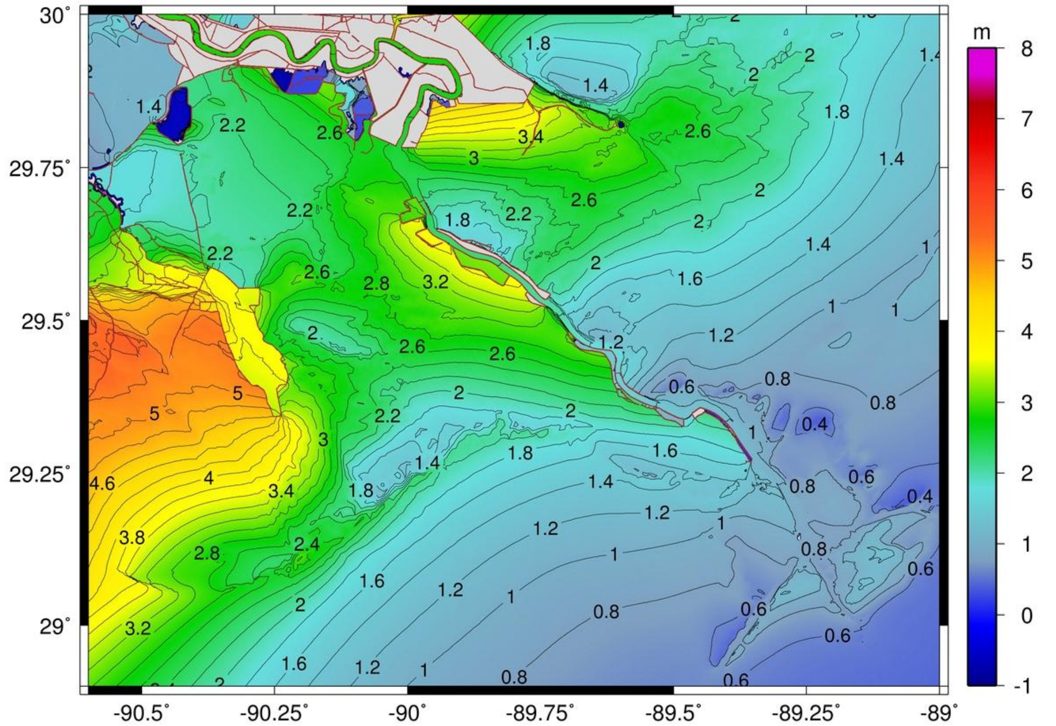


Figure 100 Maximum water levels during storm 69

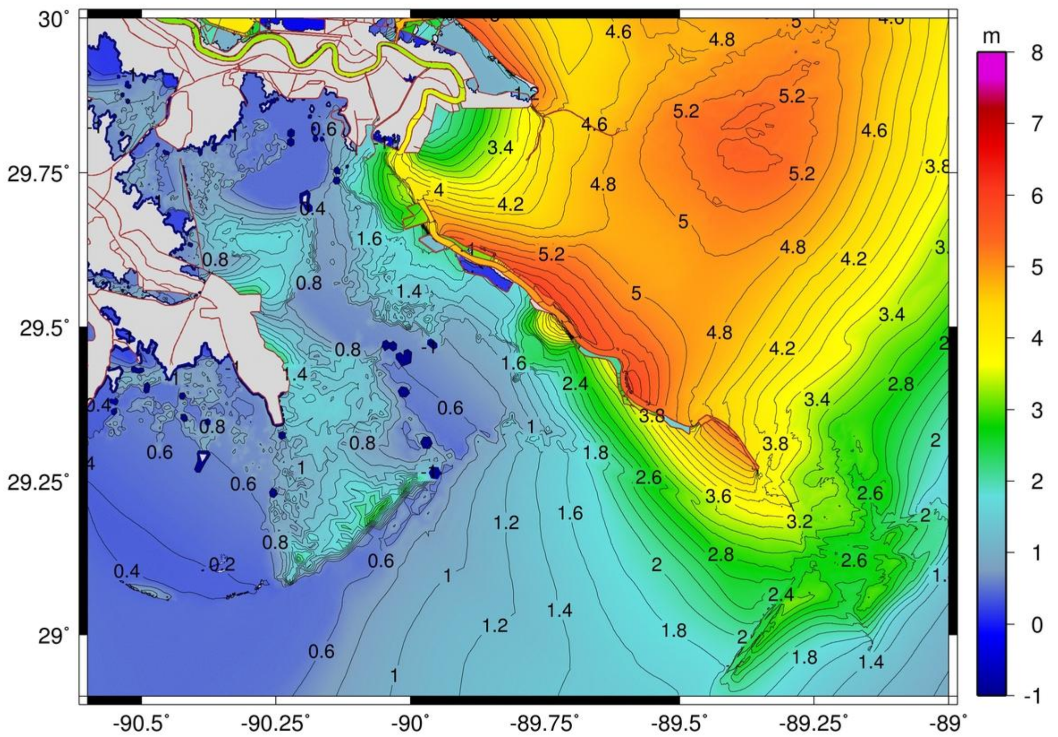


Figure 101 Maximum water levels during storm 120

Annex J
Maximum Water Level Differences

J MAXIMUM WATER LEVEL DIFFERENCES

J.1 Current levees vs. Plaquemines none

J.1.1 Storm 27

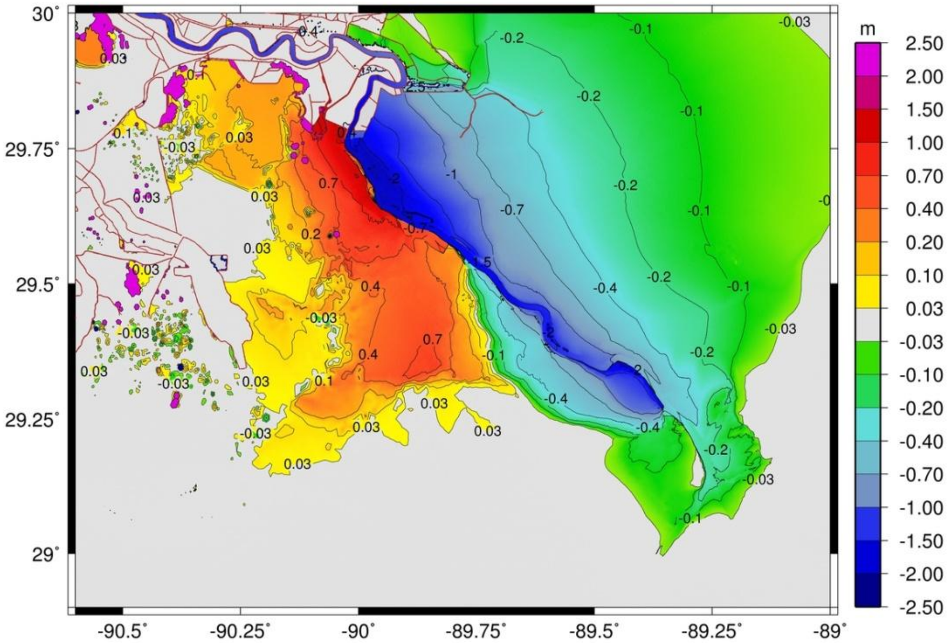


Figure 102. Differences between the Current levees and Plaquemines none, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.1.2 Storm 69

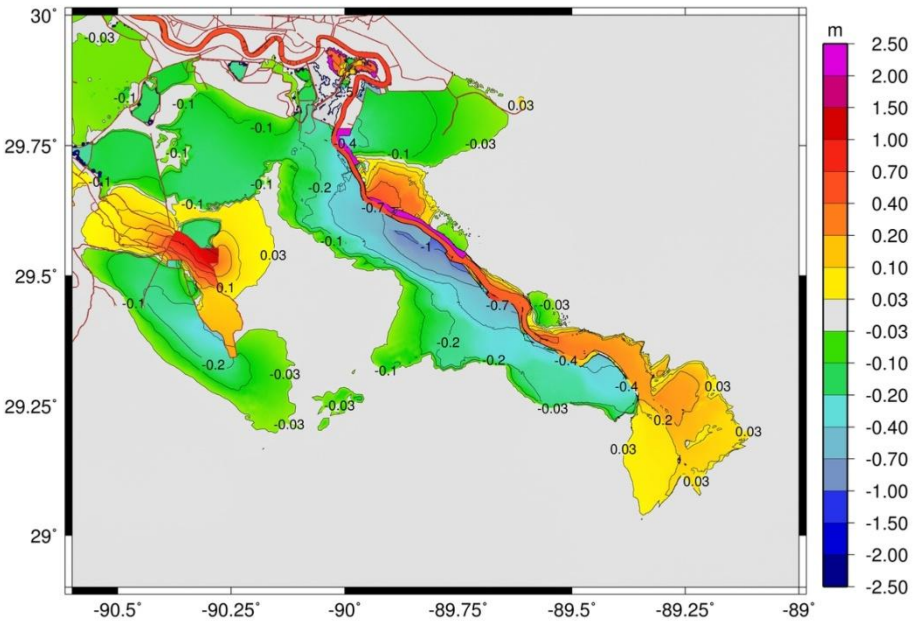


Figure 103. Differences between the current levees and Plaquemines none, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.1.3 Storm 120

