Spatiotemporal Analysis of the SLOSH and ADCIRC Storm Surge Models

A Case Study of Hurricane Ida

by

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To my wife and boys. I love you.

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Abbreviations

ADCIRC	Advanced Circulation
AER	Atmospheric and Environmental Research
AI	Artificial intelligence
ANN	Artificial neural network
AWSR2	Advanced Microwave Scanning Radiometer 2
BOE	Brown ocean effect
CERA	Climate Emergency Risk Assessment
CRC	Climate Resilience Center
DFO	Dartmouth Flood Observatory
FEMA	Federal Emergency Management Agency
FwDET	Floodwater Depth Estimation Tool
GCOM-W1	Global Change Observation Mission- Water 1
GFM	Global flood mapping
GIS	Geographic information system
GUI	Graphical user interface
GWCE	Generalized wave continuity equation
HAZUS	Hazards US
LaDOTD	Louisiana Department of Transportation and Development
MDL	Meteorological Development Laboratory
MEOW	Maximum envelopes of water
MFED	Maximum flood extent depiction
MODIS	Moderate Resolution Imaging Spectroradiometer

MOM	Maximum of MEOW
MOTF	Modeling task force
NAD	North American datum
NASA	National Aeronautics and Space Administration
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NRT	Near real time
NWS	National Weather Service
P-Surge	Probabilistic storm surge
SDP	SLOSH display program
SFED	Standard flood extent depiction
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
WGS	World Geodetic System

Abstract

Hurricane Ida struck southeastern Louisiana with winds greater than Hurricane Katrina, and truly tested the rebuilt levee systems of New Orleans and lower Louisiana. Weather and governmental agencies used predictive models to anticipate and predict storm surge locations and severity, as storm surge from hurricanes is the leading fatality cause globally during tropical events. Current tropical systems are fueled by climate change that is impacting storm strength and regularity, yet storm surge models must ensure the highest degree of accuracy. The National Oceanic and Atmospheric Administration's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) and the Climate Resilience Center 's Advanced Circulation (ADCIRC) models are two preeminent models that simulate and predict storm surge in an effort to publish evacuation orders and save lives. Hurricane Ida rapidly intensified prior to landfall, which stressed the ability of agencies to properly predict storm impacts. In this project, SLOSH and ADCIRC were tested and evaluated against each other, and against observed flooding during Hurricane Ida to determine model strengths and weaknesses. Results show that both SLOSH and ADCIRC overestimated storm surge extent, but underestimated surge depth. ADCIRC was more accurate in long range forecasting, while SLOSH was more accurate in short range forecasting. Recommendations are posed to enhance the accuracy of current storm surge models. This spatiotemporal analysis can help validate surge models against climate enhanced storms with the goal of saving as many lives as possible.

Chapter 1 Introduction

The deadliest part of any tropical system is not wind speed, but the flooding that destroys property and causes hundreds of fatalities every year (NHC 2022). Perhaps the single greatest flooding event caused by a tropical system is storm surge, the rise in seawater caused by tropical winds pushing water onshore (Didlake 2020). Tropical systems have increased in regularity and intensity over the past few decades due to climate change, which is warming the oceans that provide fuel for the storms (C2ES 2020). Accurate storm surge modeling is crucial for the public to take steps to protect their property, livelihood, and families, while inaccuracies can have catastrophic consequences. With climate change fueling ever more dangerous, powerful, and irregular storms, storm surge models must ensure the highest degree of accuracy.

Hurricane Ida traveled a similar path as Hurricane Katrina (Figure 1) and represented a true test of New Orleans and lower Louisiana's rebuilt levee systems in the wake of Katrina. Hurricane Katrina caused numerous levee breaches across the state and in particular, New Orleans in 2005. In the years following Katrina, nearly 15 billion dollars was spent to rebuild and shore up the levee system throughout New Orleans and lower Louisiana (Schleifstein 2020). Hurricane Ida made landfall on August 29, 2021 and brought with it 150 mph winds and a storm surge up to 14 feet. Fortunately, the levee system withstood Ida's onslaught, and the city was spared the devastation brought by Katrina 16 years earlier. Hurricane Ida was influenced by climate change in that it rapidly intensified prior to landfall. The irregularity of the storm's rapid intensification prior to landfall and the storm's sustainment of its strength far after making landfall enabled a swift pounding of the state which caused over 36 billion dollars in damage, over 3/4 of the state's total annual budget.

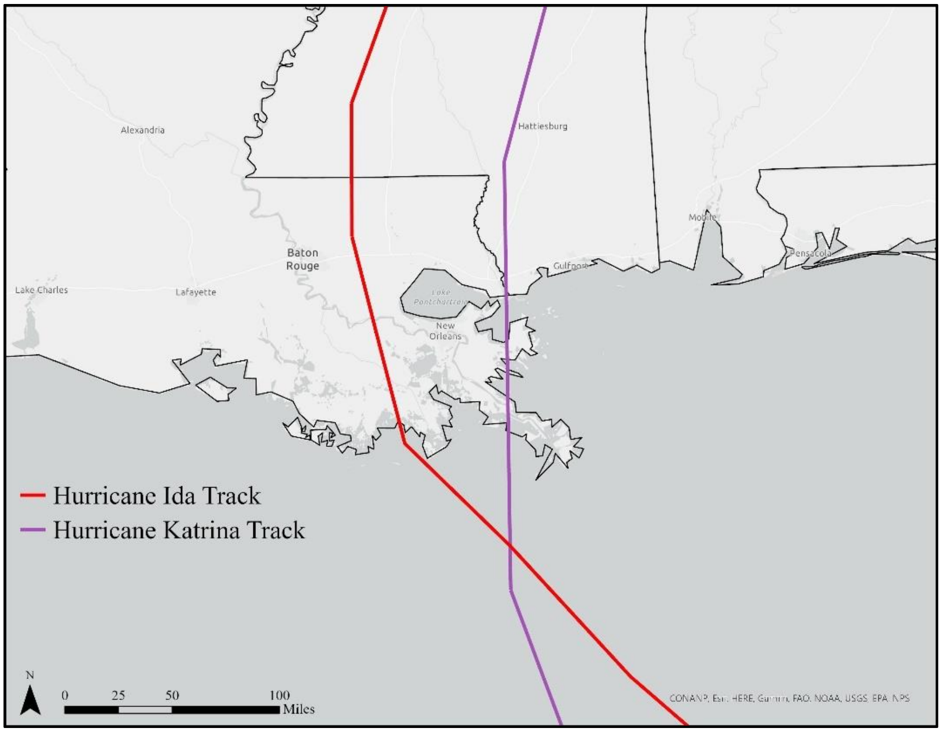

Figure 1. Hurricane Ida and Katrina track comparison

The rapid intensification of the storm, the sustainment of maximum wind speeds hours after making landfall, and a track similar to Katrina makes Hurricane Ida ripe for research for current modeling techniques in use today. Hurricane Ida's meteorological history spans from August 14 to September 1, 2021 (Beven, Hagan, and Berg 2022). This case study focuses on the three days of August 28 to 30, Hurricane Ida's peak intensity on the Louisiana coast. This case study of Hurricane Ida analyzes current storm surge modeling techniques and poses recommendations for future advancements.

1.1. Hurricane Ida

Hurricane Ida struck Louisiana with strong winds and a devastating storm surge that flooded vast amounts of lower Louisiana (Beven, Hagan, and Berg 2022). Storm surge is the abnormal raise in water due to storms and tropical systems (NOAA 2022). Beginning as a tropical wave off the west coast of Africa, Ida raced westward and maintained its status as a tropical wave until reaching tropical depression status; a tropical system with winds less than 39 mph, on August 26 in the southwestern Caribbean Sea. Six hours later the storm reached tropical storm strength and the next day reached hurricane strength. The storm struck Cuba as a category 1 hurricane on August 27 and entered the Gulf of Mexico early on the 28th.

Ida began a period of rapid intensification upon entering the Gulf of Mexico, where the waters were 86 degrees with minimal windshear, a near perfect scenario for intensification. Windshear is a difference in wind speeds over a short distance in the atmosphere and is a culprit of weakening tropical systems (Corbosiero and Molinari 2002). After 12 hours in the Gulf, Ida intensified from 80 to 105 mph. Ida further intensified from 105 to 150 mph over the next 12 hours, a total of 70 mph increases in maximum windspeeds in 24 hours.

Ida made landfall at 11:15 a.m. Central Daylight Time on August 29 at Port Fourchon, tied with the 1856 “Last Island” hurricane as the strongest to ever hit the state of Louisiana west of the mouth of the Mississippi River. The storm continued a north-northwest track, with the eye passing between New Orleans and Houma.

The hurricane maintained category 4 strength for four hours after landfall, and category 3 status a further four hours. This intensity can be attributed to the brown ocean effect (BOE). BOE is a phenomenon in which a tropical system can maintain strength or strengthen while over land due to the heat given off by moisture-rich ground (Sheppard and Andersen 2017). BOE can occur where heated marshes and wetlands (figure 2) give off latent heat similar to the ocean, allowing storms to retain strength (Andersen and Sheppard 2017). Though not specifically relating to Hurricane Ida, Andersen and Sheppard show that areas similar to lower Louisiana contain the necessary geography to allow a hurricane to retain strength after landfall, like Hurricane Ida. Ida rapidly weakened as it tracked further inland and lost contact with the marshy wetlands. The storm became extra-tropical, or absent its tropical characteristics, where cool surface air replaces the warm tropical air, as it continued through Mississippi and Tennessee.

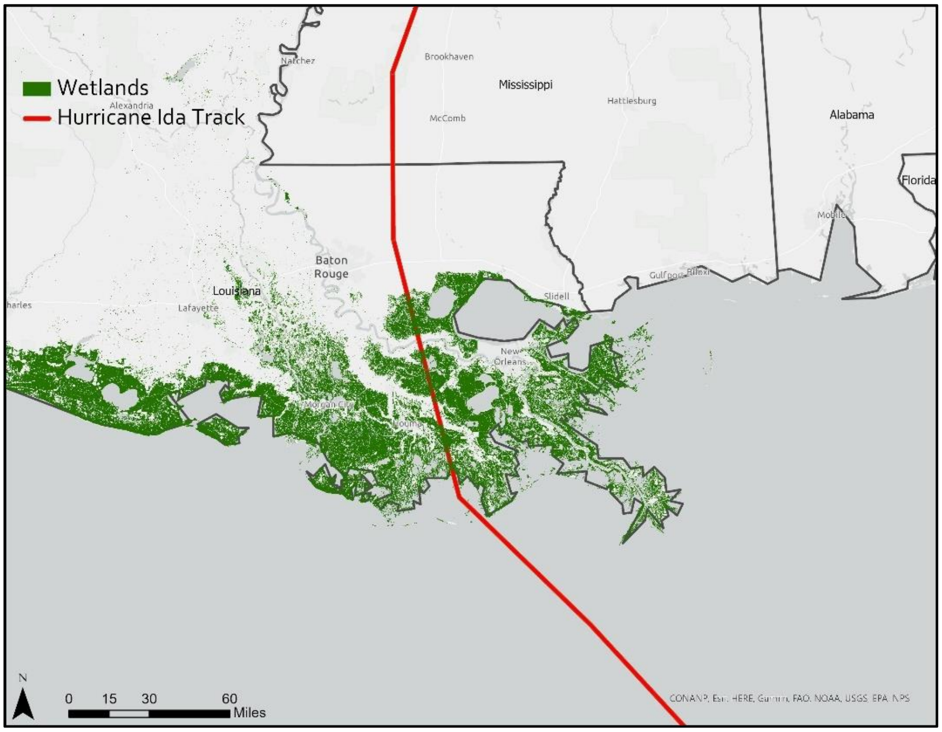

Figure 2. Wetlands of southeastern Louisiana

Hurricane Ida produced a devastating storm surge (figure 3) that reached 14 feet above ground level, and in some instances, was able to overcome levee systems. The largest storm surge was recorded in Plaquemines parish on the eastern bank of the Mississippi River. Around New Orleans and Lake Pontchartrain, a high storm surge of 8.5 feet was recorded, far less than Katrina but very dangerous, nonetheless.

Figure 3. Storm surge effects in Golden Meadow, Louisiana (Photo Credit: Luke Sharrett)

Hurricane Ida also brought massive amounts of precipitation throughout southeastern Louisiana and Mississippi. The largest rainfall total measured over 15 inches in Ponchatoula, Louisiana. The storm further produced large precipitation totals throughout the southern United States, and even produced upwards of 10 inches of rain in Pennsylvania and New Jersey while tracking as an extra-tropical system (Figure 4).

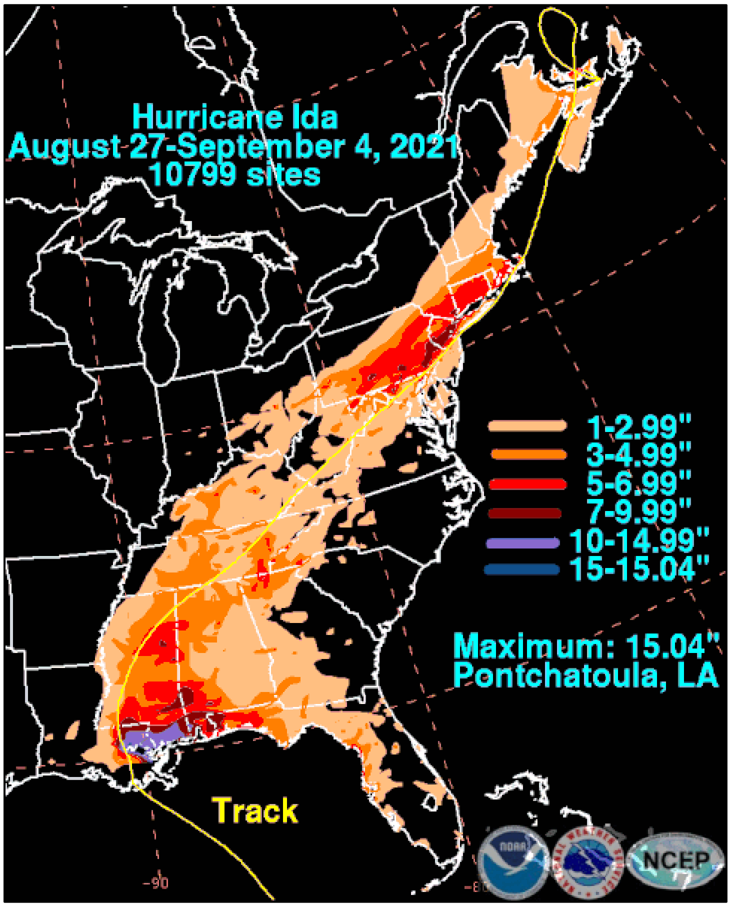

Figure 4. Total precipitation amounts from Hurricane Ida (David Roth/ NOAA 2022)

Climate change can be considered a factor with Hurricane Ida, due to its rapid intensification and strength sustainment post-landfall. Most hurricanes intensify gradually, even over warm water, however, Hurricane Ida's wind speed increased from 105 to 150 mph in a matter of hours, an almost unseen intensification rate (Zhe et al. 2022). Hurricane Ida also maintained its strength for 6-8 hours after landfall, another aspect that can be attributed to climate change A study conducted of 71 North Atlantic hurricanes found that 50 years ago hurricanes would lose 75% of their windspeed 24 hours post landfall. Current hurricanes are now losing just 50% of their windspeeds 24 hours post landfall, suggesting hurricane decay is slowing in the warming oceans (Li and Chakraborty 2020). Another climate change anomaly observed during Hurricane Ida was the BOE, which can be exacerbated by the warming climate as tropical systems can maintain or even strengthen over land, an anomalous event within nature (Sheppard and Andersen 2017).

In total, Hurricane Ida was directly responsible for 55 fatalities and a further 32 indirectly throughout Louisiana and the rest of the United States (Beven, Hagan, and Berg 2022). Over 60% of fatalities were related to drowning. Nearly 20% of deaths were reported after Ida's passing and were due to power outages that lead to heat exhaustion and stroke in the hot climate. The storm's name was retired on April 22, 2022, due to massive damage and loss of life. The name Ida will never be used for an Atlantic storm again.

1.2. Study Area

Louisiana is no stranger to tropical storms and hurricanes. The state is bordered by Texas to the west, Arkansas to the north, Mississippi to the east, and the Gulf of Mexico to the south. The warm waters of the Gulf are a main reason Louisiana ranks fourth in the United States for total number of hurricane landfalls, and third in major hurricane landfalls from 1851 through 2018 (Heil 2019). The specific study area for this research project is the southeastern portion of the state, containing 10 parishes, including the major city of New Orleans, depicted by Figure 5.

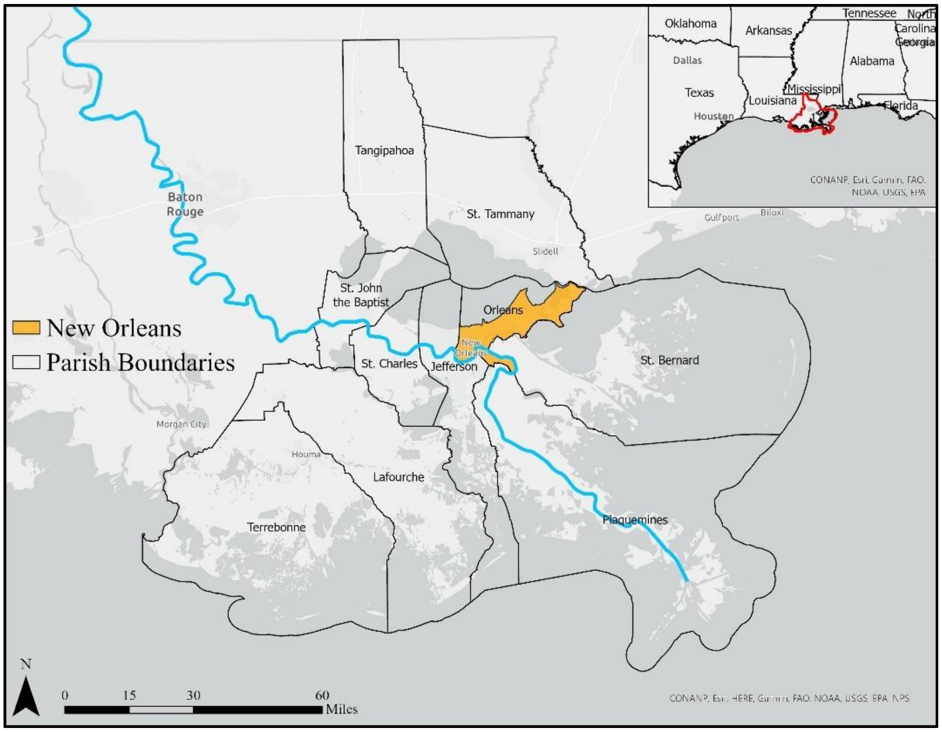

Figure 5. Study area of southeastern Louisiana and surrounding areas

New Orleans is situated between Lake Pontchartrain and the Mississippi River, which has made the city prone to flooding throughout its history. With a population of just under 400,000, New Orleans is the largest city in the United States below sea level, with only man-made levees and flood walls protecting it from sustained flooding.

The study area's proximity to the Gulf of Mexico, numerous lakes, sounds, and wetlands provides geographic vulnerabilities and ample opportunity for tropical events and extreme flooding. The water surroundings increase potential water volume during storm surge events. Figure 6 represents the study area and the numerous bodies of water that influence storm surge and flooding.

Figure 6. Bodies of water throughout the study area

1.3. Storm Surge Modeling

The United States' premier weather agency, the National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Center (NHC) creates, publishes, and updates storm surge maps for the United States, Mexico, and Caribbean. Such maps, which are not tied to a particular storm, show storm surge by a hurricane's maximum sustained windspeed category, the Saffir-Simpson scale, from 1 to 5, and shows the likelihood of flooding caused by the storm's intensity. Though storm winds are a major factor in storm surge intensity, other factors influence storm surge, such as coastline orientation, storm intensity, size, speed, and local bathymetry. Users can view the storm surge maps interactively, allowing users to manipulate the model to find and observe flooding likelihood for any area of interest. At 48 hours prior to landfall, NOAA publishes site- and storm-specific surge maps, with 6-hour updates afterwards, otherwise known as an advisory.

A NHC public advisory contains information about a tropical system to warn the public about the storm. The advisory contains a summary of the storm, any watches or warnings associated with the storm, outlook about the storm, and hazards associated with the storm (NHC 2022). NHC publishes advisories every 6 hours and SLOSH outputs are generated based on those advisories.

NOAA utilizes the SLOSH model exclusively for all its storm surge maps, while other agencies have created separate storm surge models and maps to increase accuracy and public awareness of flooding. The Climate Resilience Center (CRC), a joint academic, industrial, and governmental effort, created the Advanced Circulation (ADCIRC) model to enhance the resilience of the nation's people, infrastructure, economies, and the natural environment (Leuttich and Westerink 2012). ADCIRC simulations are made publicly available on the Coastal Emergency Risk Assessment (CERA) website, with similar interactive functions as NOAA's SLOSH site.

The SLOSH modeling approach used in this project is P-Surge, which accounts for uncertainty in wind forecasts that primarily drives storm surge. P-Surge modeling parameters include the NHC's official storm forecast, parametric wind model, and historical 5-year error statistics in track, size, and intensity. The ADCIRC model in this project uses basic parameters such as wind forecasts, atmospheric pressure, and rain. ADCIRC also incorporates other parameters like coastal bathymetry, temperature, and water salinity. The SLOSH and ADCIRC models are described extensively in the following chapter.

1.4. Hypothesis

The hypothesis for this thesis project was that the SLOSH and ADCIRC storm surge models would underestimate flooding during Hurricane Ida due to the idiosyncrasies caused by climate change. A spatiotemporal analysis was conducted in and around New Orleans to show predicted SLOSH and ADCIRC storm surge extents and depths of eight NHC advisories, compared with observed flooding. Within the study area, flooded regions were calculated per square mile and by percentage of the overall land area within the study area. Additionally, flood depth analysis of SLOSH and ADCIRC was performed in the study area, to compare surge depth averages across the study area. Comparing and contrasting flood areas by model and by advisory determined which model produced more accurate results.

1.5. Thesis Overview

This thesis project is structured with four additional chapters. Chapter Two describes previous related literature on climate change, storm surge modeling, and validation of surge models. Chapter Three describes the data and methods employed. Chapter Four details the results of the technical work completed. Chapter Five is oriented towards a discussion on storm surge techniques with recommendations for future endeavors.

Chapter 2 Related Work

Three main areas have been identified for prior research on this thesis project. The first section details the linkage between natural disasters and climate change, which is an influencer on tropical systems and their intensity and regularity. The second section describes storm surge modeling and predictions, which must be relayed to show how agencies have used various surge models in the past to warn the public. Storm surge modeling can take many different forms and processes, but three main techniques are commonly used: numerical models, data-driven models, and artificial intelligence models. The third section covers spatial analysis and validation, which will show previous endeavors to validate surge predictions from historical storms and the steps taken to achieve greater accuracy.