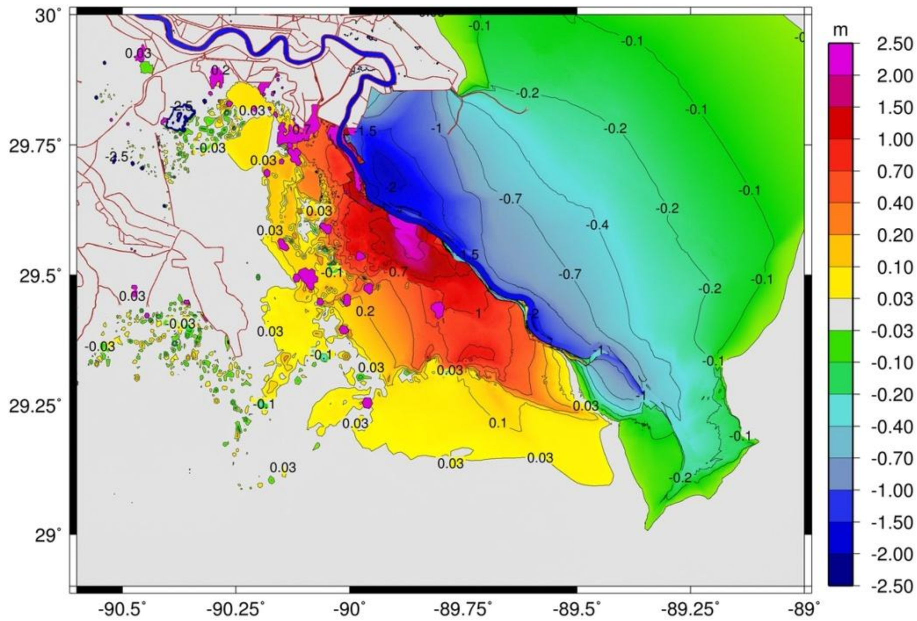


Figure 104. Differences between the Current levees and Plaquemines none, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.2 Current levees vs. Plaquemines CDP

J.2.1 Storm 27

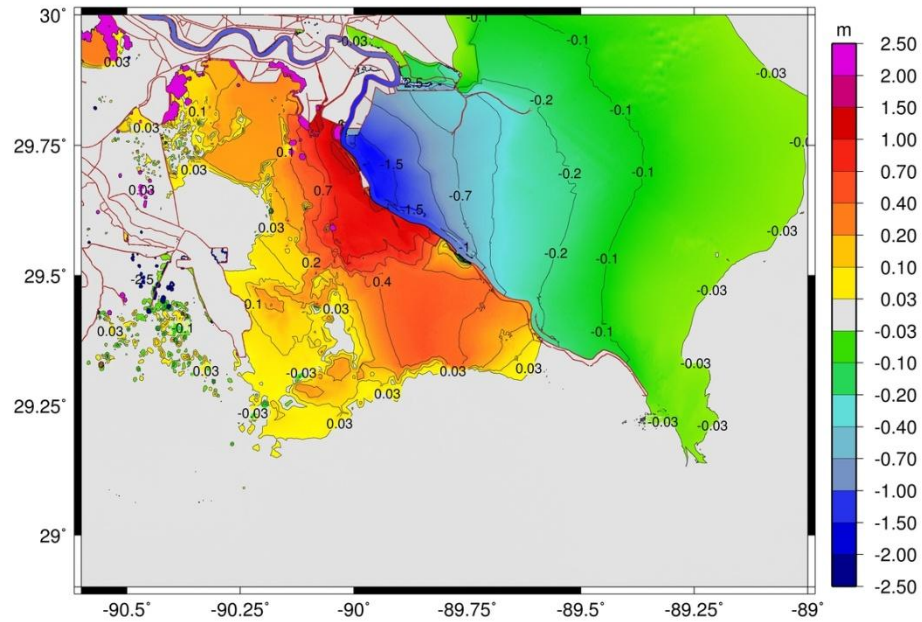


Figure 105. Differences between the Current levees and Plaquemines CDP, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.2.2 Storm 69

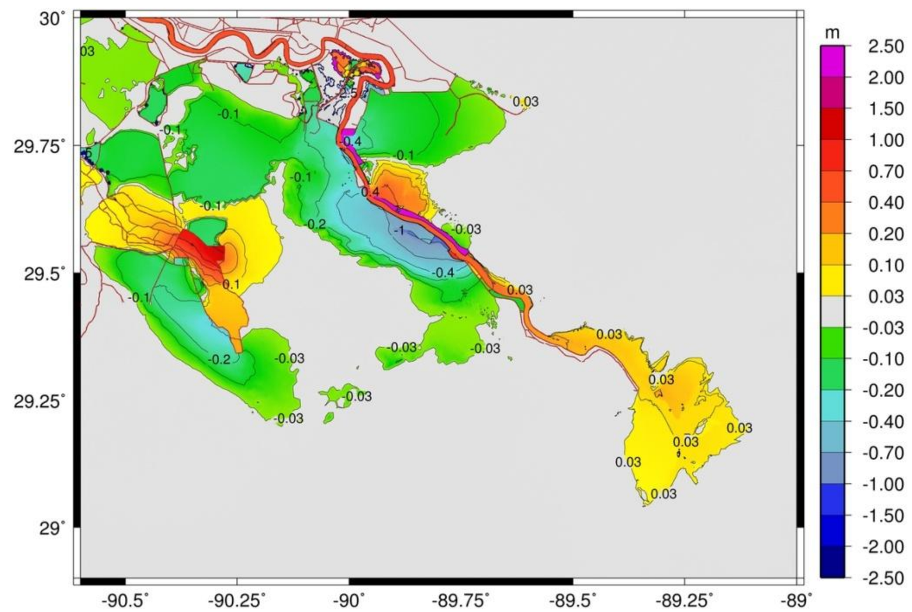


Figure 106. Differences between the Current levees and Plaquemines CDP, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.2.3 Storm 120

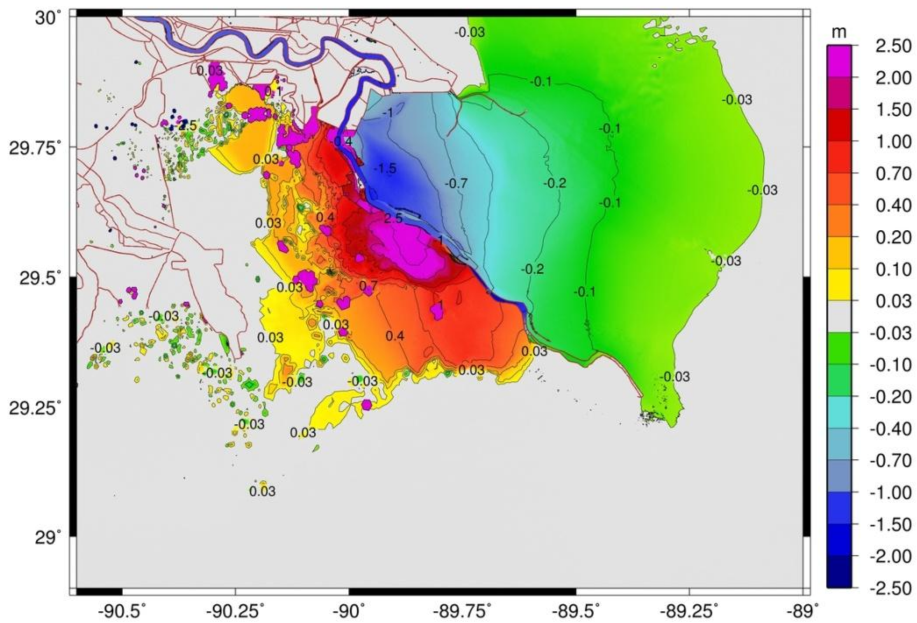


Figure 107. Differences between the Current levees and Plaquemines CDP, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.3 Current levees vs. Plaquemines Minimum

J.3.1 Storm 27

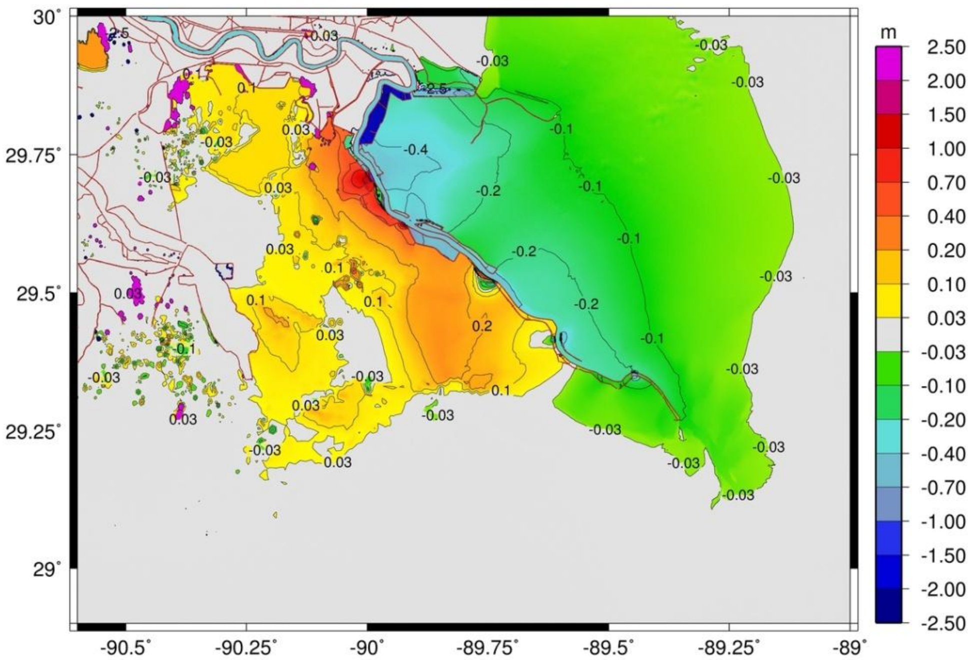


Figure 108. Differences between the Current levees and the Minimal spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.3.2 Storm 69

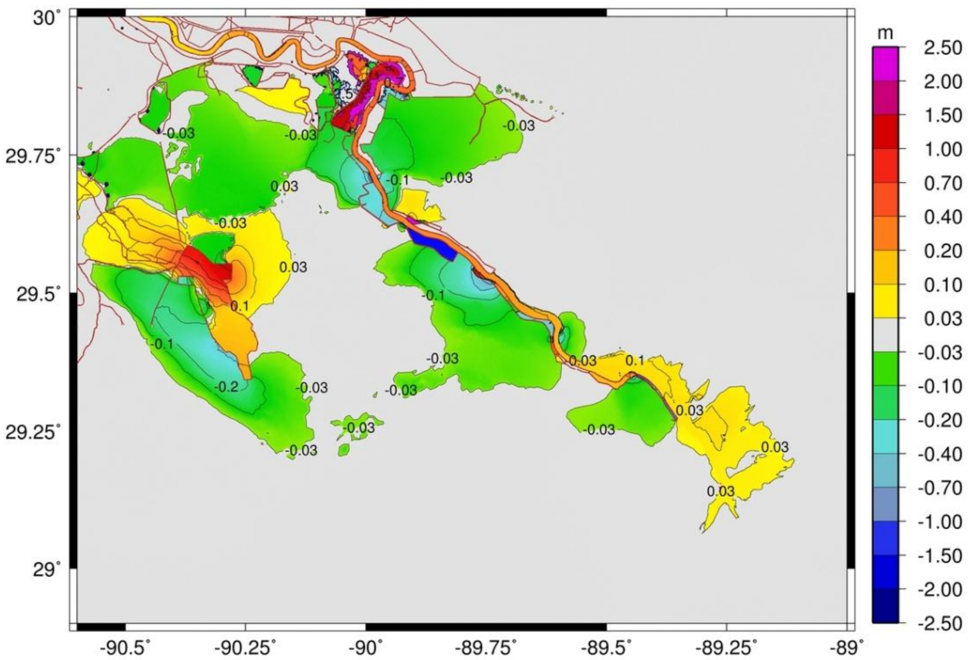


Figure 109. Differences between the Current levees and the Minimal spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.3.3 Storm 120

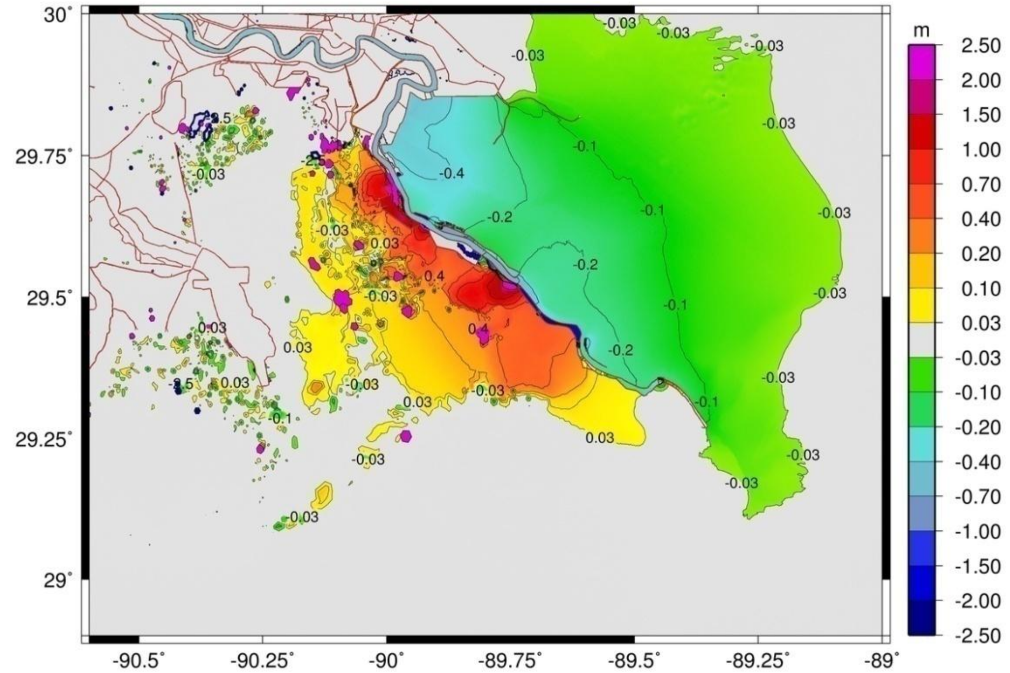


Figure 110. Differences between the Current levees and the Minimal spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.4 Current levees vs. LACPR Spillways

J.4.1 Storm 27

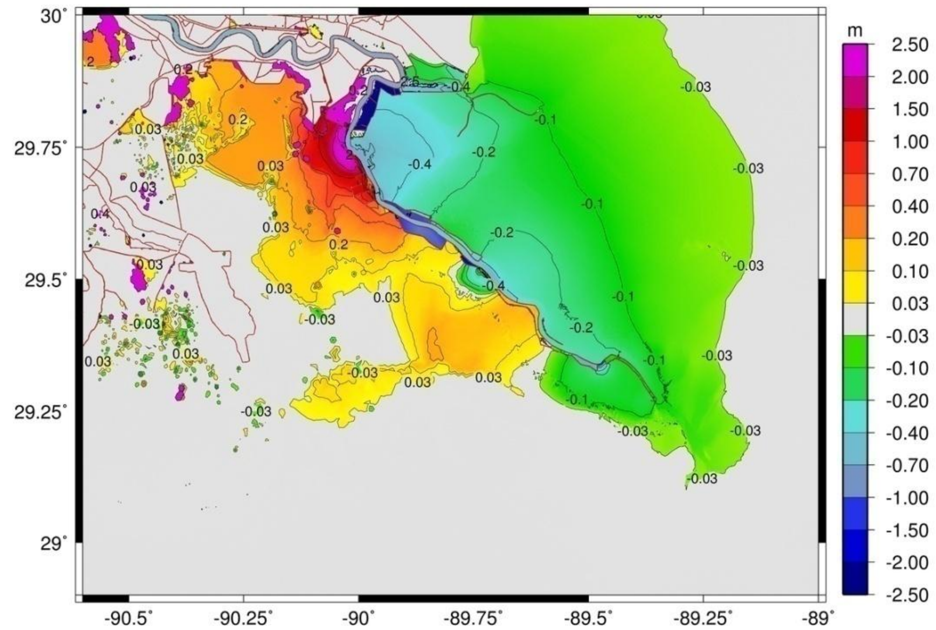


Figure 111. Differences between the Current levees and the LACPR spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.4.2 Storm 69