2.1. Natural Disasters and Climate Change

A consensus is forming in the academic community that changing climate is influencing natural disasters, their regularity, and their intensity. This section overviews climate change's impact on the environment and the effect it is having on tropical systems. Increases in global temperatures, earlier than usual tropical system development, increases in storm precipitation, and damage proliferation are covered as a part of climate change effects.

2.1.1. Temperature Increase

The International Panel on Climate Change (IPCC) releases data periodically that simulates future climate scenarios based on Representative Concentration Pathways (RCPs). RCP figures estimate changes to future climate trends based on four different scenarios of future greenhouse gas emissions. RCP rates range from 1.9 at the lower end, assuming green gas emissions stop almost immediately, to 8.5, assuming current greenhouse gas emissions stay on their current course, with intermediate RCPs in between. The RCP rates directly correlate with warming temperatures and warming ocean temperatures, which will affect hurricane strength (IPCC 2022).

The current IPCC report, the sixth edition published in 2022, gives an assessment on an increase of 1.5 degree Celsius in the near term by 2040 for RCP 1.9. Though this represents a best-case scenario, the temperature increase still comes with dire consequences. A 1.5 degree increase would cause a nearly unavoidable increase in climate hazards (IPCC 2022). The IPCC report further emphasizes that at current warming trends, hurricanes will continue to increase in frequency through at least 2050, which will increase economic loss in the United States and globally and may cause migration from coastal areas inland as people flee yearly destruction.

The IPCC report provides case studies and describes future tropical system effects caused by an RCP of 1.9. First, the report studies Hurricane Harvey, which struck Houston on August 26, 2017, and reports that the record-breaking precipitation recorded was three to ten times more likely to have occurred due to climate change (IPCC 2022). The report also states that damage along the Gulf of Mexico will increase in the future due to hurricane frequency, strength, and coastal development. Finally, the report estimates that flooding will increase due to flood zone expansion as a result of increasing hurricanes and tropical systems (IPCC 2022).

The IPCC report presents grave scenarios, even if greenhouse emissions are curbed, at least in the short term. Above all, the earth’s temperature is warming, which will affect the frequency and intensity of hurricanes over the next few decades at a minimum.

A separate study conducted by researchers at NOAA highlights the differences in average annual global temperatures from 1880-2021. Earth’s average temperature has steadily increased about 0.08 degrees Celsius per decade from 1880-1991. However, the past four decades have seen increases double, to the rate of about 0.18 degrees Celsius (Dahlman and Lindsey 2022). Further, when accounting for sea surface temperature in addition to dry surface temperature, 2021 average temperatures are 0.84 degrees Celsius warmer than the twentieth-century average.

Looking at the globe's average yearly temperature, the most recent decade holds some of the warmest years on record. In fact, 2020 was the third warmest year since 1900, and 2021 was the sixth warmest (Dahlman and Lindsey 2022). A trend is developing, particularly after the industrial revolution, that is seeing temperatures skyrocket. Projections of current warming trends show that by the year 2100, the Earth may be nearly 3 degrees Celsius warmer than averages in the mid twentieth century.

2.1.2. Hurricane Season

Tropical systems derive their strength from warm ocean water. Climate change has been warming the oceans for decades and is thus causing more disastrous hurricanes throughout the globe. Not only are warming oceans increasing strength and regularity in tropical systems, but historical date ranges in which they occur have been expanding.

The Atlantic hurricane season runs from June 1 to November 30 yearly, a range date that was chosen in 1965 by the NHC. The June to November hurricane season was chosen due to favorable conditions for tropical system development (Truchelut et al. 2022). The warming oceans are experiencing an increase in sea surface temperatures, which is expanding the favorable condition windows in the North Atlantic, particularly on the front and back end of hurricane seasons (Truchelut et al. 2022). Sea surface temperatures have risen nearly 1 degree Celsius since 1980, potentially making the months of May and April favorable for tropical development. In fact, from 2012-2020 seven tropical systems formed outside of the hurricane season range and were close enough to the US mainland to warrant watches and/ or warnings (Truchelut et al. 2022).

By observing the first and last tropical development since 1950 and then assessing the 99% confidence interval of their date ranges, new potential dates are discovered that could expand the current Atlantic hurricane season. Tropical system development, with the influence of warming oceans, has a favorable condition range of mid-May to mid-December, with those dates slowly expanding due to climate change. Truchelut's article shows that warming oceans are expanding the time tropical systems have favorable conditions for development in the Atlantic Ocean.

A study of storm distribution identified anomalies of storm development outside of the hurricane season. The study focused on storm development from 1851-2007, at a region south of 30 degrees north latitude and east of 75 degrees west latitude, which is the main formation region of Atlantic hurricanes (Kossin 2008). Trends show development range dates are increasing outside of the hurricane season, to the rate of about 1 day per decade on both the front and back end of the season.

Correlation to sea surface temperature can be a reason for hurricane development ranges increasing as the ocean is becoming warmer yearly, particularly in the date range not usually associated with hurricane development. It is further posited that a one-degree Celsius increase in sea surface temperature can correspond to a 20 day increase on the front and back end of hurricane season. A 20-day change would see the hurricane season shift from May 10 through December 20.

2.1.3. Precipitation

The warming climate and warming sea surface temperature are supercharging hurricanes and increasing their lethality (Trenberth et al. 2018). In addition to making hurricanes bigger and stronger, climate change is affecting precipitation levels in hurricanes, thereby increasing flooding and surge potential.

A study conducted on Hurricane Harvey analyzes the link between sea surface temperature and rainfall totals in 2017. The 2017 hurricane season is known as a record-breaking season due to sheer numbers of storms and the damage inflicted. NOAA measures hurricane seasons by accumulated cyclone energy (ACE), a measuring tool which accounts for different metrics to analyze a storm season. 2017 measured at 225% ACE, well above normal for typical hurricane seasons (Trenberth et al. 2018).

Hurricane Harvey dumped up to 60 inches of rain in several locations in southern Texas, creating massive flooding over large inland areas. Trenberth conducted a study which analyzed sea surface temperatures in the Gulf of Mexico, along with rainfall potential and discovered that climate change affected Hurricane Harvey's precipitation totals by 20-26% and rainfall totals in most other tropical systems by 5-15%.

Extreme precipitation events have shown a correlation with the warming climate. By observing recordings of precipitation over land areas, and by combining climate model outputs, precipitation sensitivity can be calculated. Intensification of precipitation extremes has been increasing in recent years, correlating with the rise in surface temperature (O'Gorman 2015). In addition, extreme precipitation in tropical areas appears to be the most affected by climate change, which could be a reason tropical systems are being observed with more precipitation, as tropical regions fuel hurricane growth.

2.1.4. Damage

A study conducted by Pant and Cha on future damage potential for hurricanes highlights the increasing danger due to continuing effects of climate change. Using the IPCC's future climate scenario, along with input into the Hazard US (HAZUS) software, loss potential was calculated at select major cities across the United States (Pant and Cha. 2019).

Using the IPCC's representative concentration pathway (RCP) of 8.5, which shows climate change continuing its current track, ocean temperatures are set to increase anywhere from about 2 to 4 degrees Celsius (Pant and Cha. 2019). This ocean temperature increase will increase the lethality of tropical systems, which in turn will increase damage across coastal cities in the United States.

Maximum windspeeds for hurricanes projected in the year 2100, show up to 200mph being a semi-common occurrence, which put those future storms well above the category 5 threshold. Results suggest economic loss to be more than double today's losses in 2100 with future hurricane scenarios. In particular, coastal cities south of Virginia Beach and along the Gulf of Mexico show three- and four-fold increases in damage loss in year 2100 future storm scenarios (Pant and Cha. 2019).

2.2. Numerical Storm Surge Modeling

Numerical storm surge modeling, sometimes referred to as physics modeling, is performed by a set of physics equations or algorithms applied to a grid that computes wave heights within the grid. In numerical surge modeling, a few governing equations form the basis for surge predictions. The Shallow Water Equations (SWE) and the Navier-Stokes equation of motion are two equations widely used in surge modeling (Dube et al. 2010). Those equations can then be applied to a grid mesh system of an area's coastline, which can form the basis of surge predictions. Two different techniques of mesh grids are commonly used in conjunction with the governing equations, structured and unstructured.

One of the first statistical surge models was developed by Venkatesh (1974) in a study of storm surge on the Great Lakes. Venkatesh employed a multiple regression model, with dependent variables being vertically averaged water velocity and water elevation departure from undisturbed depth, where historical water pressure and temperature data on grid points throughout the Great Lakes were input into an equation to predict wave heights (Venkatesh 1974).

Early numerical techniques employed finite difference (FD) schemes to model the Navier-Stokes equation of motion. An FD scheme is a numerical technique for solving equations by approximating derivatives with finite differences (Grossmann, Roos, and Stynes 2008). FD schemes are widely used in surge modeling and perform well in most circumstances (Dube et al. 2010). FD models employ structured grids, which can hinder the grid's ability to refine more complex coastal geometry and local flood patterns near the coast (Dube et al. 2010). Structured grids refer to the mesh basins within a surge model where surge calculations are performed. Structured grids are discrete shapes where surge calculations occur. Essentially, FD schemes in conjunction with structured grids are adequate, but are not as accurate in complex coastal geometry, like areas in lower Louisiana.

Somewhat newer unstructured grids have been used with a Finite Element (FE) scheme to solve the SWE. An FE scheme is a numerical method where differential equations are solved in multiple space variables (Bickford 1994), like an unstructured mesh grid. FE and unstructured grids allow for high resolution of small coastal features and can map complex coastal geometry well (Westerink et al. 1994). Unstructured grids are continuous and can change based on the surge model employed, which can give more accurate resolutions in areas as defined by the user. FE schemes, though possessing more resolution than FD, require large computational resources and time constraints, both disadvantages in surge forecasting (Dube et al. 2010).

The two storm surge models employed herein, SLOSH and ADCIRC, are numerical models that employ FD and FE schemes within their modeling code. SLOSH employs a structured grid mesh with FD and is thus not as accurate in complex coastal areas. ADCIRC utilizes FE schemes with unstructured grids, giving ADCIRC higher resolution in coastal inlets and barrier islands. As an FE, ADCIRC requires more resources and time to run simulations as compared to SLOSH.

2.2.1. SLOSH

SLOSH is the current model used by NOAA and the NHC. At its core, SLOSH is a computerized physics-based model that predicts storm surge based on past and hypothetical predicted storms by considering certain parameters of the tropical system (NHC 2022). Those parameters are used to create a model of the storm's wind field which drives the storm surge. SLOSH predicts storm surge by using three different approaches: deterministic, probabilistic, and composite. Though SLOSH is a single model, the different approaches used within it can make SLOSH seem like a family of related models.

Simply put, the deterministic approach with SLOSH involves mathematical equations that are applied to an area's coastline, by incorporating the unique terrestrial and aquatic micro terrain and other physical features (NHC 2022). The equations are applied to a coastline by incorporating a grid mesh, known as a basin, covering the forecast area. The model itself solves the Navier-Stokes equation of motion.

The mesh basins used in the SLOSH model are based upon polar, hyperbolic, and elliptical grids with momentum points at the corners of each grid and wave heights at the center of each grid. The mesh basin used for this project is ms8, which covers the Louisiana coastline. Figure 7 denotes the most updated mesh basins in the United States, Mexico, and Caribbean, as of January 1, 2020.

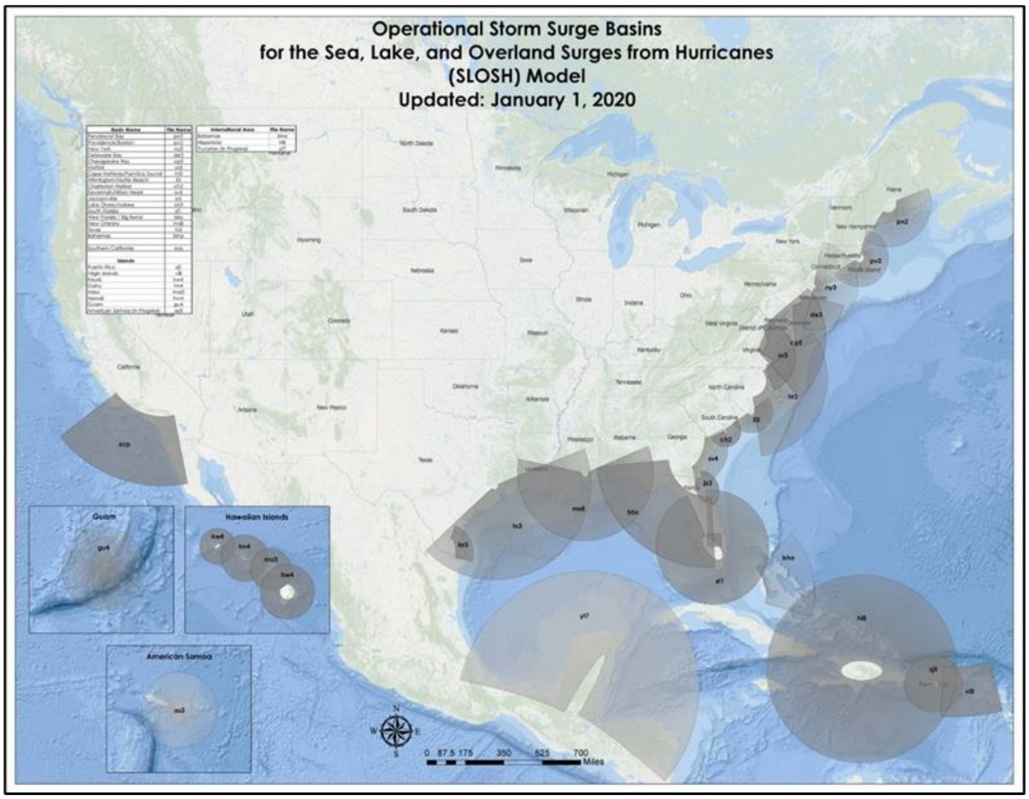

Figure 7. SLOSH mesh basins in use (NHC 2022)

The probabilistic method, also known as P-Surge, incorporates statistics of past forecast performances to generate an ensemble of different SLOSH model runs. P-Surge also accounts for the uncertainty in wind speed forecasts, mitigating the inherent error in wind speed predictions. Each ensemble member’s input within P-Surge is derived from current hurricane forecasts along with the associated five-year averages of track, cross track, and intensity errors. Essentially, within a P-Surge model, a five-year statistical error weight is added to the model to output a statistical storm surge prediction.

The composite method involves running the SLOSH model several thousand times with hypothetical hurricanes under varying storm conditions. Two outputs generated by the composite method are Maximum Envelops of Water (MEOW) and Maximum of MEOWs (MOMs). MEOW provides a worse case basin snapshot for a particular storm category and incorporates the uncertainty in landfall locations. MOM provides a conservative snapshot of where flooding may exist during a particular storm. The uncertainty that is accounted for in the composite approach makes it the best method for predicting vulnerability from storm surge and is the basis for the development of evacuation zones.

A heavy influencer of SLOSH and its model variations is historical hurricane behavior, which may be inadequate due to climate change affecting storm patterns. The past 10-20 years has seen an increase in hurricane frequency, strength, and unique steering with storm surge becoming ever more devastating.

SLOSH is the preferred model used by the National Hurricane Center due to the low cost and quick time generation for the model. Accuracy issues have been noted, however, SLOSH gives government agencies proper lead-time to decide and act on evacuation orders, where time is key over accuracy.

SLOSH has shown inaccuracies in forecasting when a storm is unusually large and when a storm is unusually slow (Ratcliff 2020). Slow storms can transport more water through the open ocean and generate forerunner storm surge due to the Earth's rotation, which can generate surge many hours prior to landfall (Snowcroft et al. 2020). Even with the low cost and quick speeds, SLOSH is still accurate to within 20% of a storm's predictive surge, another reason for its preference (Snowcroft et al. 2020).

2.2.2. ADCIRC

The Advanced Circulation (ADCIRC) model is a computer program that solves equations of motion for water on the Earth (Leuttich and Westerink 2013). In other words, ADCIRC can simulate and predict water movement over the ocean and land. The model is used by numerous academic, industrial, and governmental entities, most notably the Department of Homeland Security and the U.S. Army Corps of Engineers. The Federal Emergency Management Agency (FEMA) has validated ADCIRC and uses the model as a basis for flood risk analysis and mapping. The basis of ADCIRC is solving forms of shallow water equations and solving a vertically integrated continuity equation (Figure 8), which measures vertical flow of water for water surface elevation (Leuttich and Westerink 2004). ADCIRC computes water levels by solving the Generalized Wave Continuity Equation (GWCE) and uses an algorithm to solve GWCE.

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(UH) + \frac{\partial}{\partial y}(VH) = 0$$

where

$U, V \equiv \frac{1}{H}\int_{-h}^{\zeta} u, v \, dz =$ *depth-averaged velocities in the x,y directions*

$u, v =$ *vertically-varying velocities in the x,y directions*

$H \equiv \zeta + h =$ *total water column thickness*

$h =$ *bathymetric depth (distance from the geiod to the bottom)*

$\zeta =$ *free surface departure from the geoid*

Figure 8. ADCIRC's vertically integrated continuity equation (Leuttich and Westerink 2004)

ADCIRC also uses a mesh system (Figure 9) for its wave height calculations, but uses triangular unstructured grids instead of structured grids, which gives ADCIRC the ability to compute localized resolution within each grid mesh. ADCIRC, once hindered by long computational speeds, now uses parallel algorithms that make surge simulations rapid and capable of solution on personal computers.

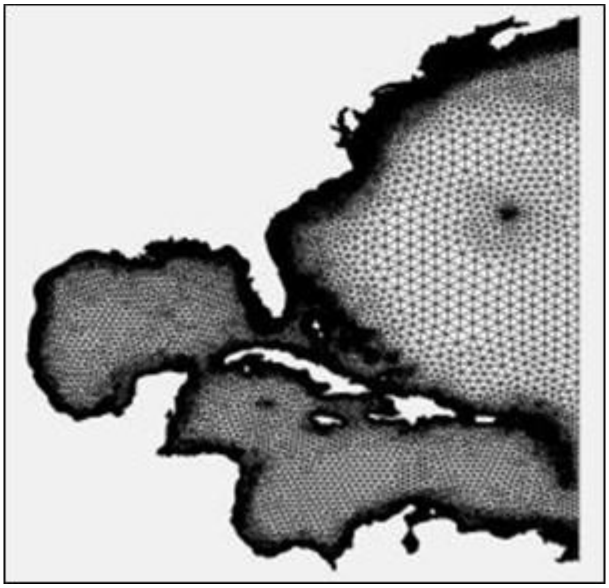

Figure 9. Example ADCIRC mesh (Leuttich and Westerink 2013)

ADCIRC is more complex and capable than SLOSH mainly due to its highly flexible mesh system (Snowcroft et al. 2020), however; the model requires more time than feasible for storm surge evacuation, where time is of greatest importance. ADCIRC is better at simulating tides propagated from the open ocean and can resolve very detailed bathymetry in coastal regions. SLOSH and ADCIRC differ in three main areas: mesh shape and resolution, mathematical methods, and physics in the model.

ADCIRC uses a flexible unstructured grid mesh system for its basins. The unstructured mesh allows for concentration in areas, like coastal regions, allowing for higher resolution. The physics in ADCIRC can generate three-dimensional solutions for ocean surface wave impacts, whereas SLOSH computes at a two-dimensional level. Table 1 shows key differences in the two models.

Table 1. Key differences between SLOSH and ADCIRC (Snowcroft et al. 2020)

	SLOSH	ADCIRC
Mesh	Structured: Shape is curvilinear, and resolution can change gradually	Unstructured: Shape is triangular, and there is large capability to vary resolutions.
Mathematical Methods	Finite difference: Use the rate of change of a quantity between two neighboring grid points to represent the continuous gradient in the equations. (Discretization of the continuous equations)	Finite element: Approximate the true answer to the equations with a combination of simpler functions. (Discretization of the true solutions)
Physics	2-dimensional: No ocean surface wave impacts	2-dimensional/ 3-dimensional: With ocean surface wave impacts
Computational Cost	Low	High

2.2.3. Data-Driven Models

Data-driven storm surge models use a combination of statistical and machine learning techniques for surge predictions (Tadesse et al. 2020). Data-driven models use predictor data sets, which are historical data that can be applied for future predictions, whereas numerical models rely on solving equations, however some numerical models incorporate data-driven methods. Meteorological and remotely sensed wind speed, sea level pressure, and sea surface temperature are common data used in data-driven modeling techniques as predictor data. Further datasets used in data-driven models involve historical surge data as derived by tidal gauges or other sources (Tadesse et al. 2020).

The data-driven model predictors are then fed into an algorithm or equation, which is the statistical portion of the data-driven model. The equation computes maximum surge height at the location of the specific tidal gauge being calculated (Tadesse et al. 2020). The equations can also be used across a grid or mesh system as with major statistical models to generate surge predictions across a large spatial area.

Machine learning algorithms, like the ones stored in ArcGIS Pro, can be used as a substitute to equations used to predict water levels. A classification technique like Random Forest can be used to simulate surge. Random Forest algorithm works by using decision trees that split based on variables. In the storm surge modeling realm, random forest decision trees consider parameters like wave heights, sea temperature, and wind speed among others.

2.2.4. Artificial Intelligence Models

An artificial neural network (ANN) is another type of machine-learning algorithm that has been used for forecasting storm surge. It is based on human brain biology and is represented by three components: input, hidden, and output layers (You and Seo 2008). The ANN storm surge model works by using 24 different storm parameters and is trained through cycles of learning where network weights are continuously updated (Ayyad et al. 2022).

Another machine-learning model that has been used to model storm surge is the cluster neural network model, which works by combining the functionality of ANN with a cluster analysis technique. This technique calculates similar distances within unsupervised data that correlate to one another (You and Seo 2008). Unsupervised data techniques find patterns in data based on relationships between data points (Kotu and Deshpande 2019). Data is then grouped based on similar function or type. AI storm surge modeling has shown promise and has been as accurate or more accurate than current numerical-based models. (You and Seo 2008).

2.3. Spatial Analysis and Validation

Storm surge models must be validated to determine the veracity of the model's predictions. No storm surge model will ever achieve total accuracy but verifying that model's performance is a step that will save future lives. Different techniques exist that assess storm surge model accuracy, but one main avenue exists, hindcast comparison. Hindcast simulations input observed storm parameters, like wind speed, direction, and atmospheric pressure, into the surge model to compare performance.

2.3.1. Hindcast

Most hindcast simulations do not map out simulated versus observed flooding, but instead employ statistical methods to compare ground truth surge levels to simulated surge levels in a series of charts and graphs (Dinapoli et al. 2020). Dinapoli et al. employed several different equations to summarize and validate surge near Buenos Aires. The hindcast model that was created was a numerical model that estimated surge based on observed windspeed and atmospheric pressure during surge events (Dinapoli et al. 2020). Those readings were input into the model itself via open-source programming languages like python. Though using a pre-operational model, results show accuracy to within 8-13% of observed surge heights during the temporal scale.