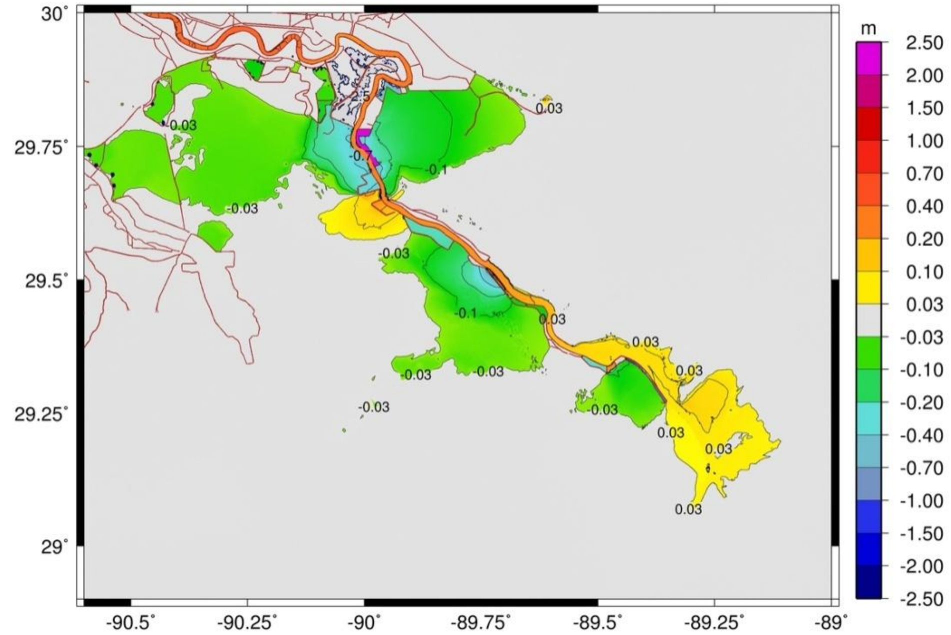


Figure 112. Differences between the Current levees and the LACPR spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.4.3 Storm 120

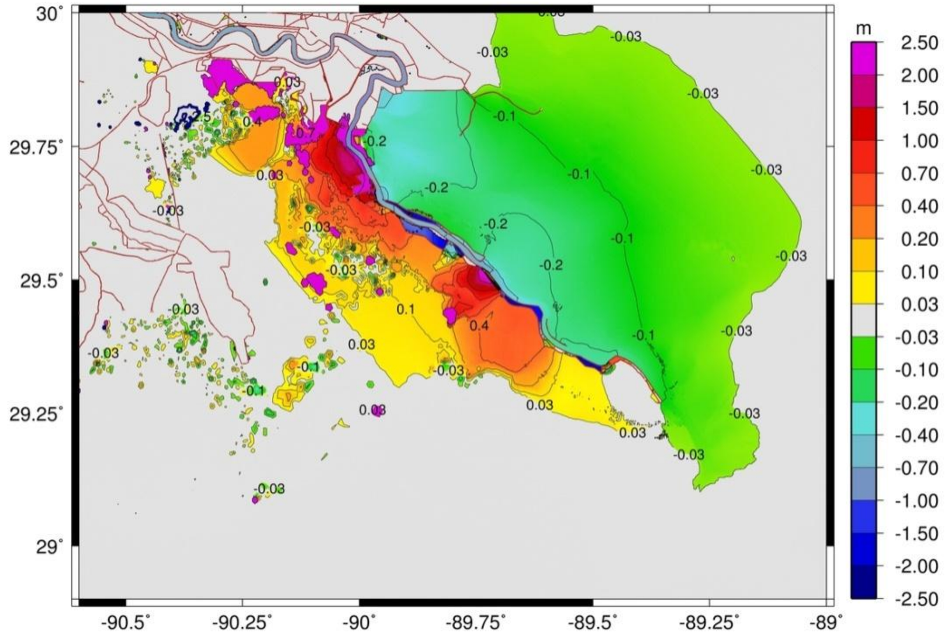


Figure 113. Differences between the Current levees and the LACPR spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.5 Current levees vs. Lowered LACPR Spillways

J.5.1 Storm 27

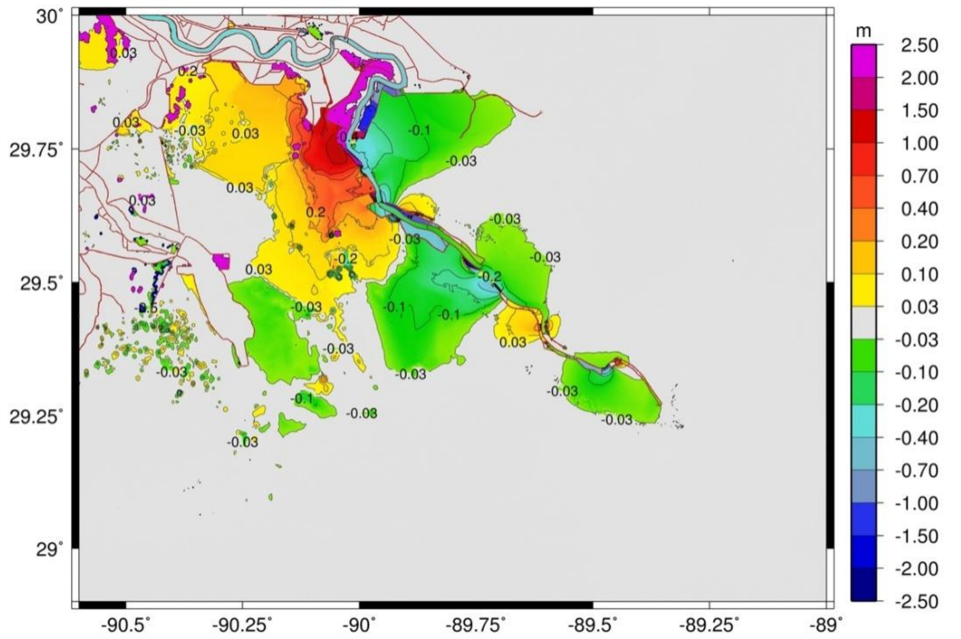


Figure 114. Differences between the Current levees and the lowered LACPR spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.5.2 Storm 69

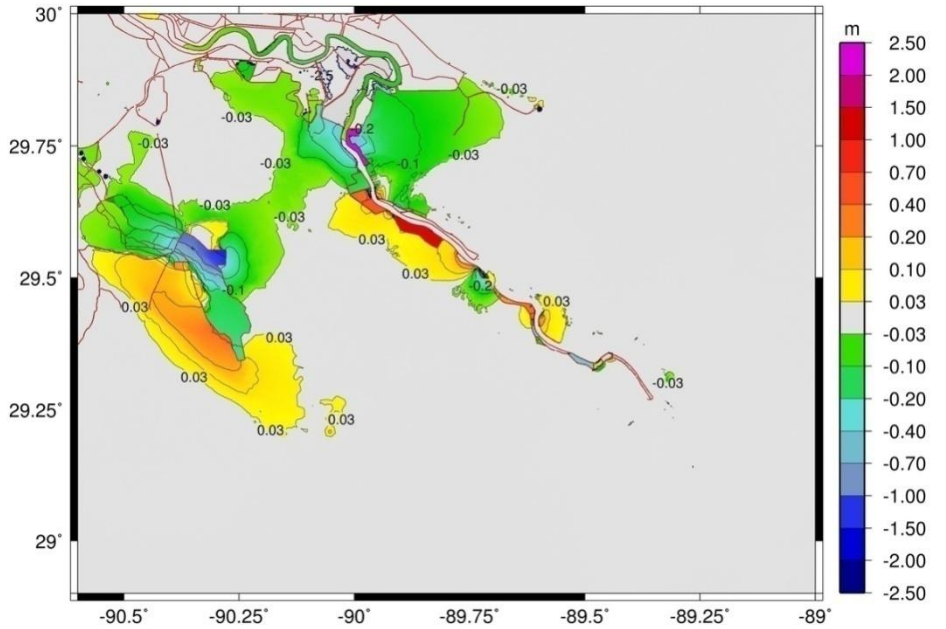


Figure 115. Differences between the Current levees and the lowered LACPR spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.5.3 Storm 120