FEMA also employs hindcast simulations to validate its surge models. As with most hindcast simulations, FEMA uses recordings from tidal gauges and high-water marks observed during a storm and compares those with the levels as computed in its surge model. FEMA possesses a system called the interactive model evaluation and diagnostic system (IMEDS) to validate its models and assess performance. Inputs to IMEDS include wind, wave, water levels, and water current parameters that can generate statistical analysis of a past storm. IMEDS includes an additional step than most hindcast simulations and shows spatially specific tidal gauges that were deemed accurate or inaccurate. IMEDS is accurate to within NOAA's standards of 80% surge height (MDL 2018) and possess robust error metrics like scatter index and skill score.

Another hindcast simulation on SLOSH and ADCIRC data performed on Hurricanes Andrew and Irma is a study by Turan et al. Turan et al. deduced that ADCIRC and SLOSH underpredicted surge during Hurricane Andrew (Turan et al. 2018). For Hurricane Irma, ADCIRC was shown as the more accurate model (Turan et al. 2018). The study produced a series of charts and graphs detailing each model's accuracy, but as with most hindcast simulations, no visualization showing SLOSH and ADCIRC differences were produced.

2.3.2. Other Validation Methods

A study completed by Veeramony et al. conducted a validation project of the Deltf3D surge model on Hurricane Ike in 2008. The Delft3D model is employed by the Naval Oceanographic Office to model surge for their prediction system (Veeramony, Condon, and Ormondt 2017). The study focused on wave height, water level, and high-water marks as observed at various recording stations. Further, the study used best forecast wind speeds based on the NHC's best advisory track, as opposed to hindcast windspeeds. Results show the Deltf3D model simulated surge heights to within 96% of observed heights at 6 of 9 recording stations. (Veeramony, Condon, and Ormondt 2017).

Another validation study was conducted on Hurricanes Ike and Wilma by Kelly et al., however, this study validated the fully adaptive storm tide (FAST) model. The FAST model, newer than SLOSH and ADCIRC, is a numerical model that solves shallow water equations like the two former models. FAST does not require the forecaster to know where fine resolution is needed in the model, unlike SLOSH and ADCIRC (Kelly et al. 2016). The study used observed wind and water figures from both hurricanes and input those figures into FAST to determine differences in the model versus ground truth. Results show FAST predicted surge heights to within 10-20% of observed surge (Kelly et al. 2016). Additionally, FAST showed quick computational speeds that even matched SLOSH, which is around 20 minutes (Kelly et al. 2016). However, additional computer cores are needed, which would inhibit FAST versus SLOSH.

Chapter 3 Methods

This research project focuses on two separate analyses to determine model accuracy. First, an analysis of flood extent throughout the study area was performed to assess the predicted extent using the SLOSH and ADCIRC models as compared to the flooding extent observed. Second, a depth analysis is conducted by comparing SLOSH, ADCIRC, and observed flooding depths across the study area. The chapter is broken down into three sections overviewing data acquisition, preparation, and analysis.

The methods and results in this chapter are organized into a time series that correlates to pre- and post-landfall of Hurricane Ida. The eight NHC advisories in this research project form the time series, with the first five occurring prior to Hurricane Ida's landfall, advisories 9-14. The final three NHC advisories, 15-17, cover post landfall. Advisory 13 is skipped during this project as it was an intermediate 3-hour advisory. Table 2 depicts each advisory along with its associated timeline.

Table 2. Timeline series

Hurricane Ida Reference	Event	Time (local)
Pre-Landfall	NHC Advisory 9	August 28, 10:00 am
	NHC Advisory 10	August 28, 4:00 pm
	NHC Advisory 11	August 28, 10:00 pm
	NHC Advisory 12	August 29, 4:00 am
	NHC Advisory 14	August 29, 10:00 am
Landfall	Landfall	August 29, 11:15 am
Post-Landfall	NHC Advisory 15	August 29, 4:00 pm
	NHC Advisory 16	August 29, 10:00 pm
	NHC Advisory 17	August 30, 4:00 am

3.1. Methods Overview

In simplified form, the workflow for extent analysis involves taking each raw raster of the storm surge prediction data and converting it into a polygon of the same surge data. The next step is clipping the polygon to the study area, and then dissolving the polygon to rid unnecessary boundary lines within the data. Next, the polygons are summarized within the study area to compute square mileage and a percentage of flooding within the study area. Results suggest both SLOSH and ADCIRC vastly overpredicted flood extent when compared to observed flooding. SLOSH over predicted flood extent by an average of 5% across the study area as compared to ADCIRC, however, SLOSH showed steady improvement throughout the temporal scale. Figure 10 shows a condensed workflow as completed with each raster dataset for flood extent analysis.

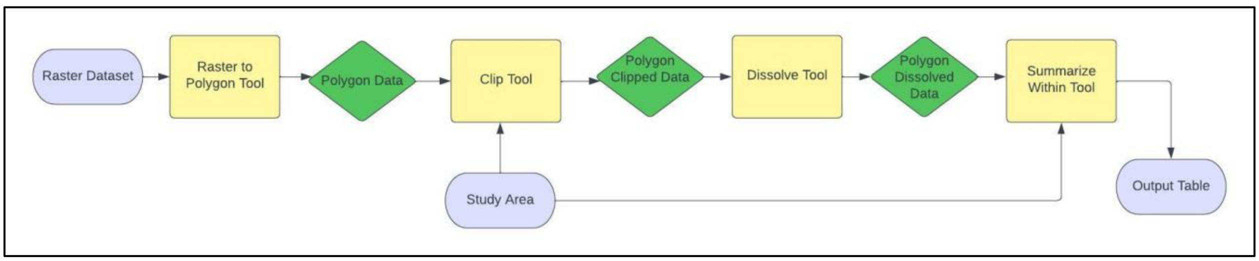

Figure 10. Simplified flood extent workflow

Depth analysis is performed to determine surge depth across the entirety of the study area. Additionally, the average surge depth per model and NHC advisory is also calculated. In simplified form, the depth analysis was performed using two different sets of geoprocessing tools. An ArcGIS tool developed by researchers at the University of Alabama can estimate flood depth by utilizing a flood extent polygon and a DEM. The Floodwater Depth Estimation Tool (FwDET) is a GIS-based tool that can estimate flood depth by using a flood extent polygon and a DEM (Cohen et al. 2019). This FwDETv 2.1 tool was utilized to generate a flood depth raster for the study area. Next, the zonal statistics tool was used for each surge model and the observed depth raster to generate average surge depth for each advisory and model. Figure 11 represents the workflow performed to conduct depth analysis across the study area.

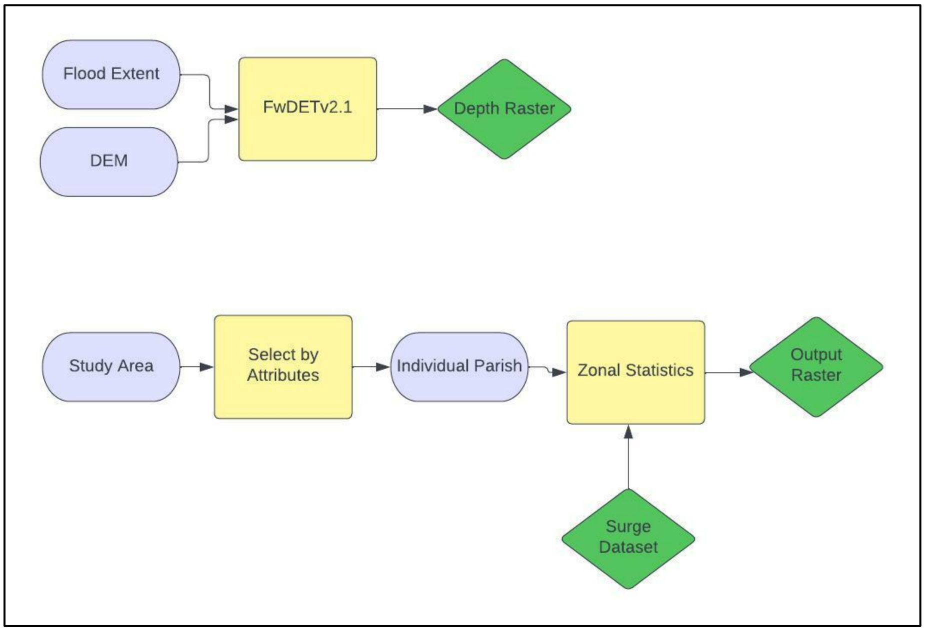

Figure 11. Simplified depth analysis workflow

3.2. Data

This section describes the data employed in this project. Table 3 provides a summary of the data while the following subsections offer more detailed information.

Table 3. Data table

Data	Original Coordinate System	Description	Resolution	Type	Source
Louisiana Parish Boundary	WGS 1984	Administrative boundaries of the study area (10 parishes)		Vector	Louisiana Department of Transportation and Development (LaDOTD)
Land Cover	NAD 1983 Albers	Land extent of the study area		Vector	USGS
Digital Elevation	NAD 1983 UTM Zone 15N	Elevation data of the study area	10 meters	Raster	Louisiana State University Center for

Model (DEM)					GeoInformatics (C4G)
Maximum Flood Extent Depiction (MFED)	WGS 1984	Maximum extent of flooding data as acquired via remote sensing	90 meters	Raster	AER FloodScan
Standard Flood Extent Depiction (SFED)	WGS 1984	Standard extent of flood data as acquired via remote sensing	90 meters	Raster	AER FloodScan
MODIS Flood (14-day composite)	WGS 1984	Flooding observed via remote sensing for the study area	250 meters	Raster	NASA NRT GFM
SLOSH storm surge prediction (8 sets, advisory 9-17)	NAD 1983	SLOSH simulation data showing predicted flooded areas	10 meters	Raster	NHC
ADCIRC storm surge prediction (8 sets, advisory 9-17)	WGS 1984	ADCIRC simulation data showing predicted flooded areas	10 meters	Raster	Coastal Emergency Risk Assessment

3.2.1. Louisiana Parish Boundary Data

The state of Louisiana's Department of Transportation and Development's open data portal was utilized to acquire the administrative boundaries for this research project. Specifically, the Louisiana parish dataset was downloaded that contained all parishes in the state. Figure 12 represent the parish boundaries downloaded for this project.

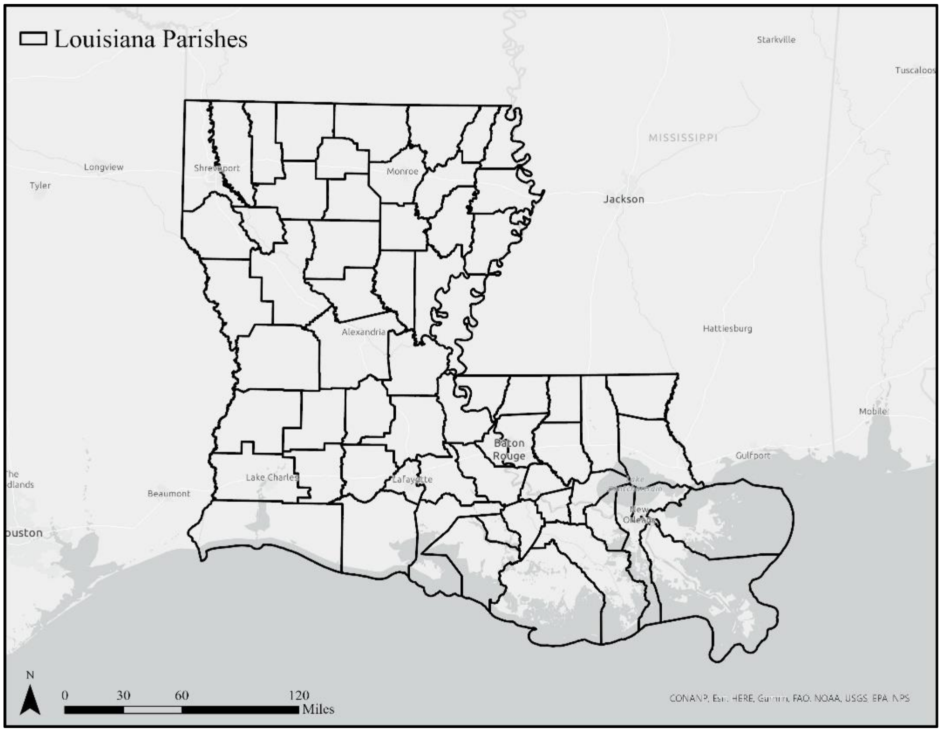

Figure 12. Louisiana parish boundaries

3.2.2. Land Cover Dataset

This research project utilized land cover data for the purpose of creating a boundary of land extent within the study area. Parish boundaries include lakes and maritime zones, which can extend many miles into the Gulf of Mexico. A dataset containing just land extent was required so that flooding extent analysis of land throughout the study area could be completed. The USGS's land cover download portal was utilized to acquire a dataset containing land cover only. The landcover dataset acquired contained the various land cover classes that exist in Louisiana (Figure 13).

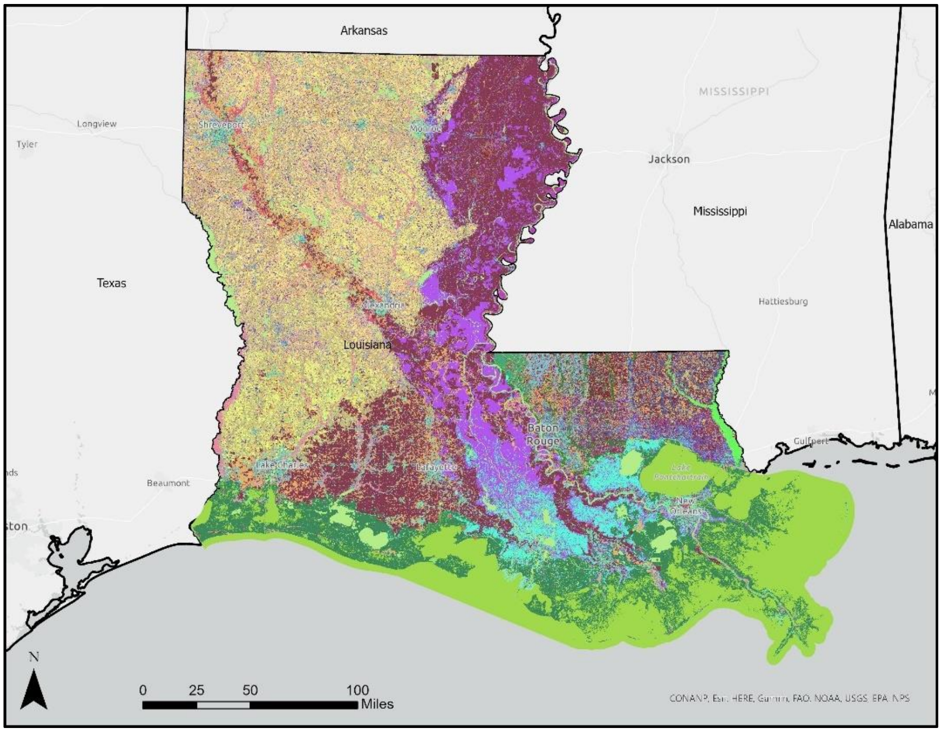

Figure 13. Raw land cover dataset

3.2.3. Digital Elevation Model

A DEM is key for use when determining surge depth, as elevation can directly corresponds to flood depths and locations. For this research project, a 10-meter DEM was acquired from the Louisiana State University's Center for GeoInformatics website. A 10-meter DEM was chosen due to both surge models also possessing the same resolution. Finer resolution DEMs were experimented with, at both 5 and 3 meters, however, the computational time was not feasible for the many datasets used in this research. Figure 14 denotes the DEM used in this project.

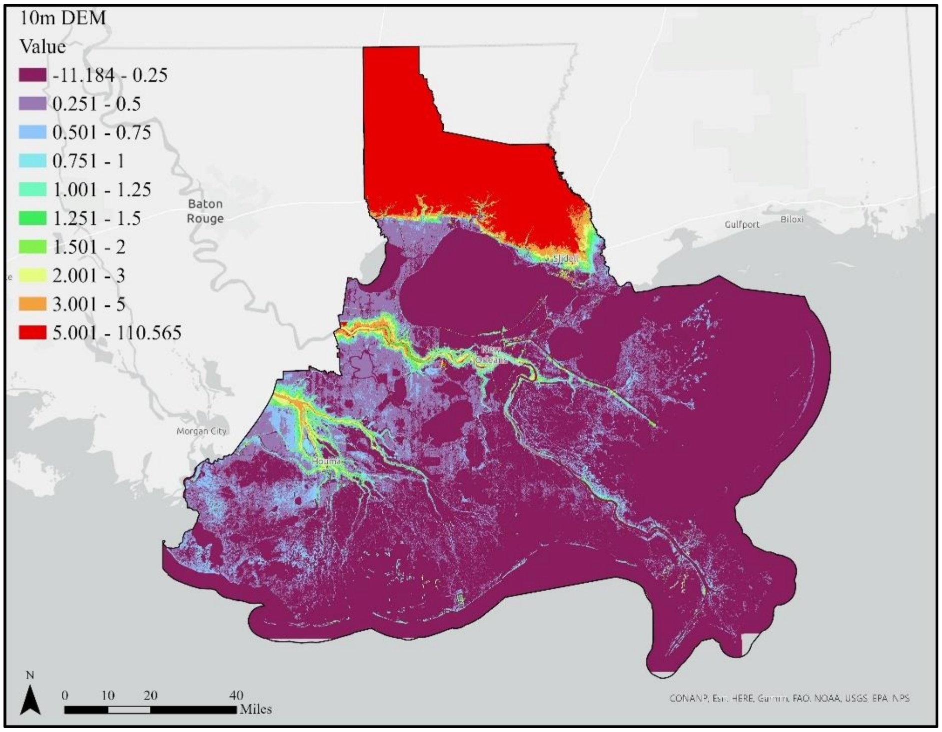

Figure 14. 10m DEM of the study area

3.2.4. SLOSH Storm Surge Prediction Data

Historical SLOSH data was acquired from the NHC's tropical system data archive website, where data on each named storm is kept for research purposes. By choosing a year and storm name, users can access a bevy of information like hurricane warning and watch locations, hurricane track locations, and storm surge warnings, among other information. Storm surge data is published and available for download for each named storm dating back to 2015. The NHC data archive only stores one type of surge data, P-Surge, a newer form of SLOSH modeling that accounts for 5-year error averages in past storms.

The SLOSH datasets are 8-bit raster TIFFs. The P-Surge data represents a flood inundation prediction for a particular area in the path of a storm. Two types of P-Surge data are available, inundation and tidal mask. The inundation dataset, used in this project, represents surge flooding inundation with past error weights assigned, which is SLOSH's newest simulation. The other dataset also includes a tidal mask layer which assigns value to areas along coastlines that inherently flood during high tides. This project worked exclusively with the inundation dataset due to same data availability of the ADCIRC surge model covered in the next section. The inundation and tidal mask datasets are divided by time and are tied to an NHC advisory. Figure 15 shows SLOSH data as pulled from NOAA's repository for NHC advisory 9.

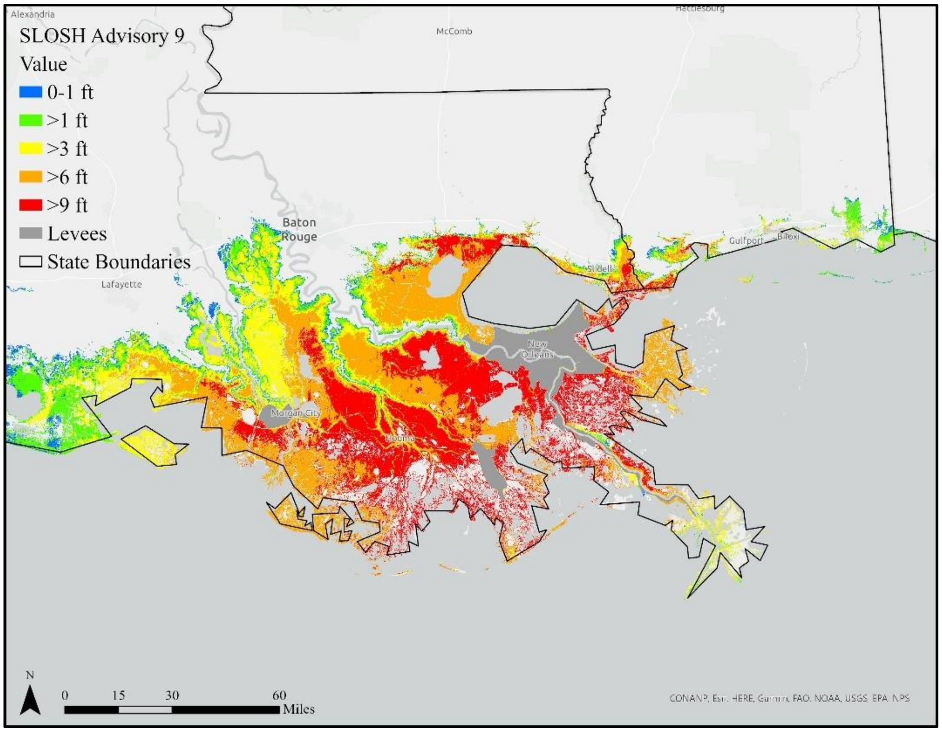

Figure 15. SLOSH advisory 9 dataset

The data shows surge extent and maximum inundation depth based on the storms current position and likely future landfall. The categories are symbolized in the exact way NOAA symbolizes their advisory data. The levees are included in the data and are included above for visualization purposes.

3.2.5. ADCIRC Storm Surge Prediction Data

ADCIRC data was found on the CERA website. CERA contains a free web-based GUI that can run ADCIRC simulations based on storm parameters or based on historical storms.

ADCIRC inundation data can be chosen by storm from 2011 to present, and by advisory. Inundation data for advisories 9 through 17 were downloaded. Each is a 32-bit raster TIFF at 10-meter resolution. Figure 16 represents ADCIRC data from NHC advisory 9.

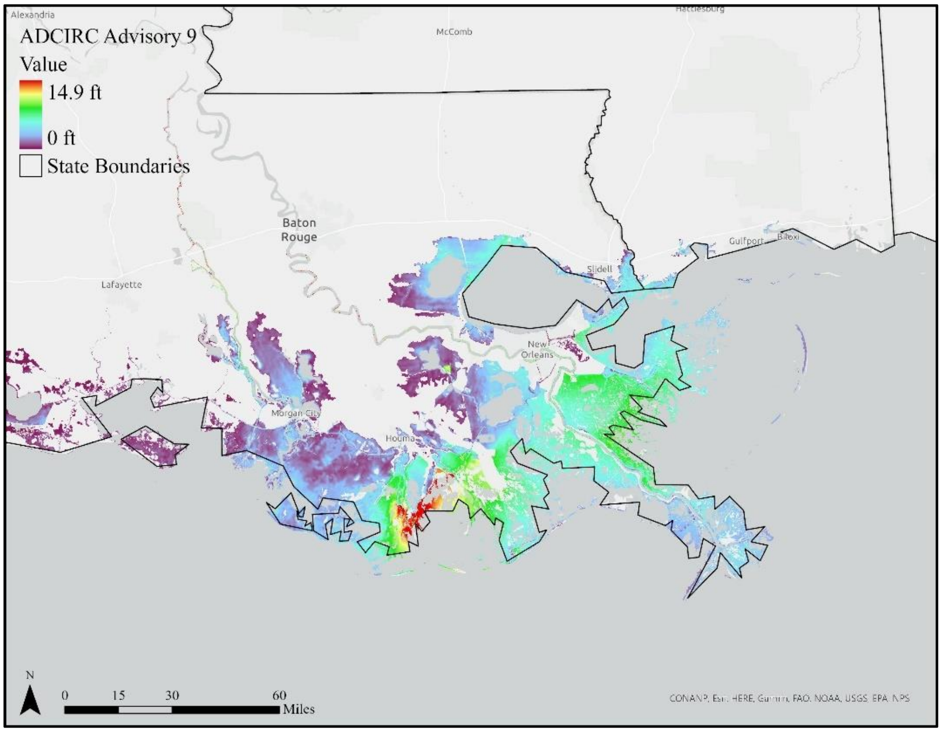

Figure 16. ADCIRC data reflecting NHC advisory 9

3.2.6. Observed Flooding Data Acquisition

Numerous sources provide historical flooding data. The reputable Dartmouth Flood Observatory (DFO) pieces together several different remote sensing datasets to build its flood extent packages for storms. Flood layers used by DFO include: 250 m MODIS, NASA’s ARIA SAR, and the European Union’s Copernicus emergency mapping service. Though DFO was the first-choice source for flood data, as of November 2022, DFO had yet to publish flood extent data from their spaceborne sensors specifically for Hurricane Ida. Two other reputable sources were identified, however, which had Hurricane Ida flood data.

The Atmospherics and Environmental Research's (AER) FloodScan program is a satellite-based remote sensing platform that provides daily maps of large-scale inland flooding. Flooding data is acquired by an Advanced Microwave Scanning Radiometer 2 (AWSR2) onboard Global Change Observation Mission-Water Satellite 1 (GCOM-W1), a Japanese satellite providing long-term Earth observation imagery. FloodScan works by applying an algorithm to its raw remotely sensed data to provide users with flood inundation mapping (Galantowicz, Picton, and Root 2021). FloodScan tracks over 99% of the Earth's surface every two days, and flood data is sensed at 90m resolution worldwide.

FloodScan provides five different datasets, and all are raster GeoTiffs: persistent water, fractional flooding, woody wetlands, MFED (maximum flood extent depiction) flooding, and SFED (standard flood extent depiction) flooding. Persistent water represents bodies of water that are permanent fixtures, like rivers, lakes, and oceans. Fractional flooding is a dataset, at 22km resolution, which represents the unfiltered raw data acquired by the AWSR2. Woody wetlands represents areas like swamps and marshes that area heavily vegetated and moist, but not flooded.

SFED is designed to generate low false positive readings for large-scale flooding events (Galantowicz, Picton, and Root 2021). Its algorithm is consistent over large temporal scales and minimizes false positive readings. Its consistency does produce conservative estimates of flood extent. MFED is designed for quick flood readings for disaster response, and as such, does not incorporate the steps in its algorithm to minimize false positives (Galantowicz, Picton, and Root 2021).

The FloodScan user's guide recommends SFED for singular extreme flooding events, and MFED for flood occurrence over time periods (Galantowicz, Picton, and Root 2021). Both categories fit with this project as Ida was a singular extreme event, and its impacts required study over a multi-day temporal scale. For those reasons, both SFED and MFED were used. Data for August 31 was chosen as that date represents the time at which flooding from Hurricane Ida was at its peak.

Coastal flooding data was acquired from National Aeronautics and Space Administration's (NASA) Near Real-Time (NRT) global flood product, remotely sensed from both Aqua and Terra satellites. Aqua and Terra are part of NASA's earth observation research project that studies precipitation, evaporation, and the cycling of water around the globe. The Moderate Resolution Imaging Spectroradiometer, better known as MODIS, generates flood data globally at 250m resolution in 10-degree tiles. Three types of data are available: MODIS flood water, which shows only flooded areas within the extent chosen; MODIS surface water, which depicts flood water before reference water is filtered within an extent; and MODIS water product, which is a combination of the two.

The MODIS water product was chosen to give a combination dataset of flooding within the study area. For this project, 3-day composite data was downloaded, because a total representation of Ida's impact was desired. Though covering a different temporal scale than FloodScan, MODIS's 3-day composite captures surge prior to and during landfall, while FloodScan captures post-landfall flood stages. Storm surge can be a multi-day event, and it was so with Hurricane Ida. To properly study the surge effects from the storm, a multi-day composite is needed of water data. Four separate 10-degree tiles were required for complete coverage of the study area.

3.3. Data Preparation

After acquiring the data, the data needed to be cleaned in preparation for analysis. This section describes the process required for each data set.

3.3.1. Coordinate System and Projection

The datasets in this research project were in varying geographic coordinate systems, but mainly in World Geodetic System (WGS) 1984 and North American Datum (NAD) of 1983. To ensure the highest degree of accuracy for this project, all datasets needed to be projected into the same coordinate system.

The study area is entirely encompassed within the southeastern portion of Louisiana, a relatively large scale. Every dataset used for this project was projected into the NAD 1983 (2011) State Plane Louisiana South FIPS 1702 (US feet) projected coordinate system. This was chosen because it employs a projection specifically created for the southern portion of Louisiana.

3.3.2. Land Extent Preparation

The raw raster land cover data was in a Geo TIFF format and contained different land classifications for the entire state of Louisiana. The dataset needed to be transformed into a polygon to act as the study area boundary for clipping other data. The water features within the study area, such as lakes and rivers, needed to be cut as to not skew flooding results in the study area. The raster data contained categorical values of land cover classification. It was reclassified to change any cell with a value for water to "no data".

The reclassified raster was converted into a polygon feature class and its features were dissolved to eliminate the numerous boundary lines within. Next, the data was clipped to the study area so the land extent would represent only the study area. Figure 17 represents the land extent of the study area, which is used for all flood analysis throughout this project.

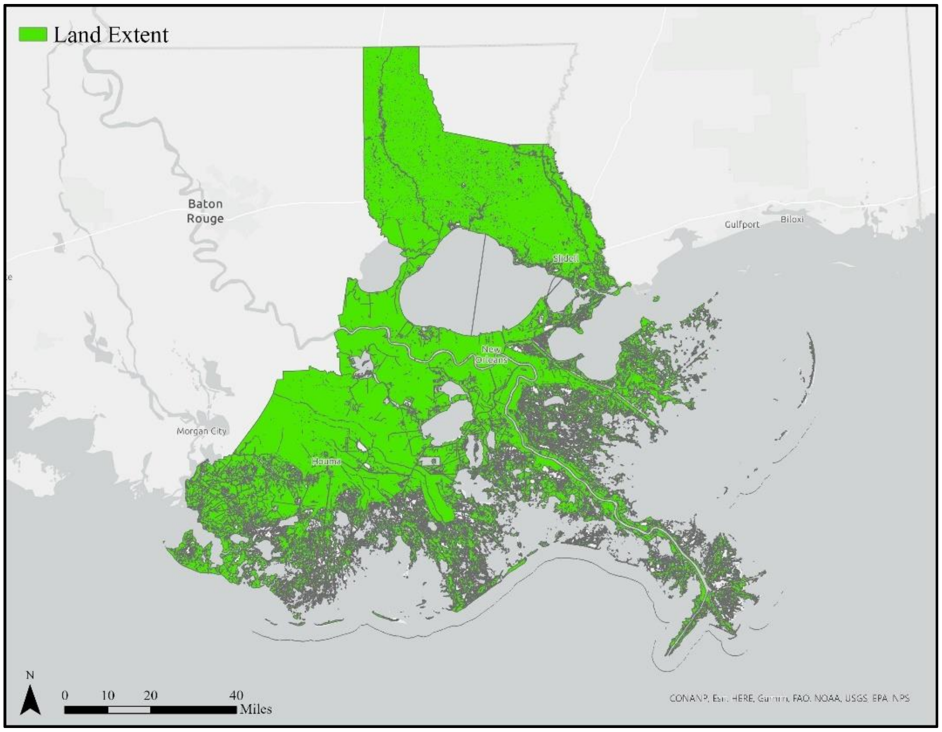

Figure 17. Land extent of study area

3.3.3. SLOSH Preparation

Figure 18 represents the preparation workflow that was performed, specific to the flood extent analysis. First, the dataset was reclassified to eliminate the levees in the data, as the levees will give erroneous flood extent results. Next, the data was converted to a polygon and clipped to the study area. The data was then dissolved to eliminate internal lines in the data for a cleaner look. All eight SLOSH advisory workflows are the same throughout.

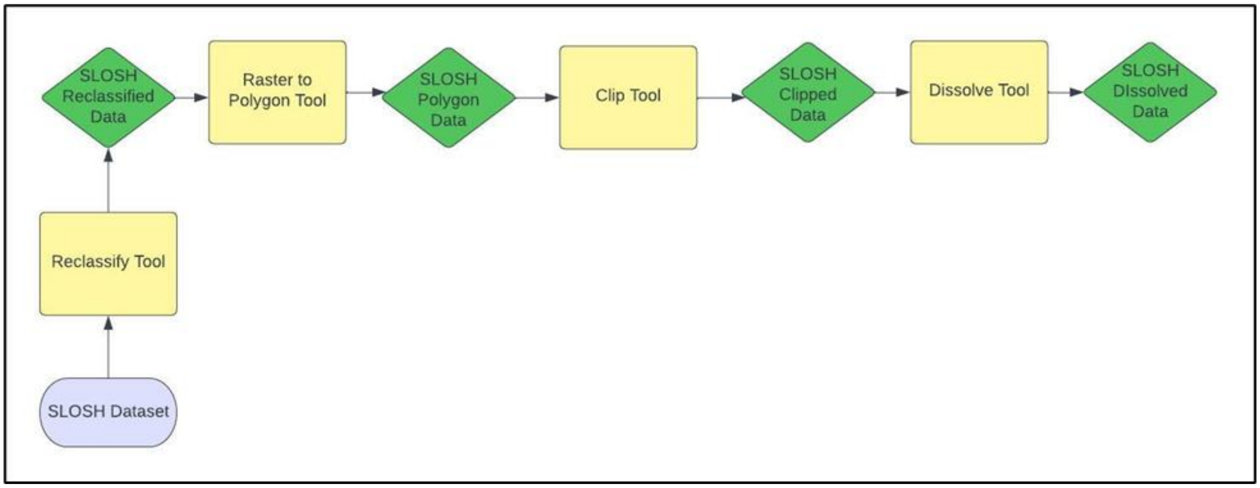

Figure 18. SLOSH preparation workflow

Value 7 in all SLOSH datasets represented levees, and thus needed to be excluded from spatial analysis. Value 7 would show as a flooded area during analysis and thus would produce an erroneous conclusion of SLOSH flooded areas. To eliminate value 7 from SLOSH, the reclassify tool was utilized by inputting the SLOSH dataset as the input raster, value as the reclass field, and changing value 7 to no data in the reclassification box. All eight SLOSH datasets were reclassified prior to conducting analysis. After reclassifying, only flooded values remained, and analysis could be conducted to determine flood extent percentage with SLOSH data. Figure 19 depicts SLOSH inundation data for advisory 9 after reclassification.

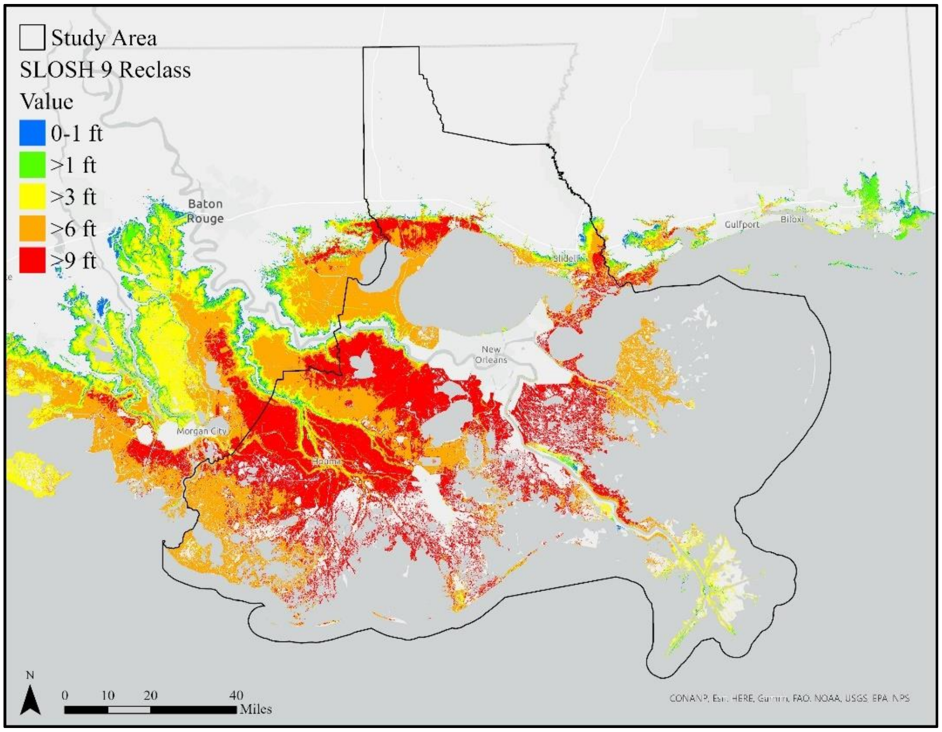

Figure 19. SLOSH surge simulation data from NHC advisory 9

The raster to polygon geoprocessing tool was utilized to convert the SLOSH data into a polygon by choosing the dataset and then value for input field (Figure 20). Next, the polygon was clipped to the study area to eliminate any excess data (Figure 20). The dissolve tool was then employed to eliminate boundary lines within the dataset.

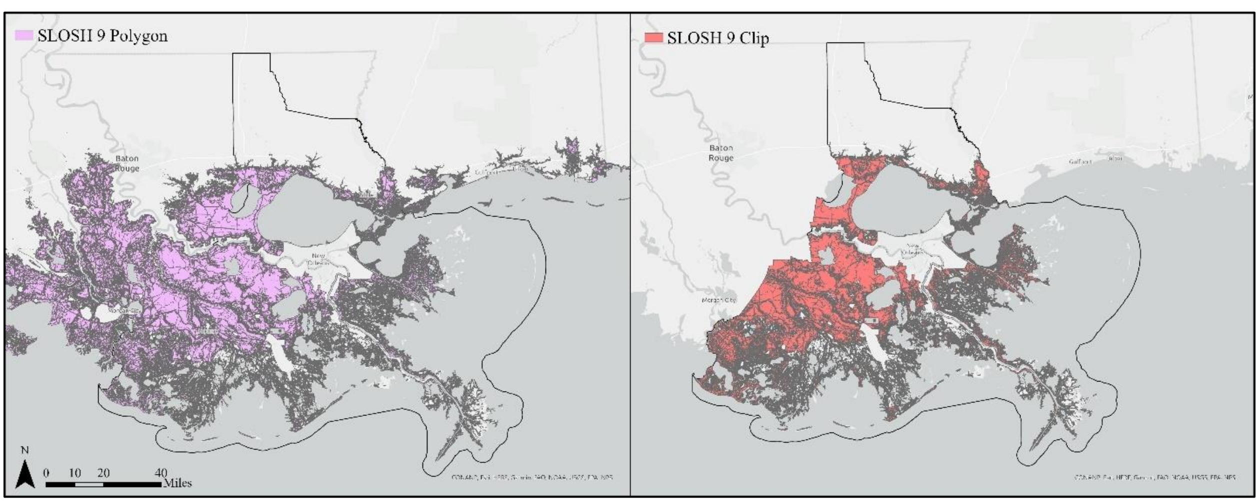

Figure 20. Raster to polygon output (left), polygon clip output (right)

3.3.4. ADCIRC Preparation

ADCIRC data could not be converted to a polygon utilizing the standard geoprocessing tool, due to the dataset not being an integer raster, and therefore raster functions were utilized. Under raster functions, the conversion set was picked, which converts the ADCIRC raster to a convertible dataset. After conversion to a colormap, the data could be converted to a polygon utilizing the raster to polygon geoprocessing tool. The new ADCIRC polygon was then clipped to the study area to eliminate excess data with the pairwise clip tool. The dissolve tool was then employed to eliminate boundary lines within the dataset. Figure 21 represents the ADCIRC preparation workflow as performed with a dataset. The same steps were performed for all eight advisories.

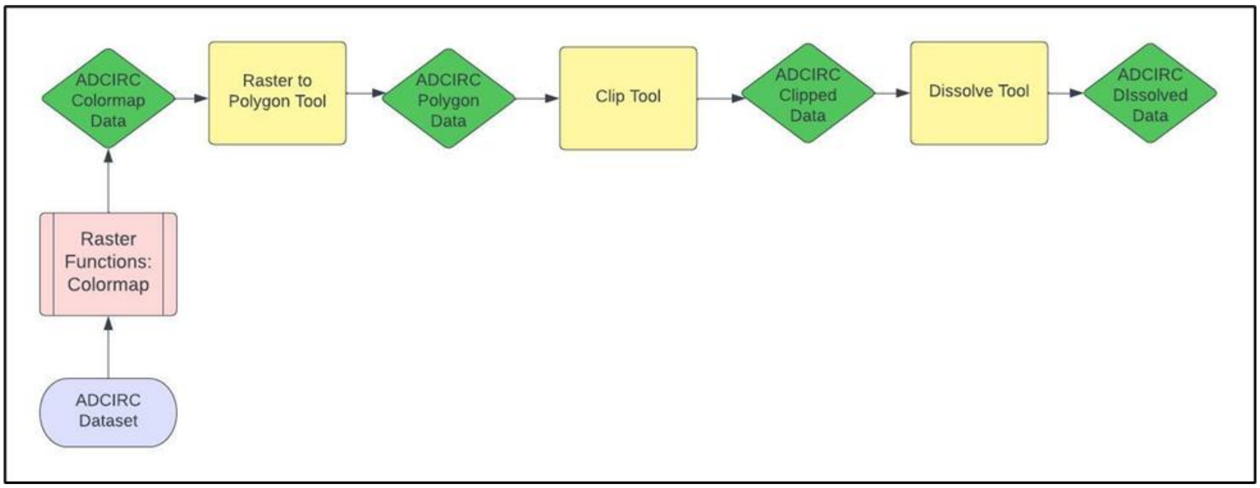

Figure 21. ADCIRC workflow

3.3.5. Observed Flooding Preparation

Additional steps were taken for the six observed flooding datasets, with the goal of combining all six into one usable shapefile for the purposes of showing total flood extent, and ease of use throughout the project. After converting all six raster sets to polygons and clipping to the study area, the merge tool was input with the four MODIS tiles to combine those, and then the two FloodScan datasets to combine those. Next, the two remaining datasets were merged to create one observed flooding polygon. The dissolve tool was then utilized to eliminate polygon boundaries within the dataset. Figure 22 represents the preparation workflow as performed for the observed flooding datasets.

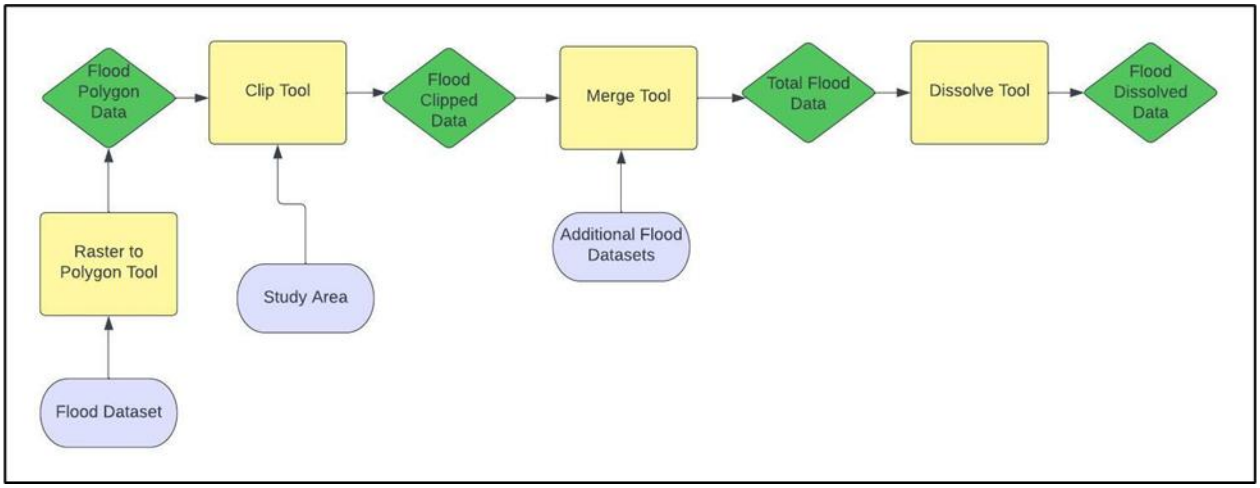

Figure 22. Observed flooding workflow

Figure 23 depicts all six flood datasets combined, which represents total flooding observed form Hurricane Ida.

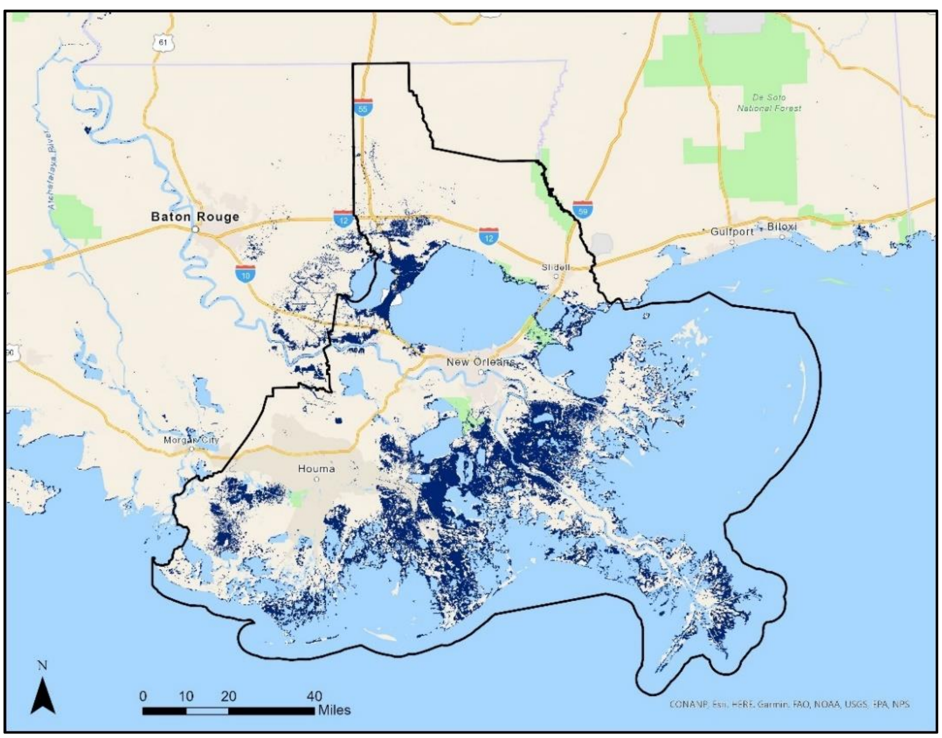

Figure 23. Extent of flood waters during Hurricane Ida

3.4. Data Analysis

After cleaning and preparing data, analysis could be conducted to determine flooded areas within the study area. This section describes how the SLOSH and ADCIRC estimates were compared against each other and the observed flooding data.