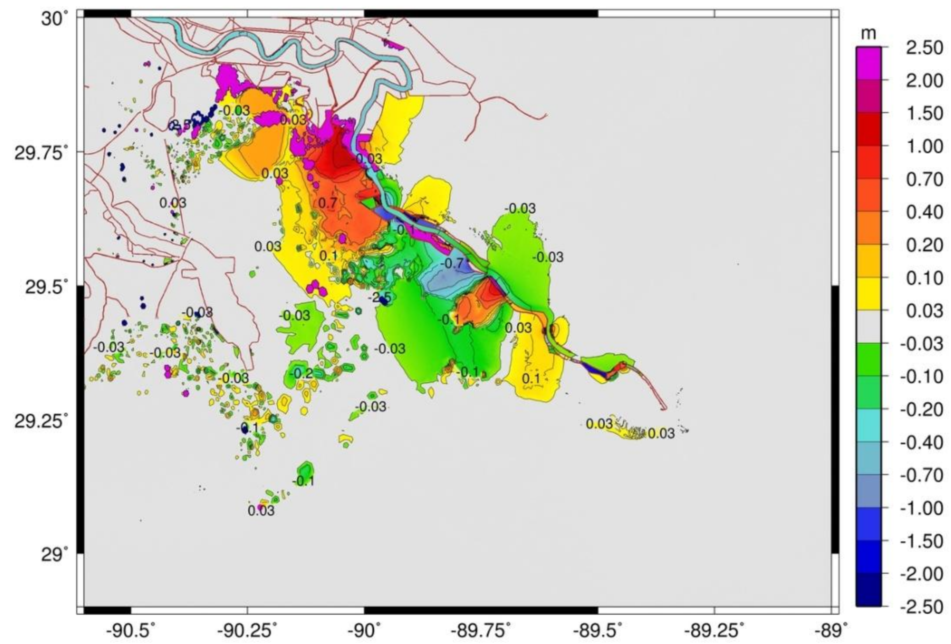


Figure 116. Differences between the Current levees and the lowered LACPR spillways, Negative values indicate water level reductions and positive values indicate an increase in maximum surge level.

J.7 Lowered LACPR Spillways vs. LACPR spillways.

J.7.1 Storm 27

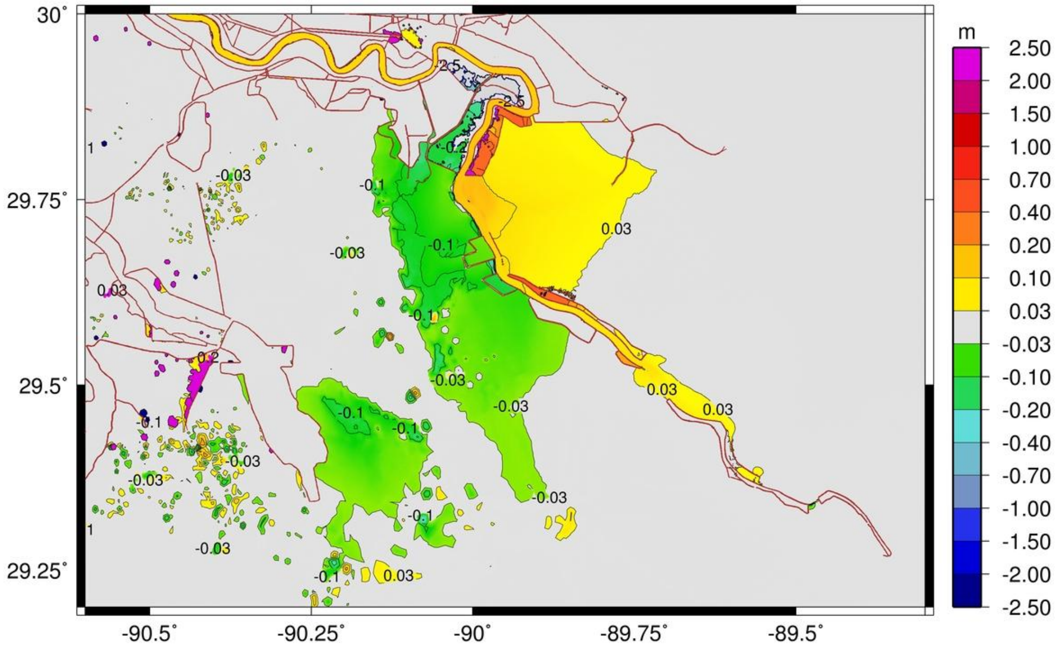


Figure 117. Differences between the lowered LACPR Spillways and the LACPR Spillways. positive values indicate a lower water level for the lowered LACPR spillways, negative values indicate a lower water level for the LACPR Spillways.

J.7.2 Storm 69

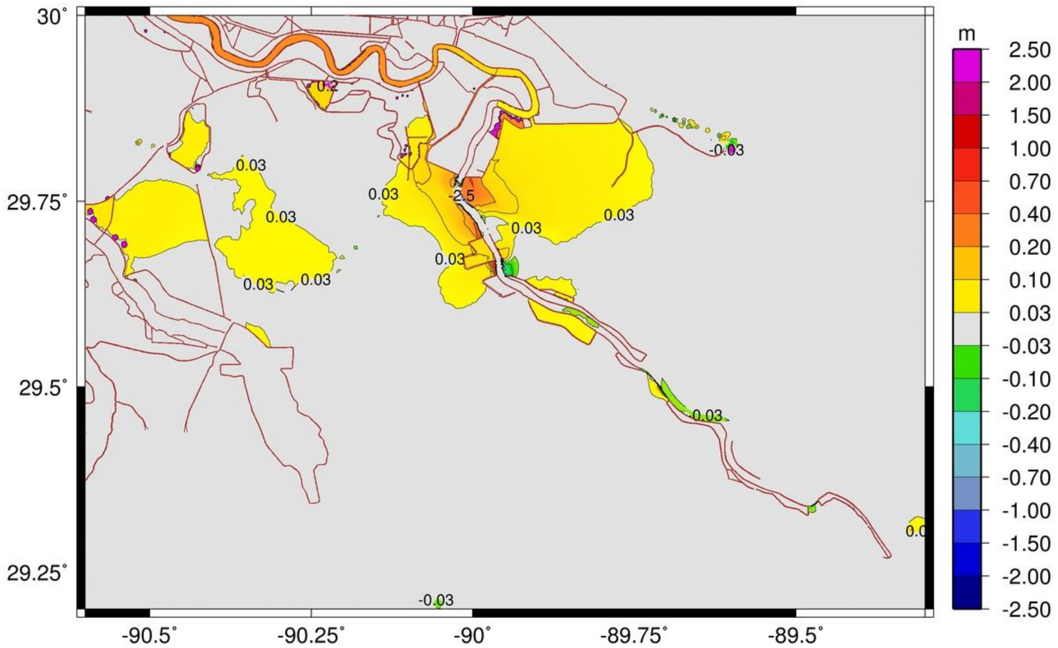


Figure 118. Differences between the lowered LACPR Spillways and the LACPR Spillways. Negative values indicate a lower water level for the lowered LACPR spillways, negative values indicate a lower water level for the LACPR Spillways.