3.4.1. Flood Extent Analysis

The summarize within geoprocessing tool was utilized to calculate the area SLOSH data is contained within the land extent portion of the study area. For the summarize within tool, the study area is chosen for input polygon, the clipped SLOSH dataset is chosen for summary features, and id and sum chosen for field and statistic, respectively. Finally, square miles are chosen for the shape unit and the tool can be performed.

For ADCIRC data, the summarize within geoprocessing tool was utilized with input polygon being the clipped ADCIRC polygon, id and sum chosen for field and statistic, and square miles chosen for shape unit. The geoprocessing tool can be run successfully.

After conducting the technical work, the summarized flooded area in square miles is contained in each model layer's attribute table, as created running the summarize within tool. First, however, the study area's square mileage must be determined to determine percentage calculations of the surge and flood datasets. The summarize within tool was run with the study area's land extent as the input and summary data, which calculates the square mileage of the study area. The land extent area was calculated to be 5,632.91 miles.

After running the summarize within tool, each model's advisory layer has summarized flood data in its attribute table. After dividing the summarized flood data with the study area's square mileage, a percentage calculation is obtained.

3.4.2. SLOSH and ADCIRC Flood Depth Analysis

A further comparison of the two storm surge models was computed by comparing surge depth throughout the study area. The FwDET tool calculates water depth by subtracting calculated flood water elevation from topographic elevation at each grid cell within the flooded area (Cohen et al. 2019). Figure 24 represents the flow chart utilized with FwDET.

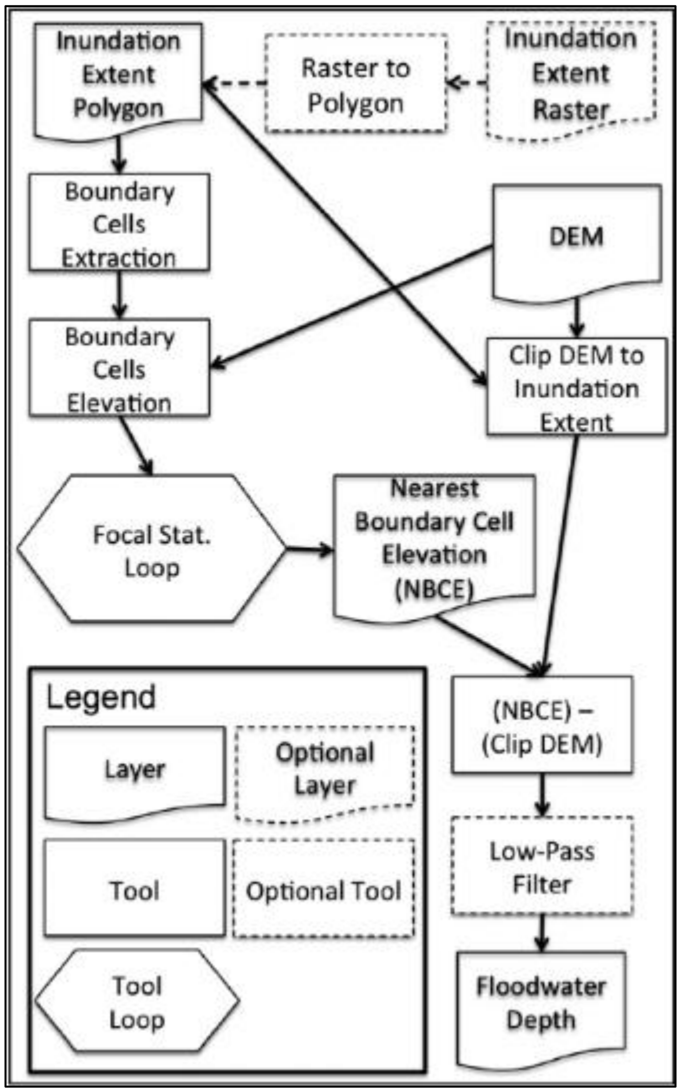

Figure 24. FwDET flow chart (Cohen et al. 2017)

The flood extent polygon, as created earlier in this chapter, was input into the tool via ArcGIS Pro, along with a 10-meter DEM of the study area. The output was a raster dataset with estimated flood depth throughout the study area. This step was repeated with the SLOSH and ADCIRC flood extent datasets to determine their flood depth as well.

The ADCIRC dataset's value can be used as is, meaning if the average value for a raster is 2, then 2 feet is the average depth for the study area. For SLOSH, further work is involved to generate the actual flood depth of the raster. SLOSH datasets have preset values in the raster as downloaded from NOAA. A value of 1 does not mean a depth of 1 foot, but instead means a depth of 0-1 foot. A value of 2 denotes depths of 1-3 feet, a value of 3 denotes depths of 3-6 feet, a value of 4 denotes depths 6-9 feet, and a value of 5 denotes depths over 9 feet. Thus, for each SLOSH output raster generated, the surge depth must be calculated against its preset value.

The zonal statistics geoprocessing tool was then utilized to compute average flood depth for the study area by surge model and advisory. SLOSH and ADCIRC predicted depth were computed per advisory using the FwDET tool and compared against the observed flooding depth. The zonal statistics tool was used for each of the 8 NHC advisories with both surge models and the observed flooding depth.

The next chapter covers results from extent and depth analysis. The extent and depth analysis provide a comparison of SLOSH and ADCIRC against observed flooding.

Chapter 4 Results

This chapter overviews the results from chapter three's workflow for the eight NHC advisories and their surge predictions. Comparisons of SLOSH, ADCIRC, and observed flooding extent and depth are included.

For all eight advisories, SLOSH and ADCIRC overestimated flood extent significantly, to the tune of about 24-31% throughout the study area over observed flooding. SLOSH and ADCIRC extent predictions, however, remained around 2-7% of each other. This indicates that both models predicted similar surge extent, albeit in different locations. For all eight advisories, ADCIRC was the more accurate model in terms of being closer to the observed flooding extent percentage, however, its dominance waned in the final four advisories. Though the less accurate model throughout this extent analysis, SLOSH showed accuracy improvement across all eight advisories, whereas ADCIRC accuracy showed slight decreases as the storm approached and passed landfall. This can suggest that ADCIRC performs better overall than SLOSH, but SLOSH performs well in short range forecasting.

In depth analysis, visual representations give the appearance of both surge models predicting more depth due to more flood extent across the study area. Once the flood data is broken down and compared by average flood depth, the two models predicted less average surge depth than the observed flooding dataset at a rate of about 20%. Both models were similar in their depth predictions with each other with ADCIRC being slightly more accurate as it was closer to observed depth in 4 of 8 advisories, and SLOSH more accurate in 3 of 8. The final advisory both models predicted the same depth. This result indicates that both models underestimated surge depth across the totality of the study area.

The chapter is organized into three sections. The first section covers NHC advisories 9-14, or pre-landfall, along with its flood extent and depth analysis. The second section covers NHC advisories 15-17, or post-landfall, along with its flood extent and depth analysis. The final section overviews the entire temporal scale and produces charts and Figures that suggest trends in the models.

4.1. Pre-Landfall Flooding Predictions: NHC Advisories 9-14

NHC advisories 9-14 represents August 28 at 10:00am (advisory 9) to August 29 at 10:00am (advisory 14), with advisories published every 6 hours in between. During this time Hurricane Ida's strength intensified rapidly. Ida's maximum sustained winds were recorded at 86 mph at advisory 9, 104 mph for advisories 10 and 11, 138 mph for advisory 12, and 150 mph for advisory 14.

4.1.1. Pre-Landfall Flood Extent Analysis

Figure 25 represents comparisons in both surge models and the observed flooding dataset for NHC advisories 9, with the idea of highlighting flood extent for the three datasets. Since both surge models overpredicted surge, the vast majority of observed flooding was successfully predicted by SLOSH and ADCIRC. There were still slight areas where observed flooding went unpredicted with both models. Though covering similar extent percentages across the study area, SLOSH and ADCIRC differed in flood locations. The other pre-landfall advisory maps are in the appendix.

In all five advisories, SLOSH showed two areas where it predicted flooding more than ADCIRC: the Mississippi River southwest of Lake Pontchartrain and Bayou Lafourche, otherwise known as the Chetimachas River (figure 25).

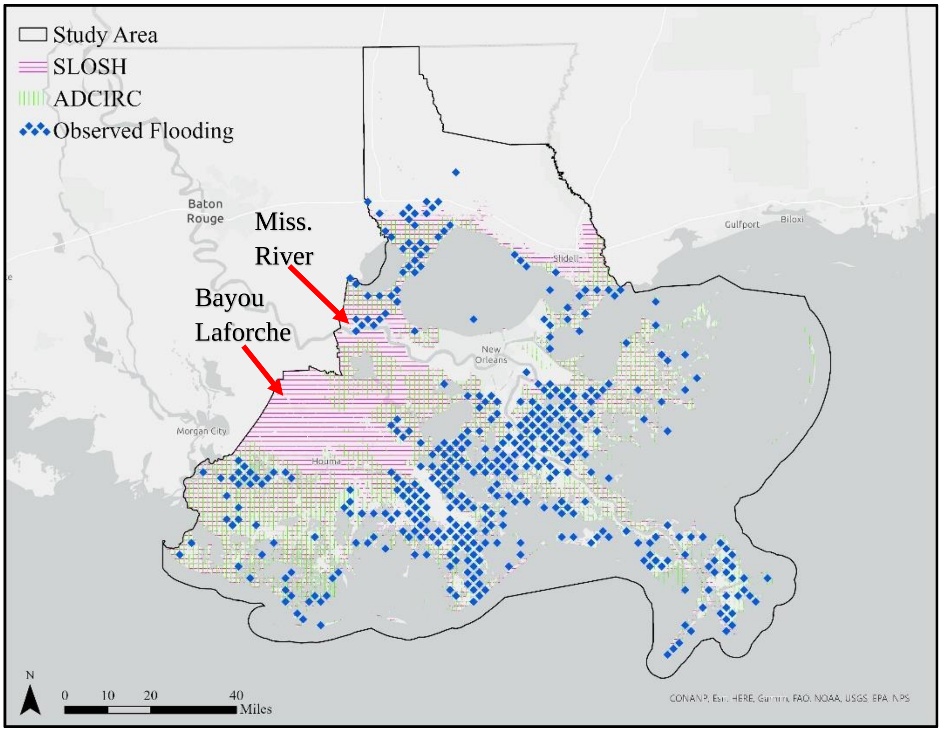

Figure 25. Pre-Landfall Advisory 9 Flood Extent

Table 4 shows the areal and percentage of flood extent within the study area. As previously discussed SLOSH and ADCIRC overestimated flooding significantly, with ADCIRC being more accurate over advisories 9-14.

Table 4. Advisories 9-14 areal and percentage result analysis

	Sq Mi within Study Area	Study Area Sq Mi Total	Flooded Percentage
Study Area		5,632.91	
Observed Flooding Extent	1,024.3	“ “	18.18%
SLOSH 9	3,089.4	“ ”	53.37%
ADCIRC 9	2,920.8	“ “	45.60%
SLOSH 10	3,098.3	“ “	53.53%
ADCIRC 10	3,067.8	“ “	46.97%
SLOSH 11	3,024.5	“ ”	52.23%
ADCIRC 11	2,917.3	“ “	45.53%
SLOSH 12	3,073.3	“ “	53.09%
ADCIRC 12	3,035.8	“ “	47.61%

SLOSH 14	2,845.6	“ ”	50.52%
ADCIRC 14	2,664.9	“ “	47.31%

4.1.2. Pre-Landfall 9-14 Depth Analysis

Visually, observed flooding shows deeper closer to the coast, with pockets scattered near Lakes Pontchartrain and Maurepas. ADCIRC predicted similar results to observed flooding, albeit at a greater extent throughout the study area. SLOSH, on the other hand, shows light flooding closer to the coast and deeper flooding inland concentrating at Bayou Lafourche, an area ADCIRC negated. Visually speaking, ADCIRC’s flood depth was more in line with observed flooding than SLOSH. Figure 26 represents flood depths for advisory 9. The other advisory depth analysis maps are located in the appendix.

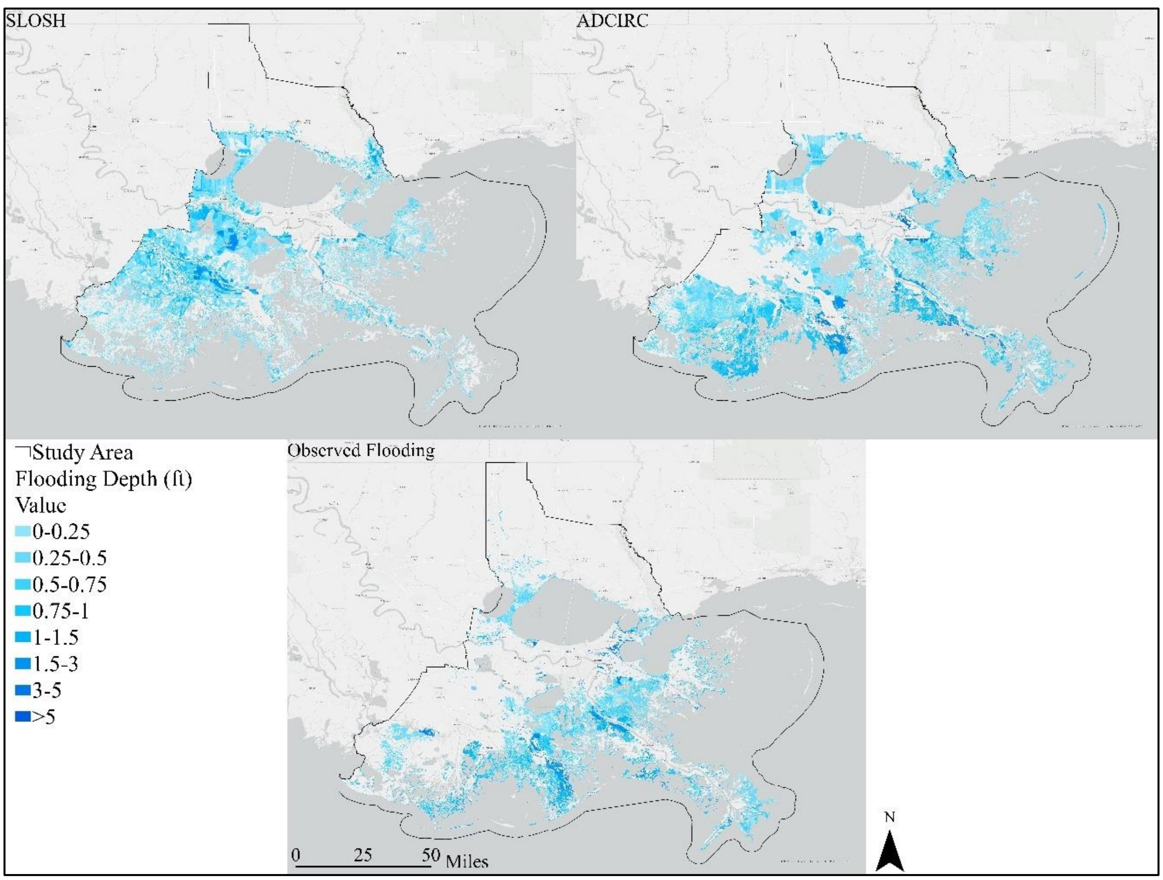

Figure 26. Depth Analysis for NHC Advisory 9

Averaging surge depth across the entire study area for both models and observed flooding gives another avenue to compare results. Both models predicted less average surge depth than observed flooding. SLOSH was more accurate in 3 of the 5 pre-landfall advisories, with ADCIRC more accurate in 2 of 5. Figure 27 shows the average depth across the pre-landfall advisories.

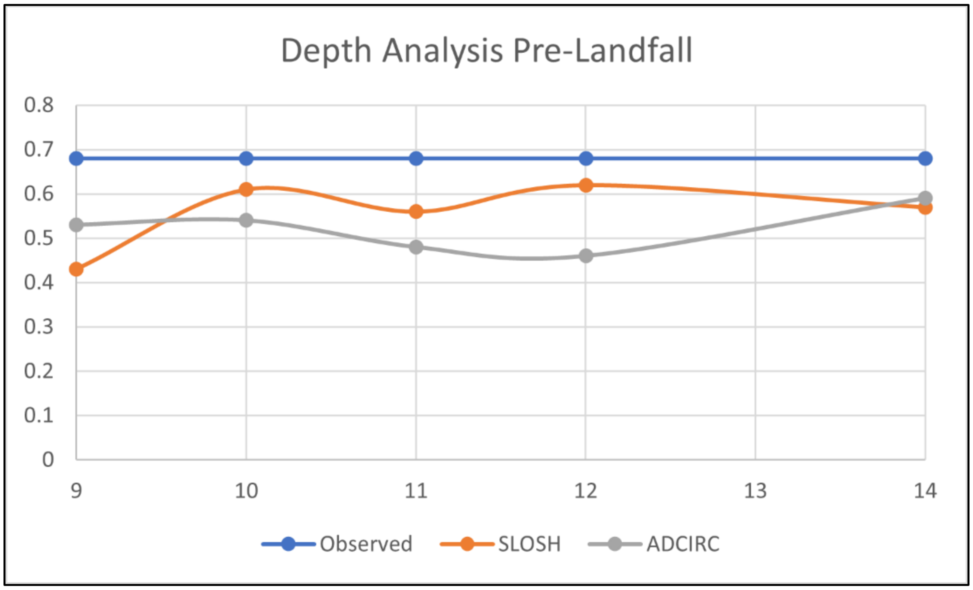

Figure 27. Pre-Landfall depth analysis in feet

4.2. Post-Landfall Flooding Predictions: NHC Advisories 15-17

NHC advisories 15-17 represents the time following landfall, but specifically covers August 29 at 04:00pm to August 30 at 04:00am, with advisories published every 6 hours in between. During this time Ida would slowly weaken with maximum sustained wind speeds of 132 mph, 104 mph, and 58 mph for advisories 15-17, respectively.

4.2.1. NHC Advisories 15-17 Flood Extent Analysis

Figure 28 represents the flood extent analysis for NHC advisory 15. As with the previous advisories, observed flooding is predicted well with the two models. A few areas exist where observed flooding was not predicted, but they are isolated west and north of Lake Pontchartrain, along with small pockets towards the coast. Two main areas still exist that show SLOSH extent different than that of ADCIRC. Those areas are the same as the first five advisories, the Mississippi River southwest of Lake Pontchartrain, and Bayou Lafourche. The other post-landfall advisory extent maps are located in the appendix.

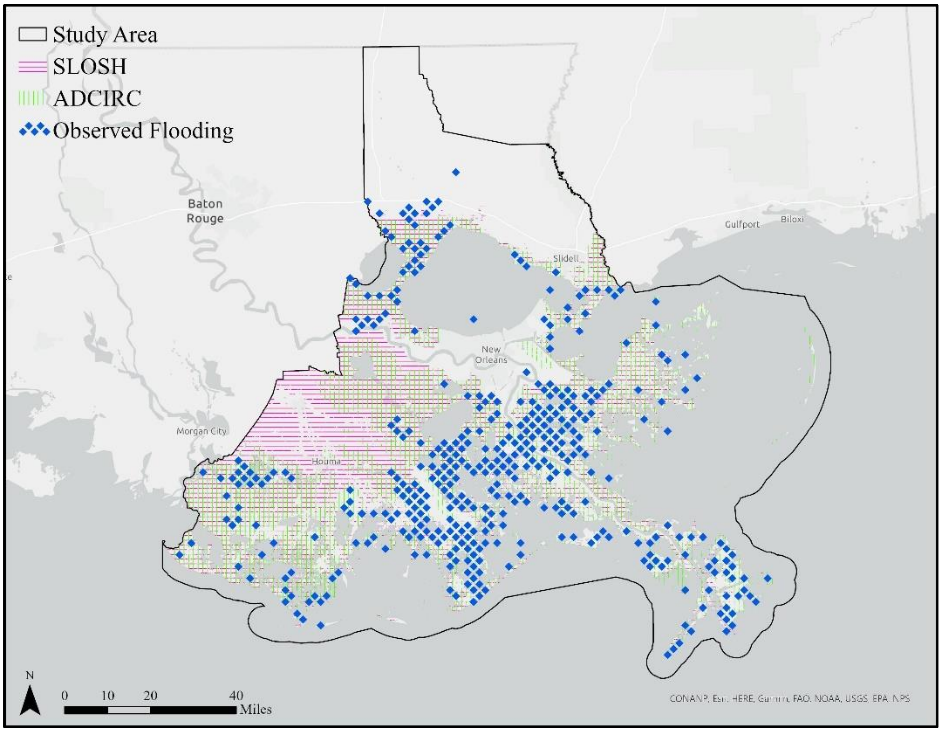

Figure 28. Post-Landfall Advisory 15 Flood Extent

The areal and percentage table from the study area analysis suggests differences in the results from the previous five advisories. NHC advisories 9-14 show ADCIRC as the more accurate model over SLOSH to around 5% in most cases. With NHC advisories 15-17, ADCIRC was still the more accurate model, but down to around 2.5%. Table 5 shows the areal and percentage analysis with SLOSH and ADCIRC. This analysis can suggest that ADCIRC is the more accurate model overall, especially in long range forecasting, whereas SLOSH can be accurate in post-landfall applications.

Table 5. Advisories 15-17 areal and percentage result analysis

	Sq Mi within Study Area	Study Area Sq Mi Total	Flooded Percentage
Study Area		5,632.9	
Observed Flooding Extent	1024.3	" "	18.18%
SLOSH 15	2834.2	" "	50.31%
ADCIRC 15	2742.5	" "	48.69%
SLOSH 16	2776.7	" "	49.29%
ADCIRC 16	2655.2	" "	47.14%
SLOSH 17	2790.9	" "	49.55%
ADCIRC 17	2623.1	" "	46.57%

4.2.2. Post-Landfall Depth Analysis

Surge depth post landfall shows similar results to pre landfall in that ADCIRC appears to be the more accurate of the two in predicting depth across the study area. SLOSH does predict far less depth in advisories 15 and 16 as the storm moves further inland. ADCIRC predicts far deeper surge in post landfall towards the coast but appears deeper than observed flooding. One notable anomaly is with the SLOSH model at advisory 17, where areas around the Mississippi River and Bayou Lafourche show significant surge depth. This could be attributed to the rivers surpassing their flood stages post landfall. Figure 29 represents flood depths for advisory 15. The other post-landfall depth analysis maps are located in the appendix.

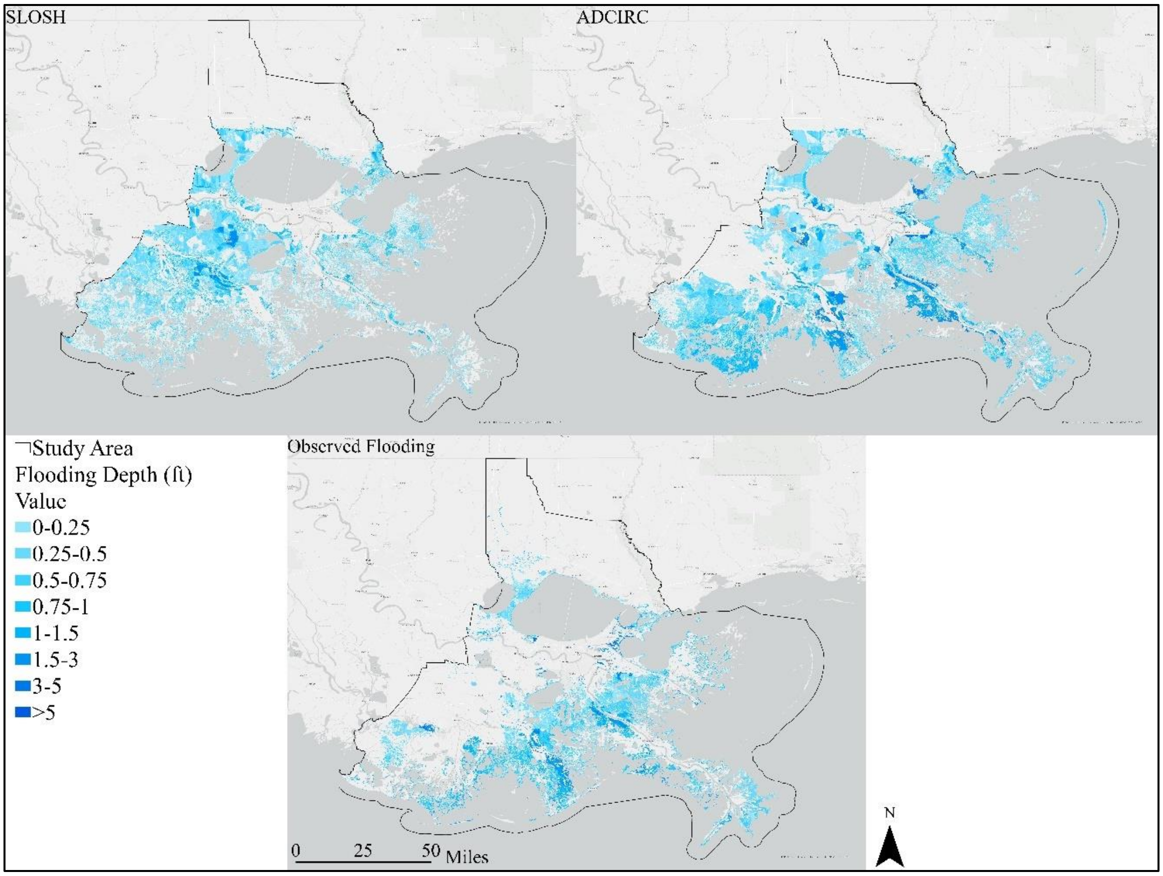

Figure 29. Depth Analysis for NHC Advisory 15

For the three advisories post-landfall, ADCIRC was the more accurate in predicting average surge depth. Both models still predicted less average depth than actual observed depth. Figure 30 shows the post landfall depth analysis for the surge models and observed flooding.

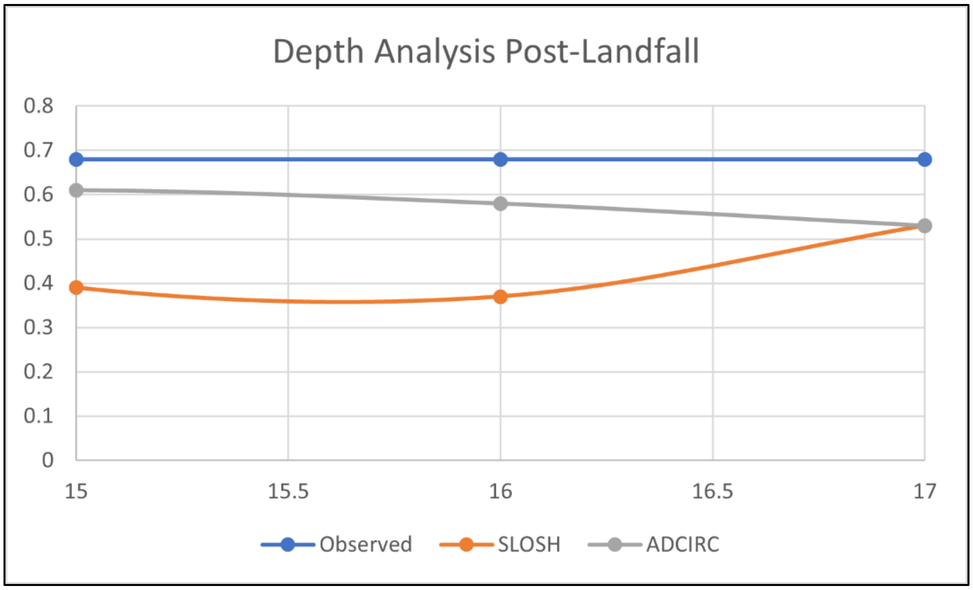

Figure 30. Post-Landfall depth analysis in feet

4.3. Overall Extent Analysis

Figures 31 and 32 show bar charts of the flooding extent analysis throughout the study area with SLOSH and ADCRIC during all eight NHC advisories. The results show that SLOSH consistently improved its extent forecasting against the 18.18% observed flooding extent percentage. SLOSH's own extent percentage improved as Ida crept closer to landfall and even improved after landfall.

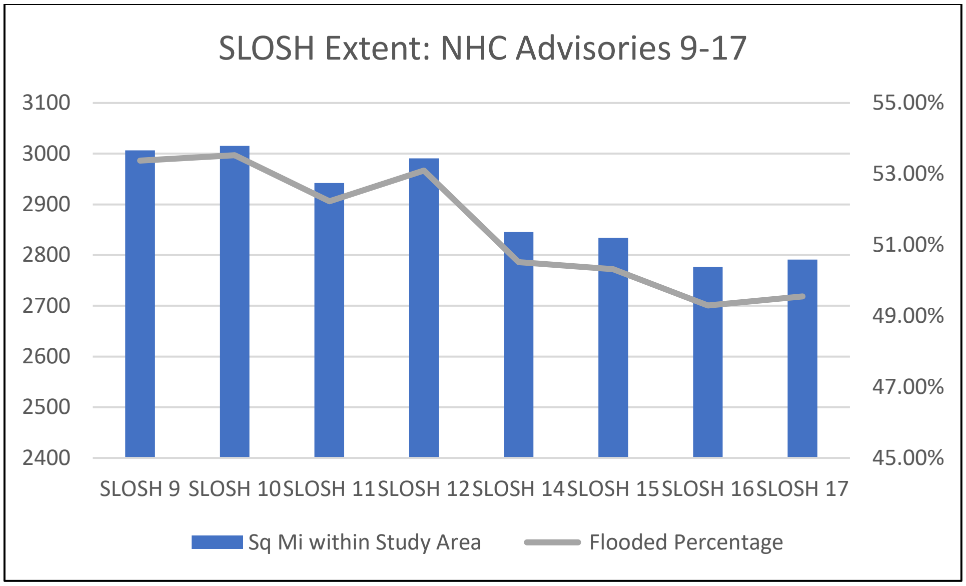

Figure 31. SLOSH flood extent percentage analysis

ADCIRC shows a pattern nearly opposite of SLOSH, as accuracy decreased slightly throughout the temporal scale. ADCIRC was more accurate through all eight advisories but is not as accurate in the final four. ADCIRC still produced better results prior to and after landfall, even with Ida's unforeseen intensification.

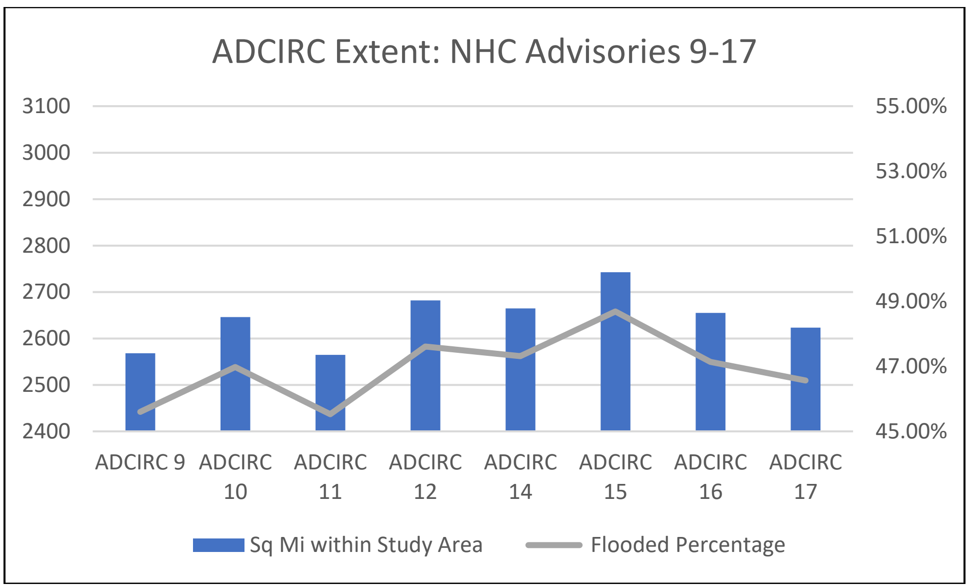

Figure 32. ADCIRC flood extent percentage analysis

Overall, the percentage analysis over the entire temporal scale suggests ADCIRC is the better model for forecasting. However, SLOSH shows performance nearly on par with ADCIRC in the time just prior to and during landfall. Coupled with the monetary and time advantages SLOSH possesses over ADCIRC, SLOSH can predict surge adequately enough for planning and evacuation. Both models appear to maintain high enough accuracy, at least with surge extent, to work against modern tropical systems, as Ida's rapid intensification did not affect SLOSH and ADCIRC as was hypothesized.

4.4. Overall Depth Analysis

Overall, both surge models predicted less average depth across the study area when compared with observed flooding. When factoring which model was more accurate, ADCIRC comes slightly out on top. ADCIRC was more accurate in 4 of the 8 advisories, whereas SLOSH was more accurate in 3 of 8. The final advisory both models predicted the same average surge depth. Figure 33 denotes the depth analysis chart across the entire temporal scale.

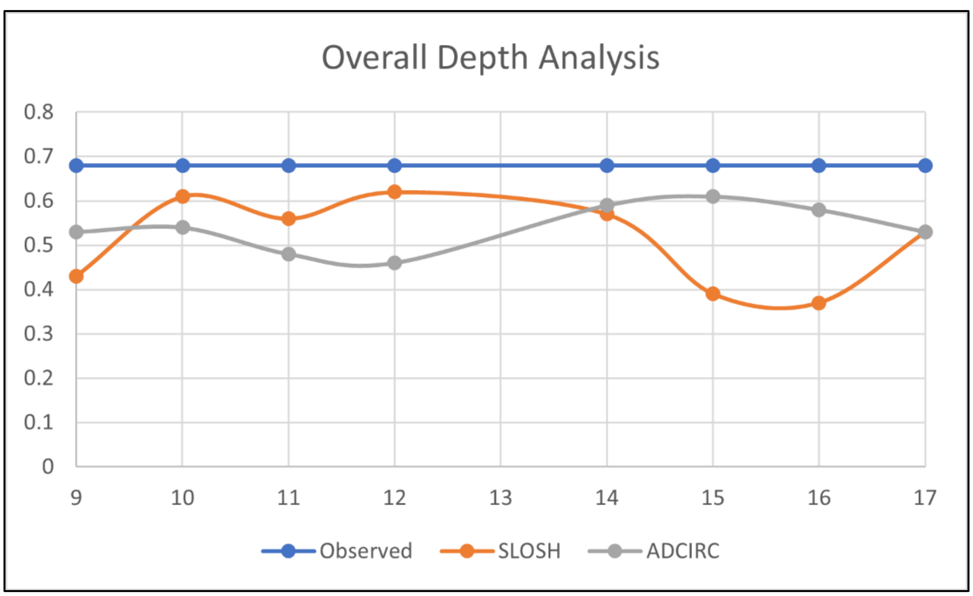

Figure 33. Overall depth analysis in feet

While adequately predicting flood extent, caution should be exercised when claiming it adequately predicted flood depth. Both models underpredicted average surge depth, at a rate of about 20% or about 0.15 feet. While not appearing to be a big difference, even finite underestimations of depth can be disastrous. While not affecting flood extent, the surge models did underestimate surge depth as hypothesized.

4.5. Locality Analysis

Using satellite imagery and zooming into areas within the study area can help shed light on the differences in the models. The locality analysis was used to determine spatial patterns within the surge and flood datasets. Identifying spatial patterns within the flooded areas can help determine model differences based on the spatial environment. Additionally, deciphering if certain topographic areas hinder or help surge is useful. Figure 34 denotes an overview of a locality analysis with each location's figure letter that is referenced later.

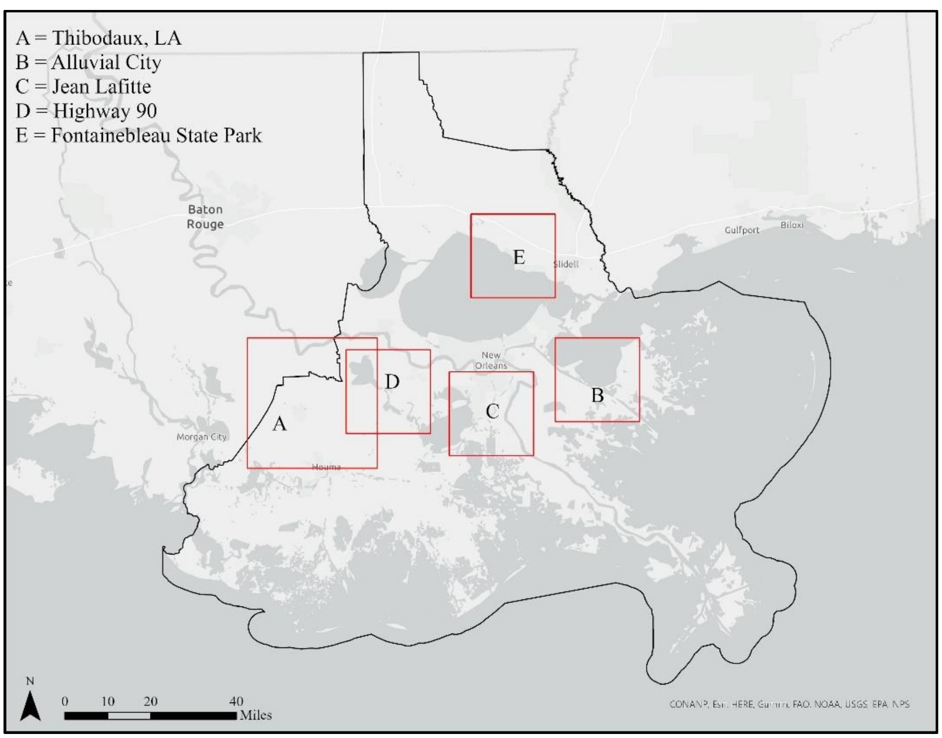

Figure 34. Locality analysis overview

The following figures represent a close-up of five separate locations, along with a discussion for each. Each location was chosen due to its unique environmental characteristics and the presence of flooding in each dataset. Figure 35 denotes an area centered on Thibodaux, Louisiana, and a section of Bayou Lafourche. Of note, the red lines on the maps represent the study area boundary.

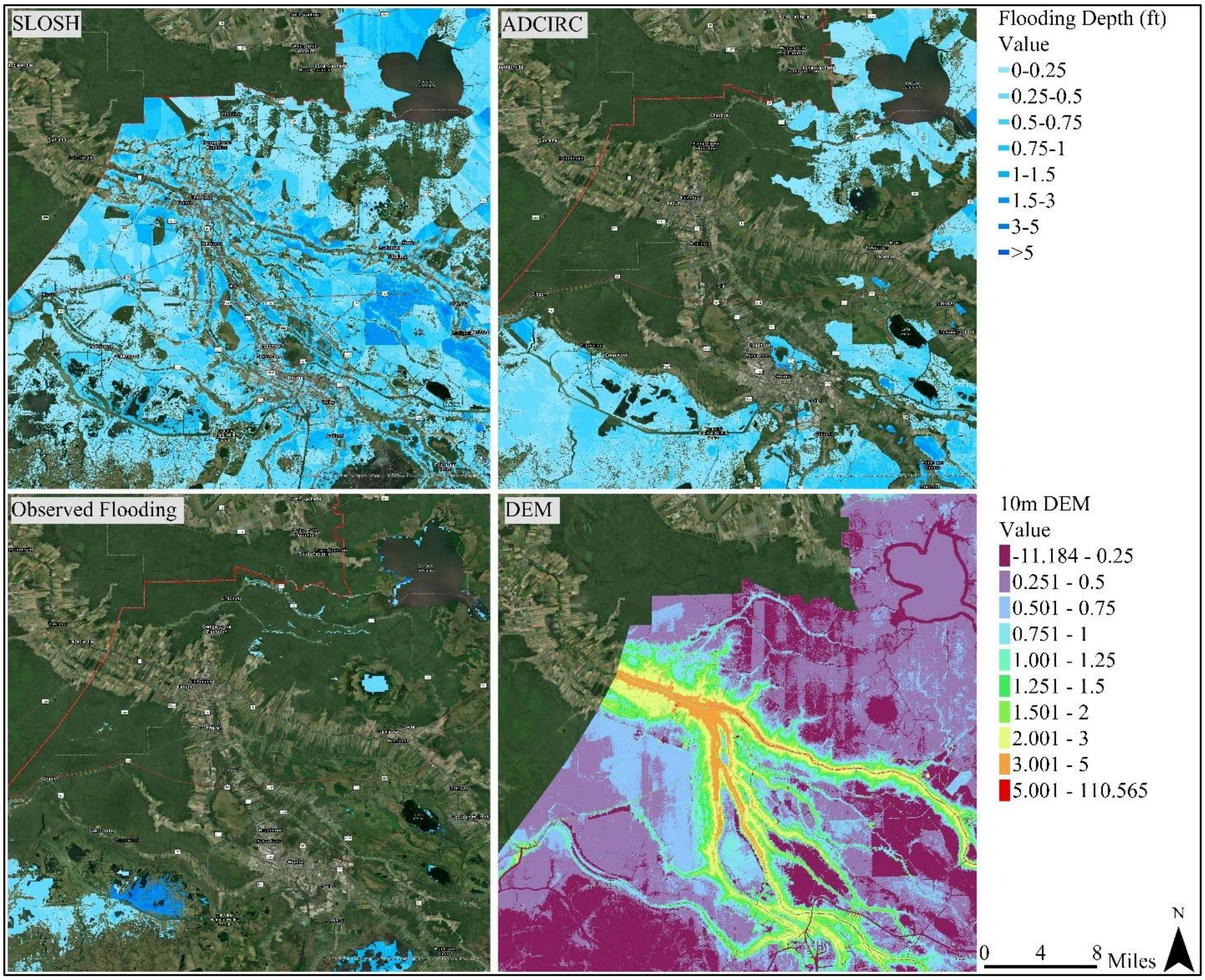

Figure 35. Thibodaux, LA and Bayou Lafourche flood analysis

As represented in the figure, SLOSH predicted heavy flooding in this section of Bayou Lafourche's basin. By comparing the models with the DEM used in this study, a correlation can be made between flooding and elevation. Essentially, SLOSH predicted a deeper surge in this area, which allowed its surge extent to be greater and cover more land in this section of the study area. Also note that both models do a poor job in predicting overall surge in this location. That could be due to the inland nature of this location, as it is nearly 50 miles from the coast. Figure 36 represents an area centered on Alluvial City, Louisiana.

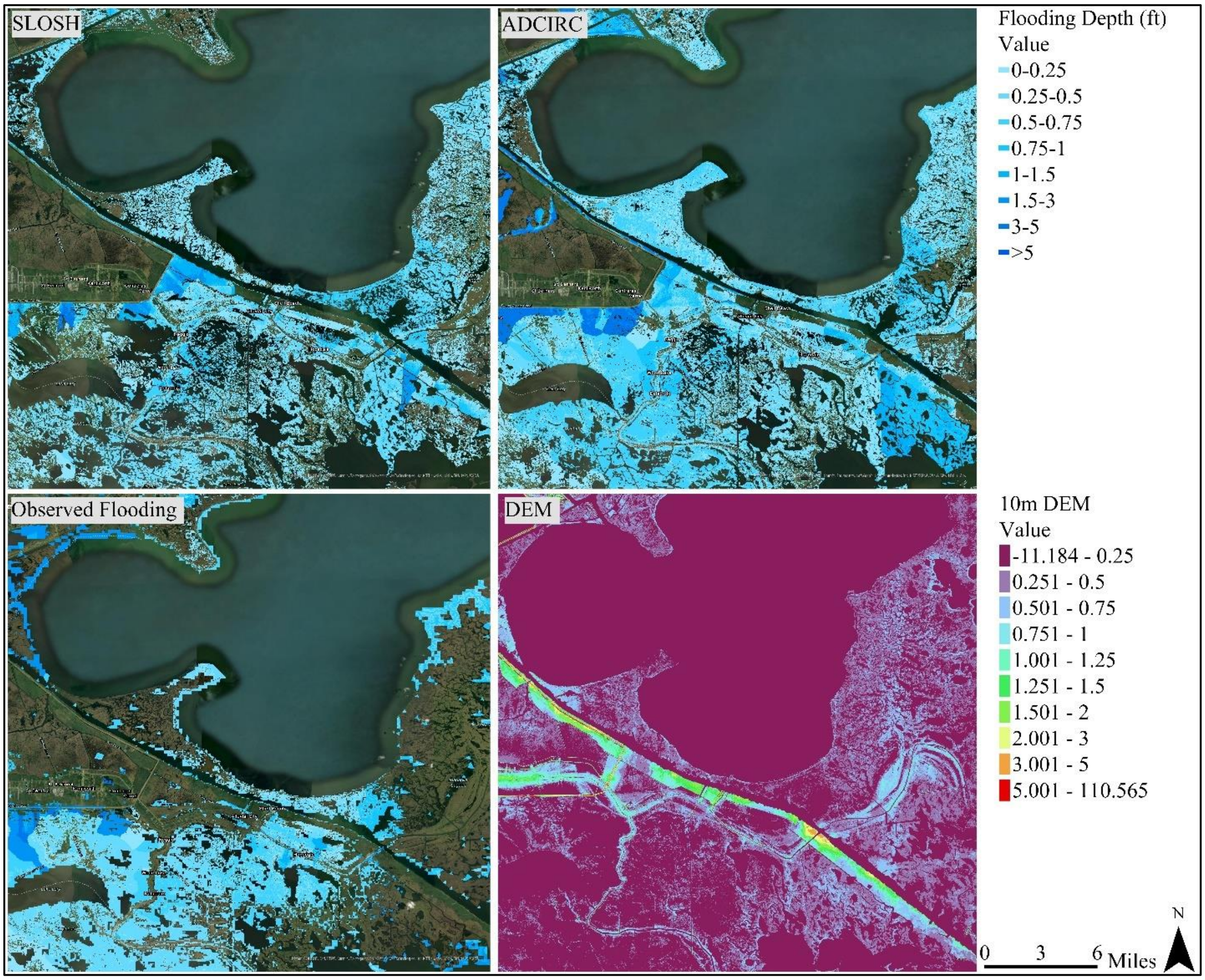

Figure 36. Alluvial City flood analysis

All three satellite imagery datasets contain flooding, with SLOSH showing less extent. All three datasets do follow the elevation as depicted in the center of each map which shows an outflow canal with a flood levee at higher elevation. On visual inspection however, ADCIRC appears to be the better model at predicting flood extent and depth, especially in the area south of

Alluvial City. Even though this area is closer to the coast, SLOSH does produce results similar to ADCIRC and observed flooding. Figure 37 represents Jean Lafitte, a small town just south of New Orleans.