J.7.3 Storm 120

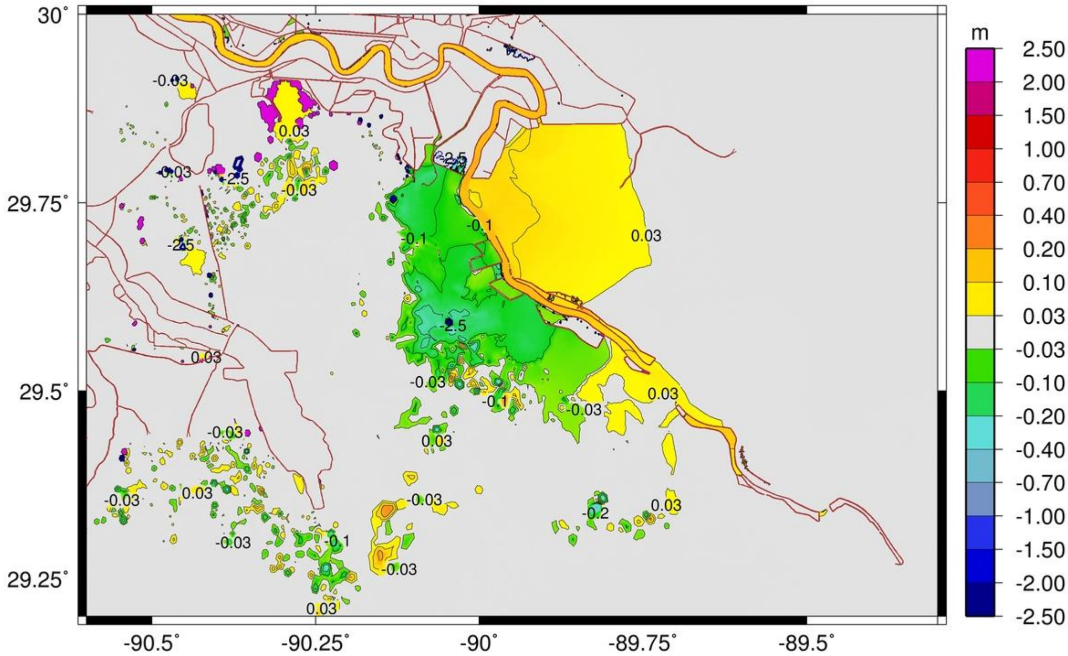


Figure 119. Differences between the lowered LACPR Spillways and the LACPR Spillways. Negative values indicate a reduction of the water level due to the removal of the natural river banks.

J.8 Plaquemines None vs. Plaquemines CDP

J.8.1 Storm 27

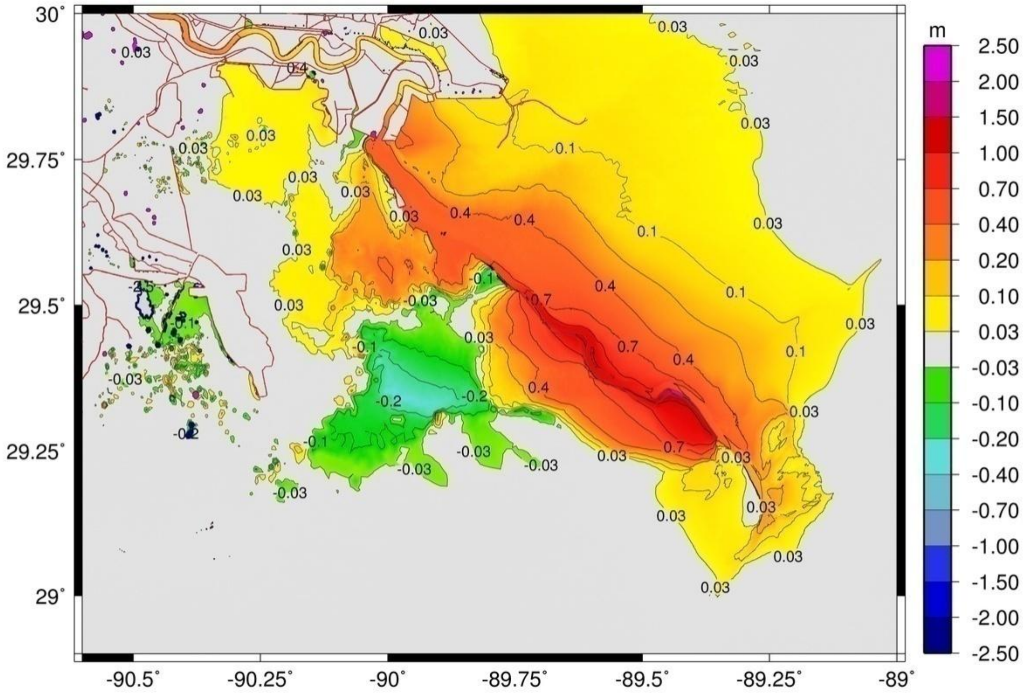


Figure 120. Differences between Plaquemines None and Plaquemines CDP, Negative values indicate a lower water level for Plaquemines None, positive values indicate an a lower water level for Plaquemines CDP.

J.8.2 Storm 69

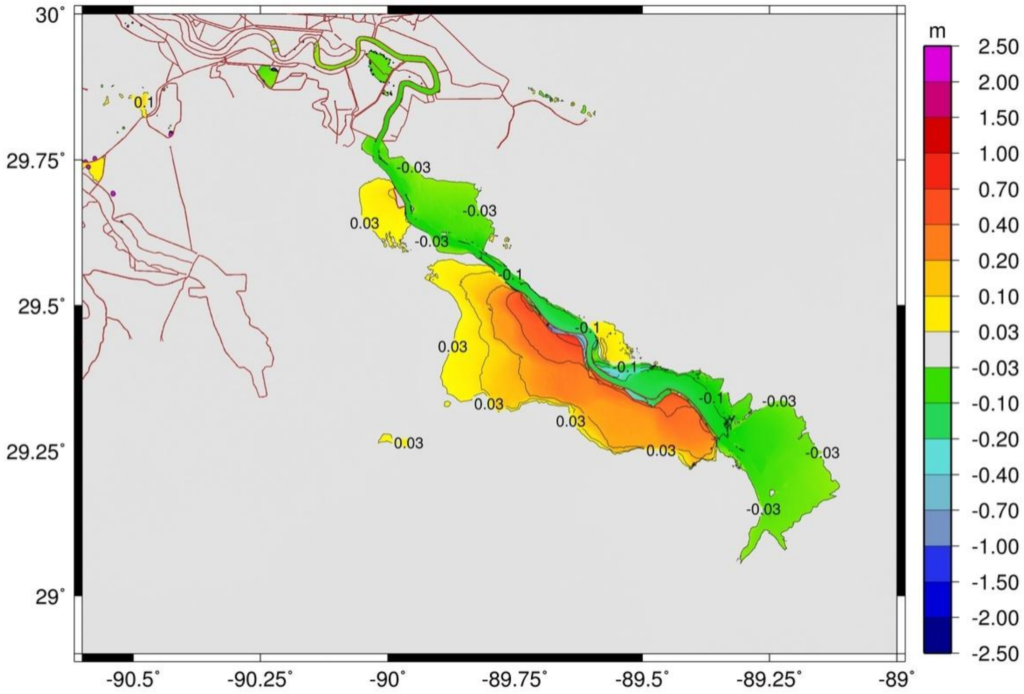


Figure 121. Differences between Plaquemines None and Plaquemines CDP, Negative values indicate a lower water level for Plaquemines None, positive values indicate an a lower water level for Plaquemines CDP.

J.8.3 Storm 120

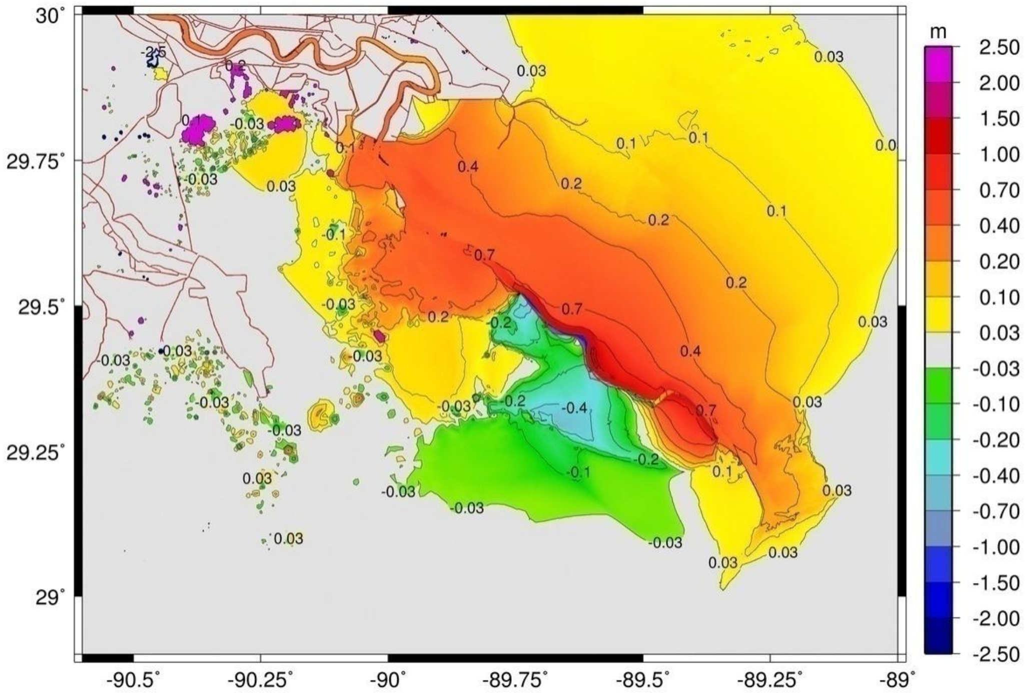


Figure 122. Differences between Plaquemines None and Plaquemines CDP, Negative values indicate a lower water level for Plaquemines None, positive values indicate an a lower water level for Plaquemines CDP.