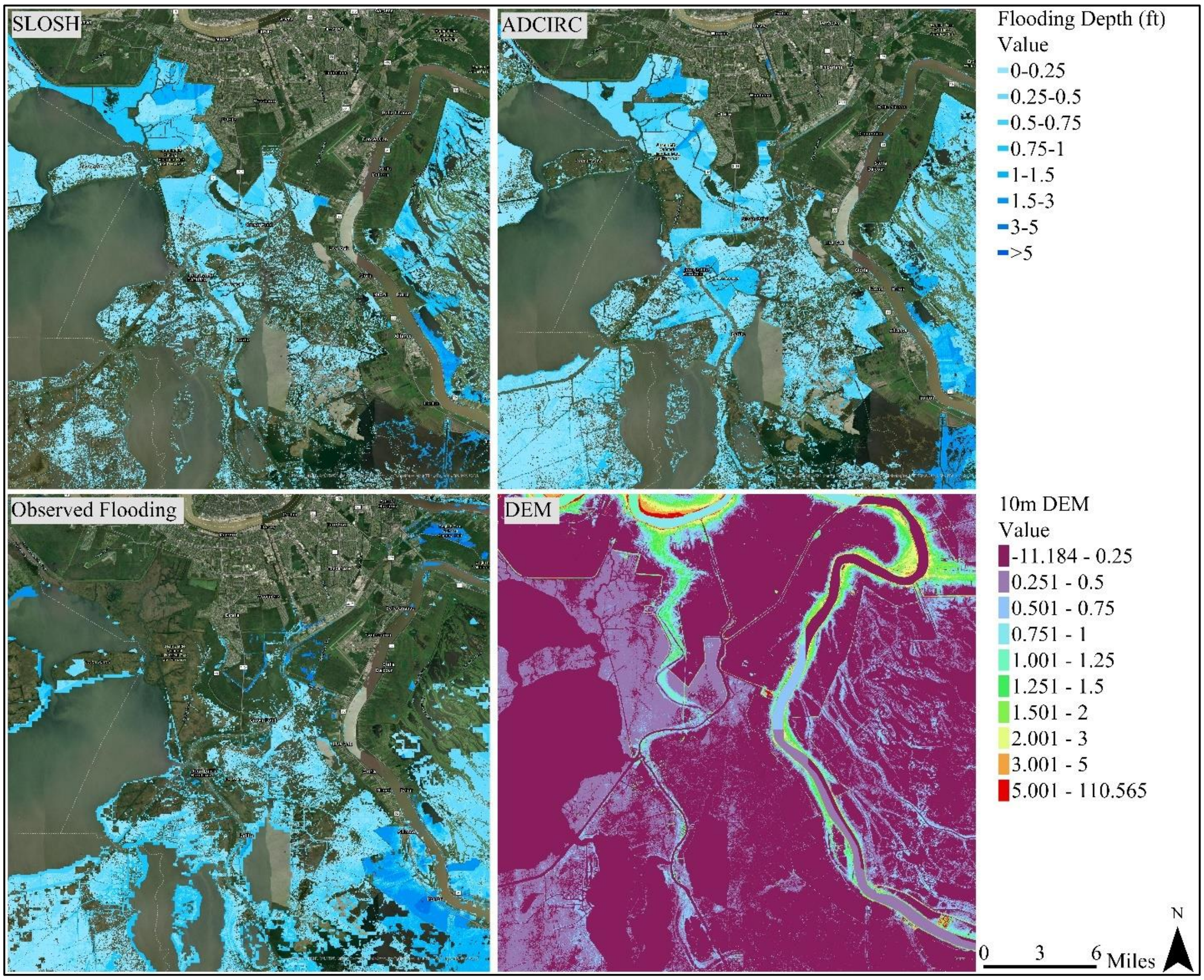

Figure 37. Jean Lafitte flood analysis

The two surge models accurately predicted zero flooding within the city of New Orleans, and that can be attributed to the levees surrounding the city. Both models also accurately predicted minimal flooding on the banks of the Mississippi as the higher elevation denotes in the DEM. The areas immediately north and west of Jean Lafitte show both models predicting heavy flooding, which is absent in observed flooding. Lesser flood depth due to higher elevation can be a simple reason, with the two models predicting inland lake surge as a more complicated one. Overall, ADCIRC's prediction is more in line with observed flooding, which saw SLOSH underpredict flooding in the southern area of the map. Louisiana State Highway 90 is the focus of figure 38, a highway that cuts through the southern part of the state.

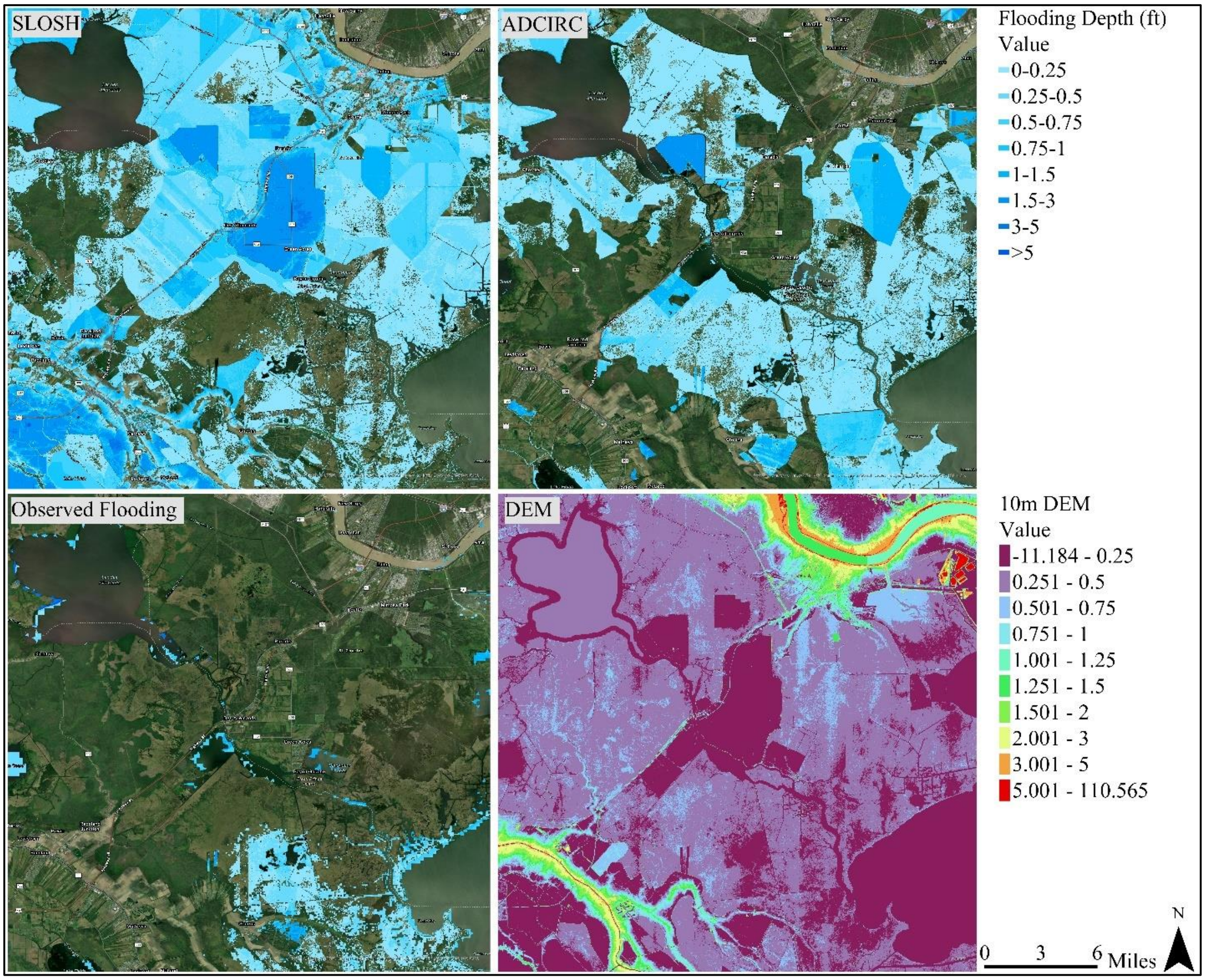

Figure 38. Highway 90 flood analysis

This location shows a significant difference in what the two models predicted against observed flooding. Scarcely any areas show observed flooding, where both surge models predicted heavy flood amounts with SLOSH predicting the heaviest and most widespread. It is clear that both models expected surge from the two large bodies of water to inundate the region.

ADCIRC's extent is contained locally to the two large lakes in the area, whereas SLOSH shows a complete flood of the entire map. However, the small area that did flood was not foreseen by SLOSH at all. ADCIRC, though heavily overpredicting flood in this location, did successfully predict the flood that was observed, another indication that ADCIRC was better in this specific location. Figure 39 represents the final flood analysis location, Fontainebleau State Park on the north side of Lake Pontchartrain.

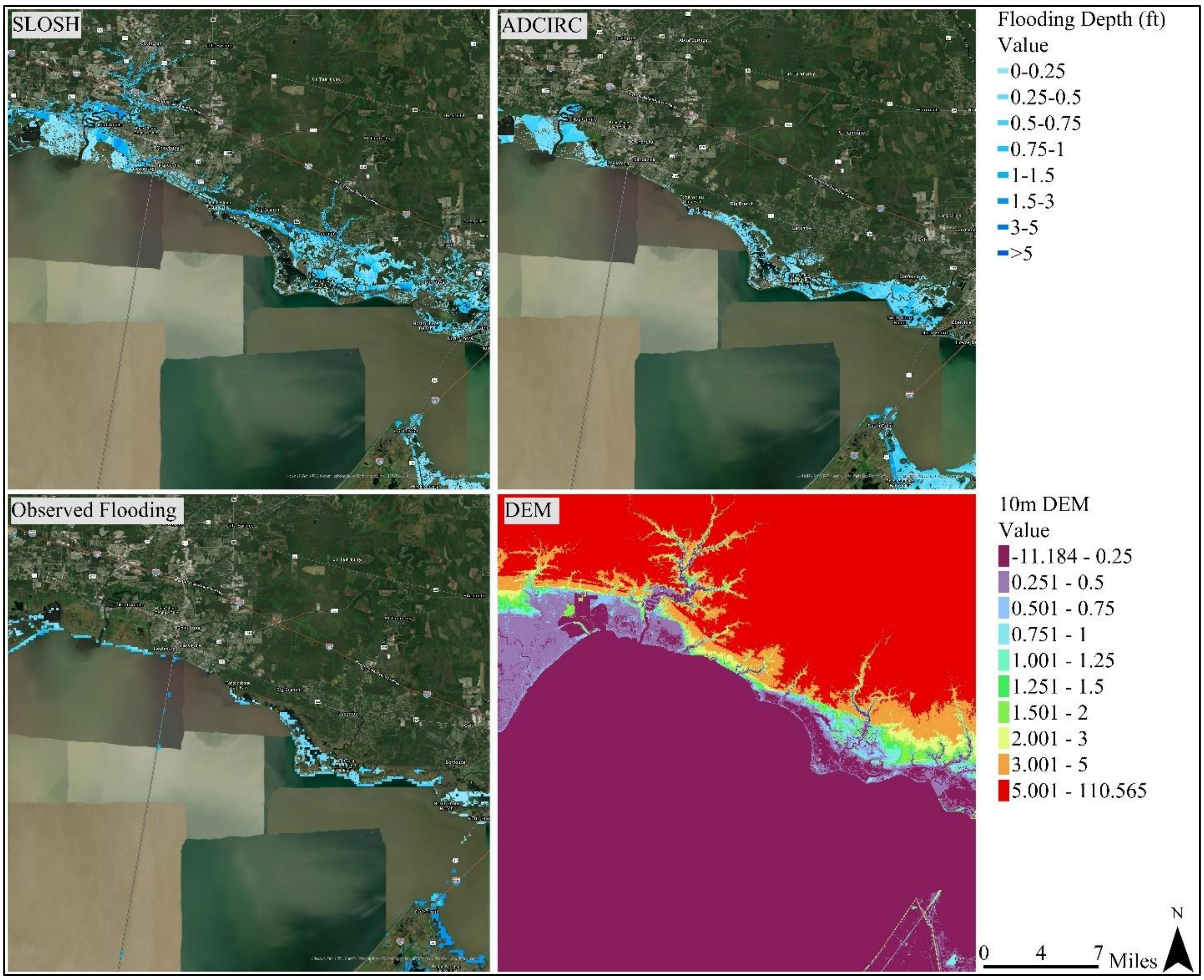

Figure 39. Fontainebleau State Park flood analysis

The north side of Lake Pontchartrain saw scarce flooding, which was adequately predicted, albeit in larger amounts. Observed flooding only shows areas in the very low-lying elevations near the banks of the lake as flooded, where the two models extended flooding further inland. SLOSH shows more flood depth and extent and goes deep into the various river and stream systems that flow into Lake Pontchartrain, which can be easily seen on the DEM. A visual inspection confirms ADCIRC was more accurate with flood predictions in this location.

Chapter 5 Discussion

This chapter discusses the outputs, limitations, and future research of storm surge modeling. Highlights include a discussion of the results that were discovered and the intricacies of studying storm surge. Then, discussions on limitations inherent to modeling environmental phenomenon. Next, further avenues of research are posed that can provide additional ways to analyze surge flooding. Finally, recommendations for future modeling techniques are posed that may be able to provide more accurate surge data.

5.1. Storm Surge Analysis

In terms of this thesis' hypothesis, flood extent was successfully predicted, albeit at a much larger scale. For flood depth, the two models underestimated depth, as hypothesized. The results in both extent and depth analysis show ADCIRC as the more accurate model overall, with SLOSH being more accurate at certain times along the temporal scale. Ironically, both models performed the best at advisory 14, just prior to landfall.

NHC uses SLOSH due to its quick simulation speeds and easy computational strain. SLOSH, though not as accurate in this particular study, produces accurate enough results for the evacuation of people in surge predicted areas. The NHC's reasoning for using SLOSH is also the reason ADCIRC is not employed by the NHC. High computational needs, which in turn costs more money, along with slower surge simulation results.

Overall, in this study, ADCIRC was the more accurate model predicting flood extent and depth. SLOSH appeared to show a significant lack of coastal flooding but did predict heavy inland flooding. ADCIRC was more in line with observed flooding, heavier coastal flooding with limited inland flooding. The biggest difference with SLOSH was the prediction of heavier surge from inland lakes and Bayou Lafourche spilling its banks and inundating its surroundings.

ADCIRC on the other hand predicted flood better than SLOSH but did anticipate more coastal flooding than what was observed and predicted some surge from inland lakes.

A reason for SLOSH's inability to adequately predict coastal flooding in this project could be attributed to its use of structured mesh grids. The structured mesh grids are a bad match for Louisiana's complex geography with its many barrier islands, marshes, and tidal swamps. SLOSH's mesh grids cannot vary resolution in those shallow coastal regions that inundate Louisiana's coastline, and as such, struggled to replicate surge in coastal areas. ADCIRC, with its unstructured mesh grids, can produce fine resolution which can capture Louisiana's coastal regions and bathymetry that can assist with surge predictions in those areas.

The goal in surge modeling is to provide necessary lead-time to issue evacuation orders. With evacuation orders being issued many days in advance of storm surge, long range prediction accuracy is required for proper evacuations, which hints at ADCIRC being the best model in that sense. Once other factors are included, such as time and money, SLOSH may be the more preferred model, depending on time and money tolerance.

5.2. Research Limitations

Limitations influence research projects, but also open opportunities for more thorough research in future endeavors. The large scale of this research project produced limitations in certain areas, and they are included below.

One of the aims of this research project is to compare observed flooding against storm surge model flooding predictions. No observed flooding dataset will be totally accurate due to the idiosyncrasies of how the data is acquired, like remote sensing in this case. Hurricane Ida's precipitation influenced and contributed to flooding throughout the study area, in addition to storm surge. This disclaimer acknowledges the fact that precipitation from Ida probably skewed the observed flooding data throughout this project.

Resolution differences in the data used in this project can also skew results. The surge models and the DEM are in 10 meters, whereas most of the flooding data is 90 meters. Using a flood dataset that is closer to 10 meters can improve results throughout the project. The observed flooding, with its coarse resolution, can skew flood areas throughout the study area.

5.2.1. Flooding Data

The ability to create an accurate dataset depicting flooding from an event is nearly impossible even with today's technology. Satellites and other remote sensing technologies have the ability to capture flood areas, but they do come with limitations. For instance, the observed flooding in this dataset was pieced together from several sources, sources that can contain false positives with flood acquisition, along with the inability to predict flood in heavily wooded areas that permeate the study area.

The observed flooding dataset compiled in this project lacked flood depth in the data. A somewhat experimental ArcGIS tool, FwDET, was used to create the depth in the flood data. The tool has produced accurate results in past research projects, but the accuracy of the flood depth derived and used in this project has not been studied.

5.2.2. Storm Surge Data

This research project focused on maximum inundation for both SLOSH and ADCIRC, mainly due to data availability. For SLOSH, maximum inundation surge means P-Surge, one of the three methods SLOSH predicts surge. However, the composite method is known as the best surge predictions method, meaning perhaps SLOSH would have produced more accurate results as such.

Both SLOSH and ADCIRC data for this research project represented maximum surge and water inundation based on the NHC forecast advisory time the data represents. For example, NHC advisory 9 data from both SLOSH and ADCIRC represents the maximum inundation the study area may receive based on the NHC track of the storm at advisory 9's release. The data does not represent flooding at the NHC advisory release date and time. The data does not necessarily represent surge at landfall either, but is a representation of maximum inundation, which could occur at any time, although periods near landfall are usually the occasion.

5.2.3. Environment

Predicting storm surge is an art, in a way in which it can never be perfect. No computer can possibly mimic the environment or simulate completely accurate storm surge. Surge models can incorporate a bevy of environmental parameters intended to simulate nature's storm surge and its effects. The very nature of being unable to simulate nature means that storm surge predictions will never achieve complete accuracy. Additionally, surge models create their predictions based on weather forecasting, which has errors in its own right. Ultimately, this research project provides a baseline showing which surge model performed best under the chosen circumstances. Tweaking one parameter even slightly, will give totally different outputs and interpretations to a different researcher.

The study area itself can be considered a limitation in this project. Louisiana's coastal geography lends itself to ADCIRC being the more accurate model due simply to the use of unstructured mesh grids. A separate study in an area with less complex coastal geography may make for a more thorough analysis, as one model won't necessarily start with a disadvantage.

5.2.4. Temporal Scale

The temporal scale in this project started about 24 hours prior to landfall. Considering evacuations are published multiple days in advance of a hurricanes landfall, a study of increased temporal scale may produce better results.

At the start of the temporal scale, evacuations are already in place, and for the most part, people have moved out of harm's way. A study comprising a temporal scale starting at 96 hours before landfall will give a better view of which surge model predicted better results compared to actual surge flooding. A 96 hour prior to landfall study will give better indications on whether SLOSH or ADCIRC's predictions were adequate with what surge the storm produced. Additionally, hurricanes can have drastic changes in movements in the final 96 hours, further complicating surge model study.

5.3. Future Research

A main area research can be expounded upon is in the flooding data. A few different avenues exist to acquire and/ or create more data. DFO posts excellent flooding datasets on its website depository but has not completed the Hurricane Ida data as of this thesis. It is unsure whether the flood data will ever be compiled by DFO for Ida but having a complete set of flood data without having to piece it together would be beneficial.

Using tidal and flood gauges throughout the study area would be an additional help to confirm the legitimacy of flood depth during this research. The city of New Orleans and other locations throughout the study area have numerous gauges that are designed to detect flooding levels, and that would have helped this project gauge how accurate the FwDET tool is.

Incorporating more storm surge models can give a wider scope of discovery and learning. SLOSH and ADCIRC are but two of numerous other surge models, and others such as SWAN, FAST, and Delft3D could give a greater sense of modeling accuracy. This author is unaware of research comparing multiple surge models past three, so expanding a surge comparison to five or more would be exciting and eye opening.

Finally, these results have real-world policy implications. Storm surge modeling directly drives evacuation orders that can potentially impact millions of citizens. While an evacuation order is simple on the surface, the decision to issue that order cannot be taken lightly. Plainly, an inaccurate surge prediction can lead to the wrong areas evacuated, and areas that were not under evacuation orders can be devastated. The logistical burden of evacuating millions of people can strain the socioeconomic balance of the locale under evacuation orders and can make such evacuation extremely difficult. Storm surge prediction must be accurate, but the evacuation orders that accompany it must be shrewd.

5.4. Conclusion

Storm surge will likely never be predicted perfectly, even with newer technologies like artificial intelligence taking hold. However, providing the public with surge models that can give an edge in accuracy is the goal. Though a conclusion was made of what surge model is more accurate for the particular time and place of this research project, that does not necessarily mean that the surge model is more accurate in every application, as the weather and environment change at a moment’s notice. Storm surge modeling is not an exact science, but research of this type can save lives, and that is worth the research time.