Annex K
Dominant Storms

K DOMINANT STORMS

K.1 Plaquemines None

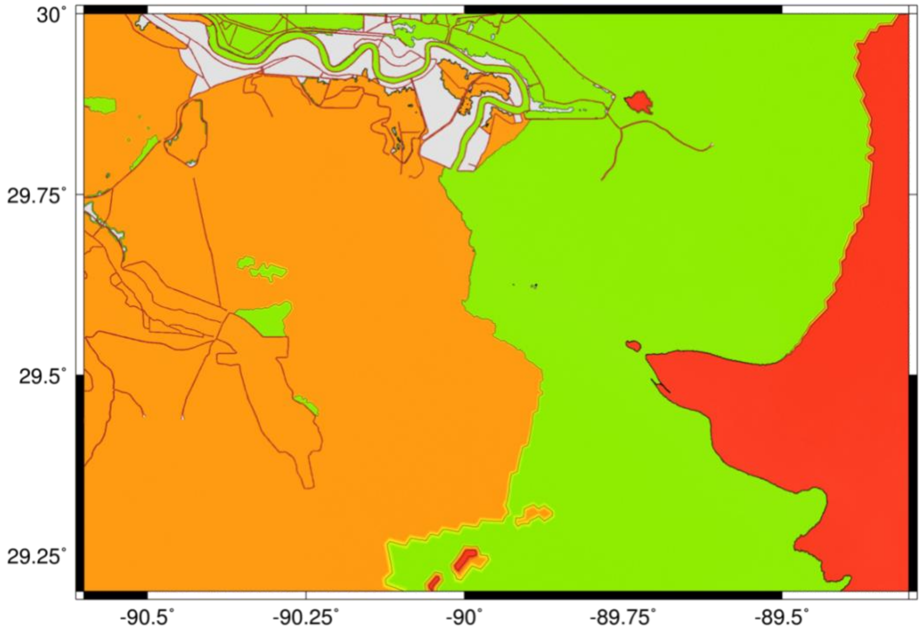


Figure 123. Regional overview of the storms which produce the highest water levels within the study area. The orange color indicates the locations where storm 69 produces the highest water levels, within green areas the water levels are highest during storm 27 and within the red indicated regions storm 120 is dominant.

K.2 Plaquemines CDP

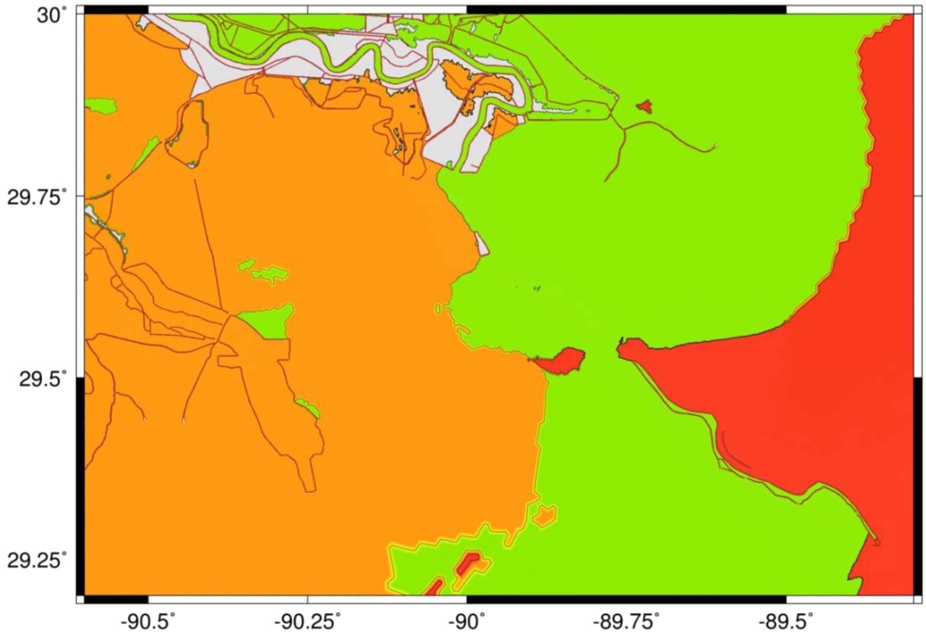


Figure 124. Regional overview of the storms which produce the highest water levels within the study area. The orange color indicates the locations where storm 69 produces the highest water levels, within green areas the water levels are highest during storm 27 and within the red indicated regions storm 120 is dominant.

K.3 Plaquemines Minimum

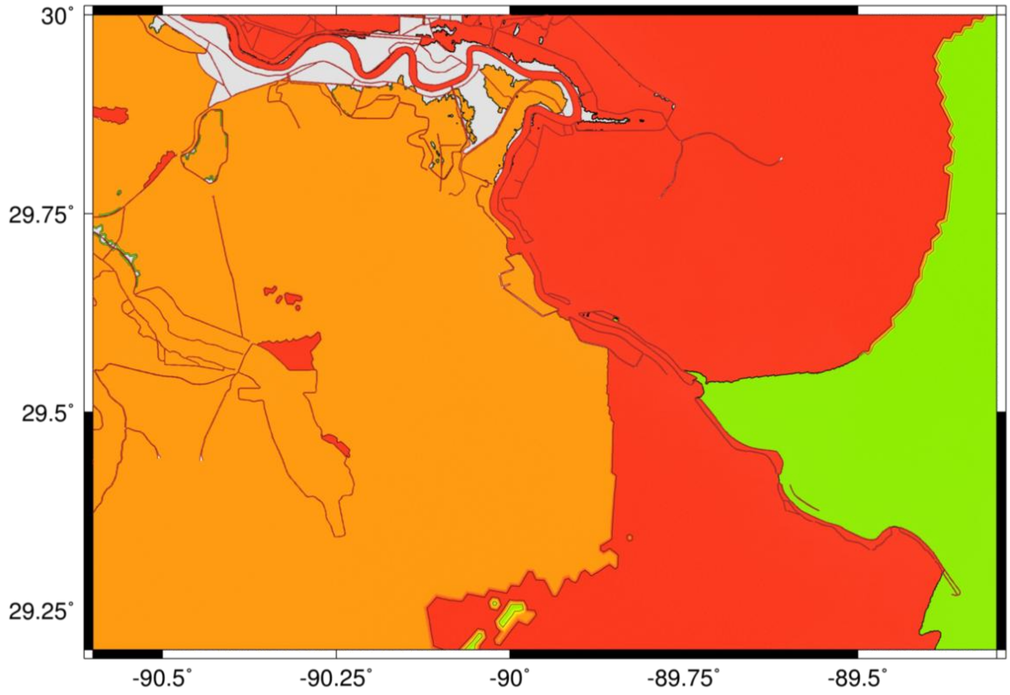


Figure 125. Regional overview of the storms which produce the highest water levels within the study area. The orange color indicates the locations where storm 69 produces the highest water levels, within red areas the water levels are highest during storm 27 and within the green indicated regions storm 120 is dominant.

K.4 LACPR Spillways

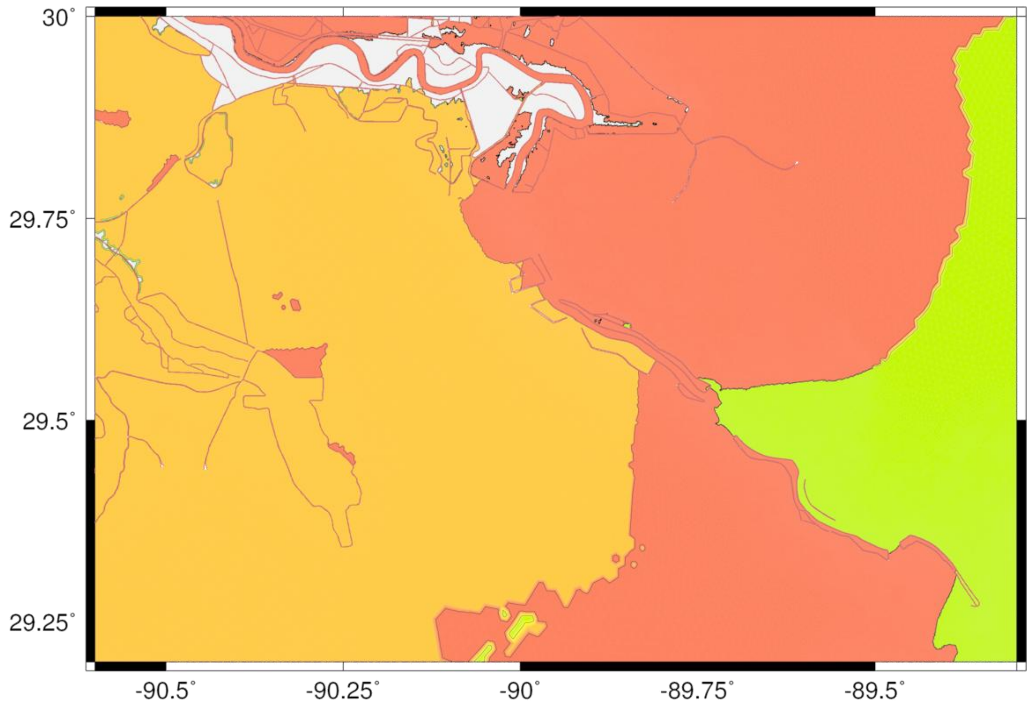


Figure 126. Regional overview of the storms which produce the highest water levels within the study area. The orange color indicates the locations where storm 69 produces the highest water levels, within red areas the water levels are highest during storm 27 and within the green indicated regions storm 120 is dominant.

K.5 Lowered LACPR Spillways

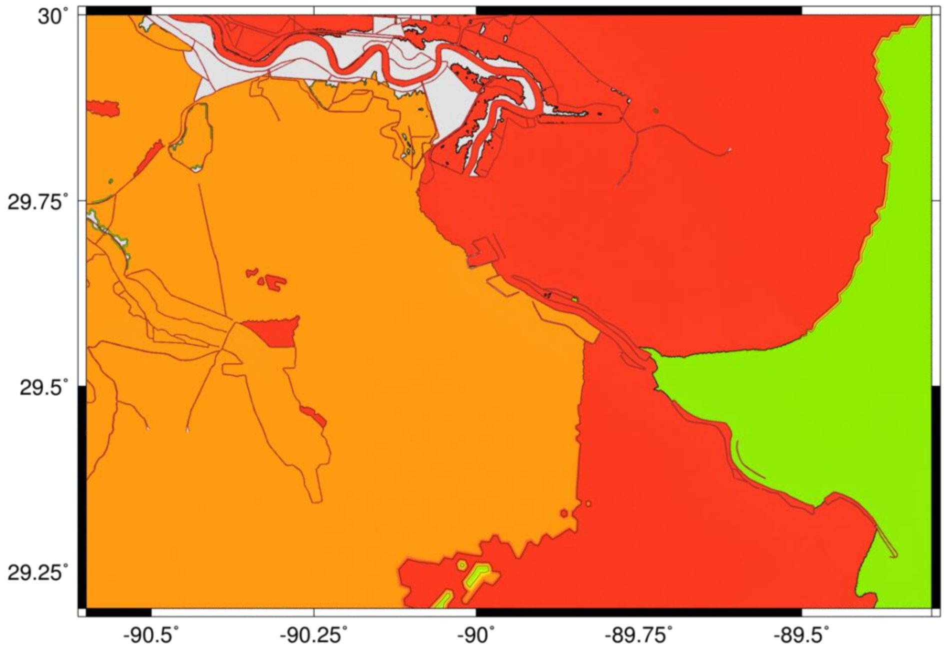


Figure 127. Regional overview of the storms which produce the highest water levels within the study area. The orange color indicates the locations where storm 69 produces the highest water levels, within red areas the water levels are highest during storm 27 and within the green indicated regions storm 120 is dominant.

Annex L
Map of the Region

L MAP

L.1 Topographic features and locations near New Orleans

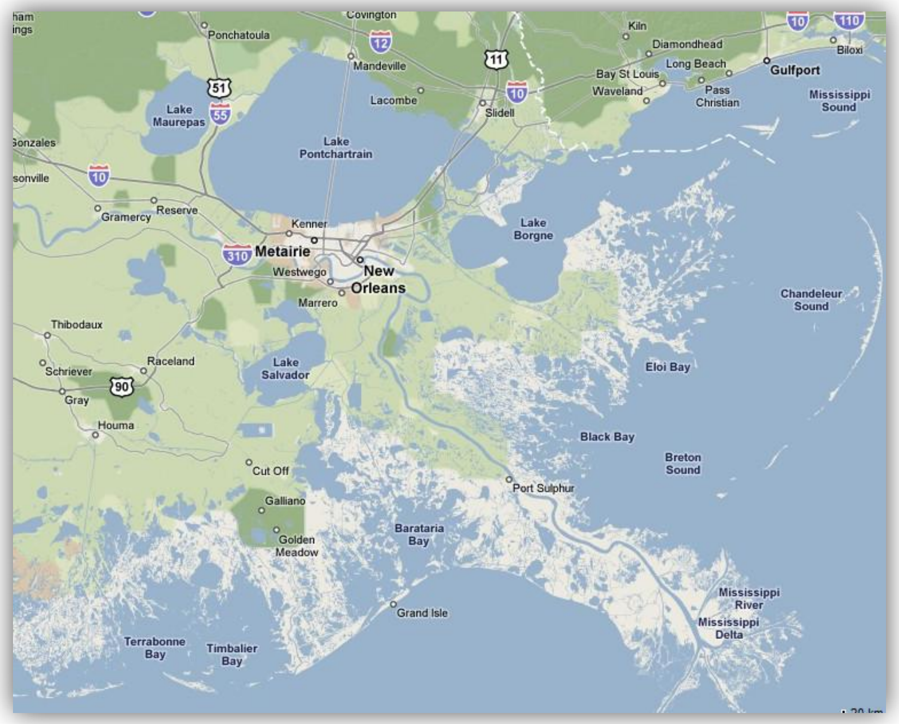


Figure 128. Topographic features and water bodies near New Orleans.

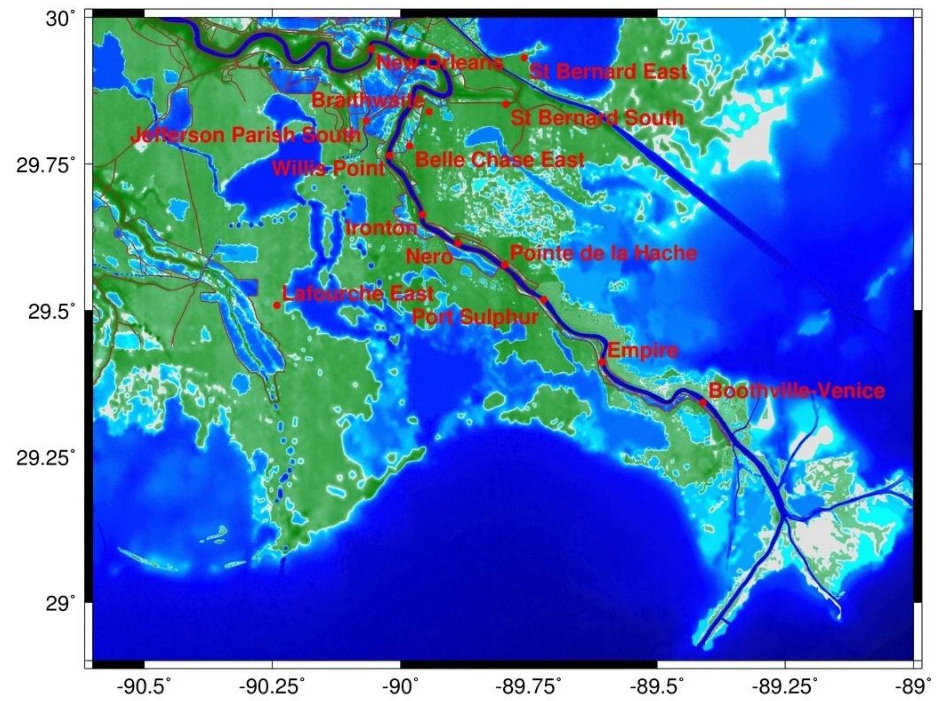


Figure 129. Important locations within the study area