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Appendix A Surge Extent by Advisory

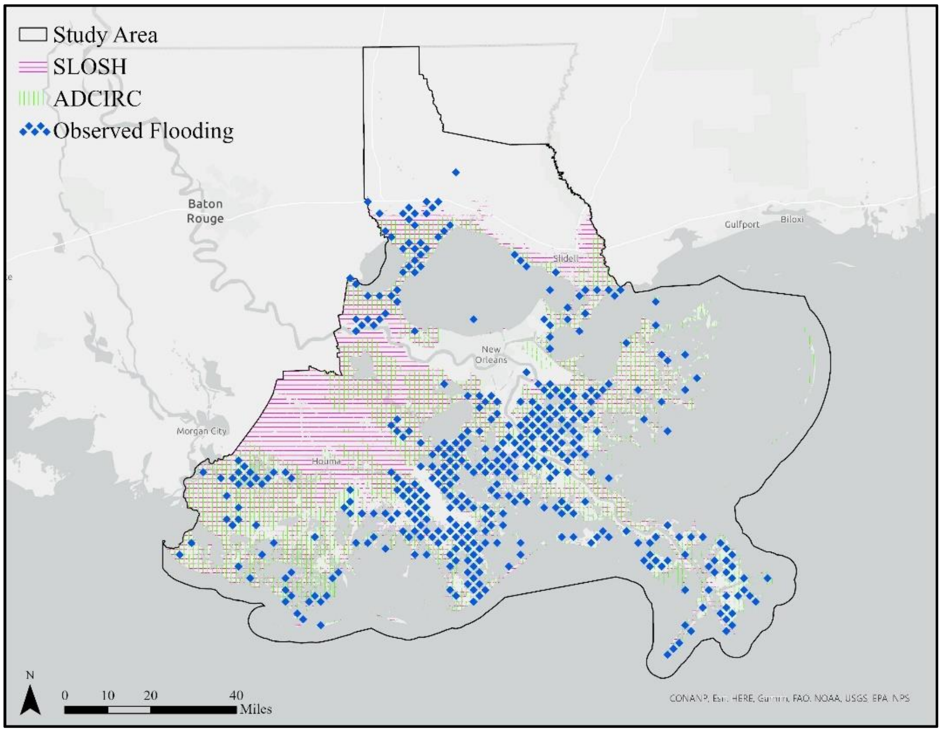

Figure 40. Advisory 10 Extent Analysis

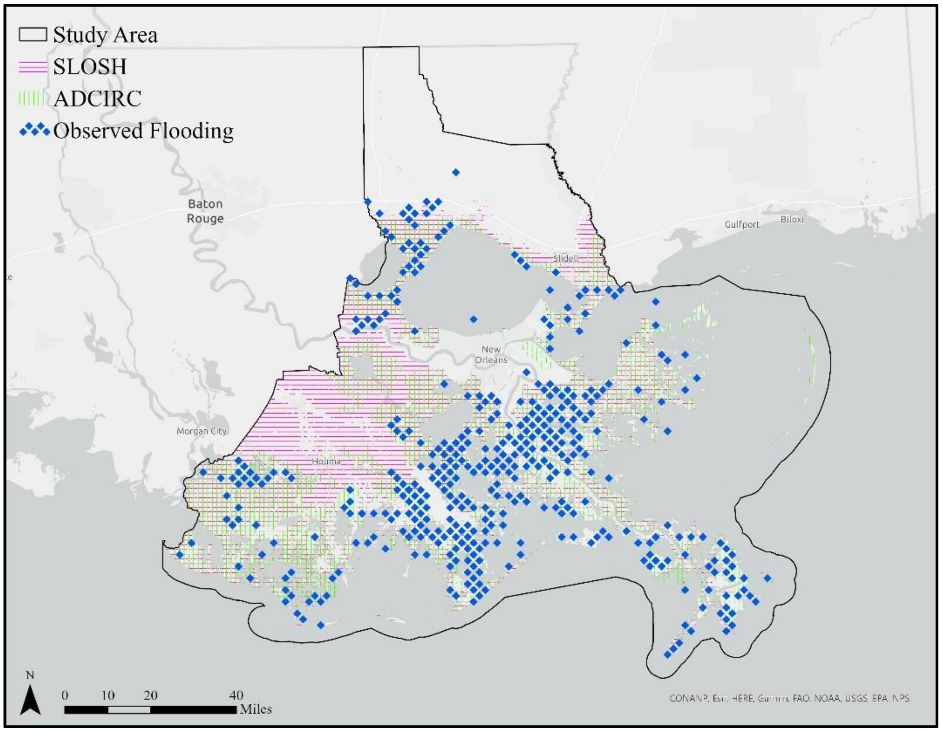

Figure 41. Advisory 11 Extent Analysis

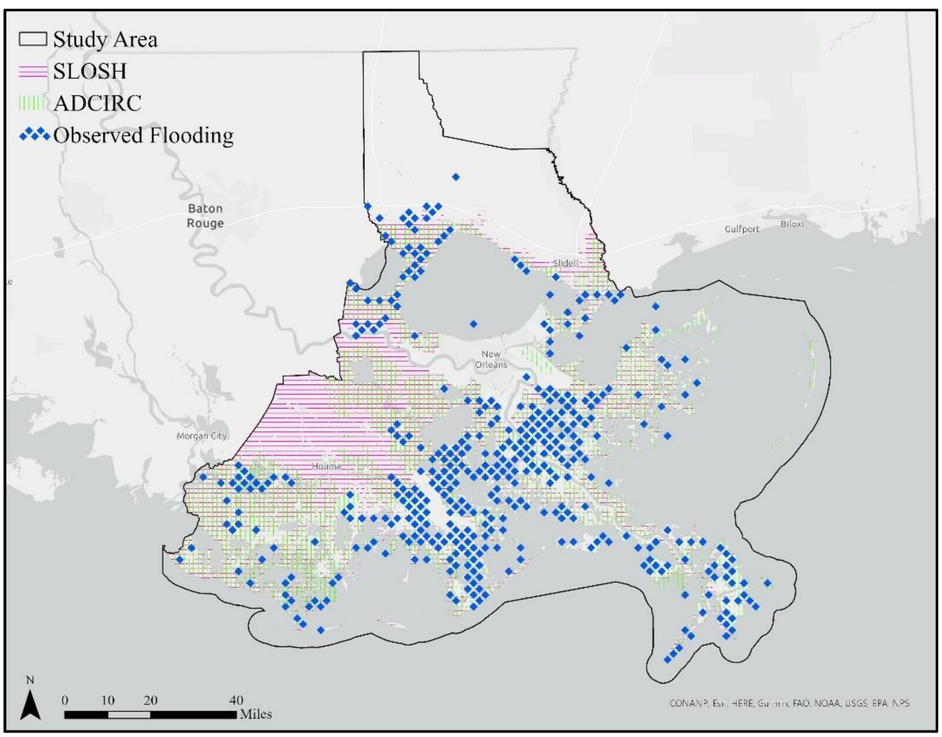

Figure 42. Advisory 12 Extent Analysis

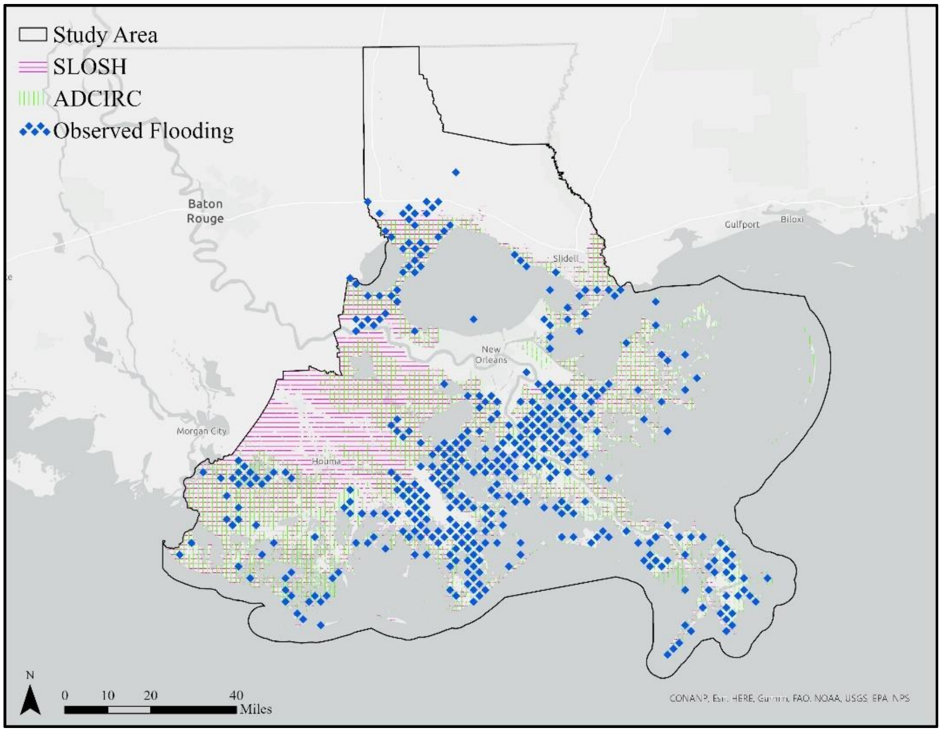

Figure 43. Advisory 14 Extent Analysis

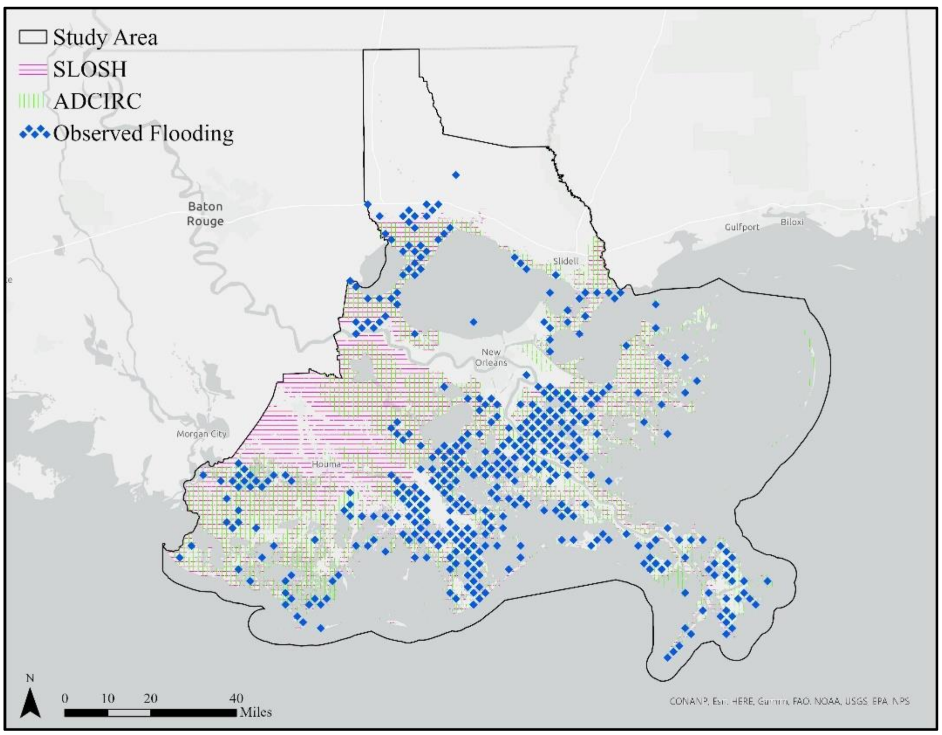

Figure 44. Advisory 16 Extent Analysis

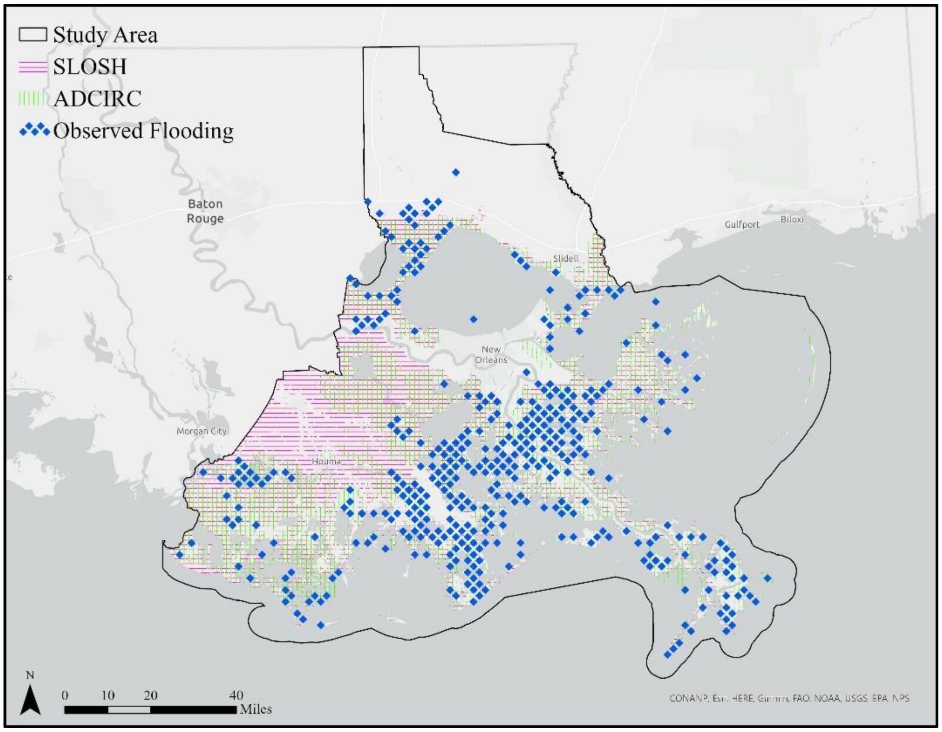

Figure 45. Advisory 17 Extent Analysis

Appendix B Surge Depth by Parish

Table 6. Depth difference chart in NHC advisories 9-14

Parish	Advisory	SLOSH Depth per ft	ADCIRC Depth per ft	Delta (ft)	Observed Depth (ft)
Jefferson	9	8.19	3.2	4.99	6.18
	10	8.52	3.93	4.59	
	11	6.75	3.75	3	
	12	8.88	4.61	4.27	
	14	6.21	5.28	0.93	
Lafourche	9	7.38	2.92	4.46	1.55
	10	6.51	3.47	3.04	
	11	3.48	2.7	0.78	
	12	7.38	4	3.38	
	14	3.96	4.11	-0.15	
Orleans	9	7.62	2.91	4.71	5.83
	10	8.55	4	4.55	
	11	8.61	4.87	3.74	
	12	8.61	4.77	3.84	
	14	3.15	4.9	-1.75	
Plaquemines	9	6.72	3.46	3.26	2.28
	10	7.74	4.16	3.58	
	11	7.74	5.27	2.47	
	12	7.02	5.13	1.89	
	14	5.1	5.57	-0.47	
St. Bernard	9	6.75	3.69	3.06	2.52
	10	8.82	4.7	4.12	
	11	8.85	5.52	3.33	
	12	6.66	5.29	1.37	
	14	3.42	5.5	-2.08	
St. Charles	9	8.1	1.81	6.29	4.73
	10	7.41	2.28	5.13	
	11	5.55	2.11	3.44	
	12	8.22	2.61	5.61	
	14	5.85	2.65	3.2	
St. John the Baptist	9	6.06	1.7	4.36	3.00
	10	6.12	2.13	3.99	
	11	4.47	2.08	2.39	
	12	5.91	2.71	3.2	

	14	3.24	2.64	0.6	
St. Tammany	9	4.98	2.63	2.25	10.1
	10	5.85	3.38	2.47	
	11	6.03	4.01	2.02	
	12	4.14	3.95	0.19	
	14	2.96	4.03	-1.07	
Tangipahoa	9	6.93	2.68	4.25	5.92
	10	7.89	3.24	4.65	
	11	7.47	3.7	3.77	
	12	6.36	3.9	2.46	
	14	4.08	4.12	-0.04	
Terrebonne	9	7.65	2.73	4.92	1.75
	10	5.52	1.64	3.88	
	11	2.9	1.3	1.6	
	12	4.56	1.44	3.12	
	14	1.3	1.25	0.05	

Table 7. Depth difference chart in NHC advisories 15-17

Parish	Advisory	SLOSH Depth per ft	ADCIRC Depth per ft	Delta	Observed Depth (ft)
Jefferson	15	6.42	5.75	0.67	6.18
	16	5.07	5.54	-0.47	
	17	4.47	5.32	-0.85	
Lafourche	15	6.84	4.28	2.56	1.55
	16	2.84	2.68	0.16	
	17	2.78	2.13	0.65	
Orleans	15	2.6	5.01	-2.41	5.83
	16	2.26	4.55	-2.29	
	17	2.12	2.41	-0.29	
Plaquemines	15	3.78	5.27	-1.49	2.28
	16	2.56	4.34	-1.78	
	17	2.62	3.57	-1.05	
St. Bernard	15	3	5.67	2.67	2.52
	16	2.84	4.5	-1.66	
	17	2.68	3.11	-0.43	
St. Charles	15	5.94	2.99	2.95	4.73
	16	6.12	2.98	3.14	
	17	4.59	2.84	1.75	
St. John the Baptist	15	2.98	3.43	-0.45	3.00
	16	3.09	3.07	0.02	

	17	1.82	2.23	-0.41	
St. Tammany	15	1.76	4.2	-2.44	10.10
	16	1.76	4.15	-2.55	
	17	1.6	3.75	-2.15	
Tangipahoa	15	3.9	5.04	-1.14	5.92
	16	4.77	4.51	0.26	
	17	2.9	4.43	-1.53	
Terrebonne	15	1.02	1.31	-0.29	1.75
	16	0.78	1.04	-0.26	
	17	0.98	1.02	-0.04	

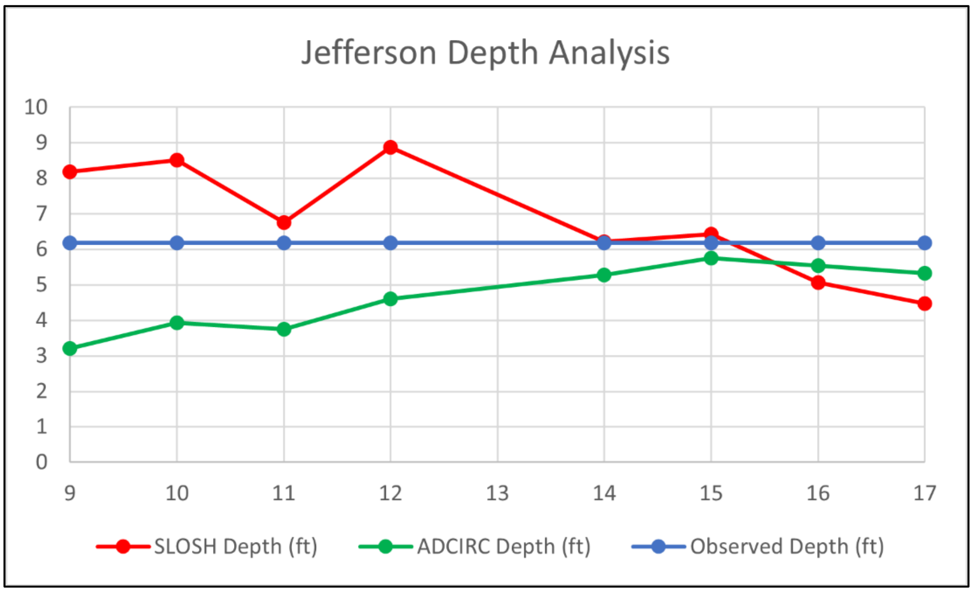

Figure 46. Jefferson Parish Depth Analysis

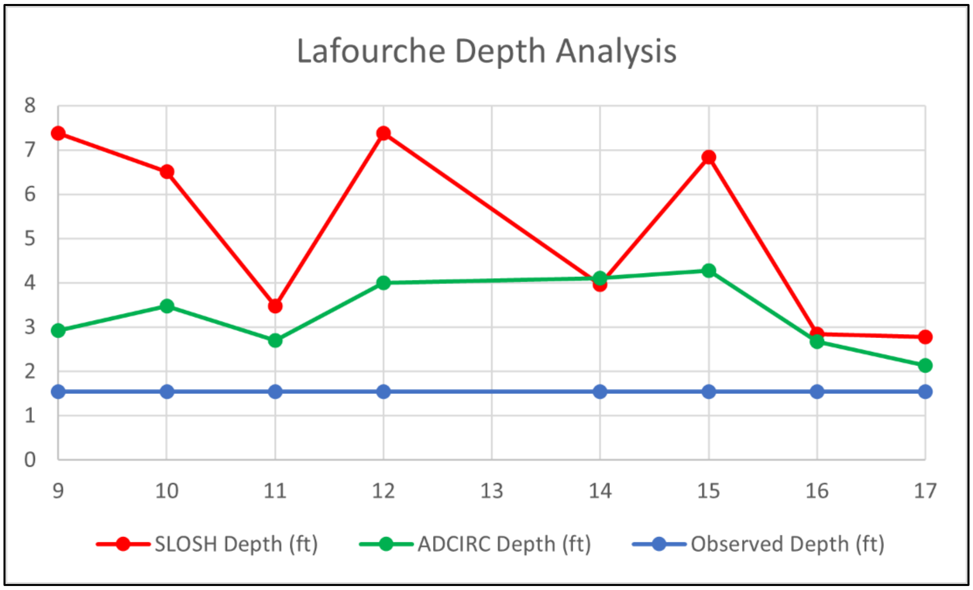

Figure 47. Lafourche Parish Depth Analysis

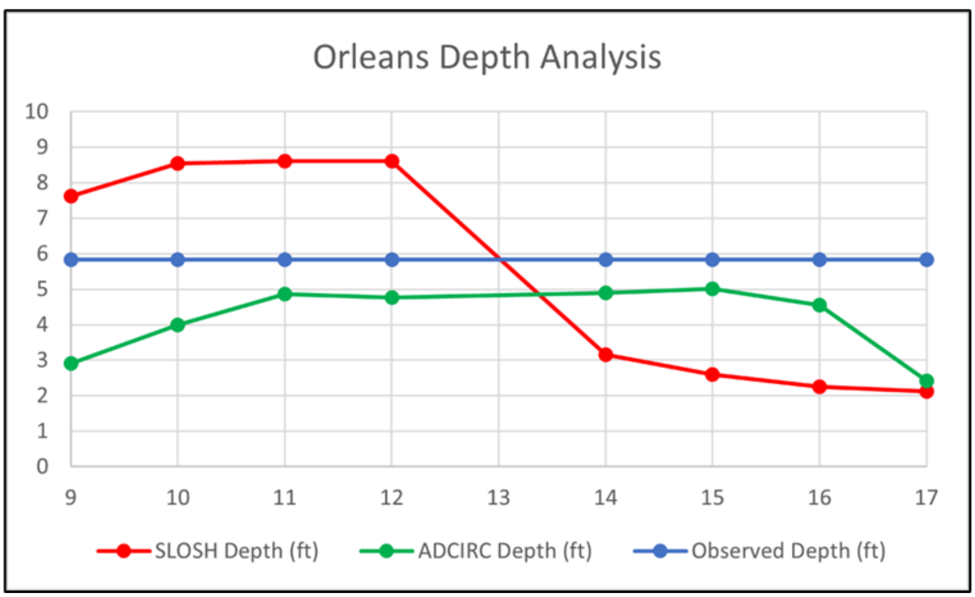

Figure 48. Orleans Parish Depth Analysis

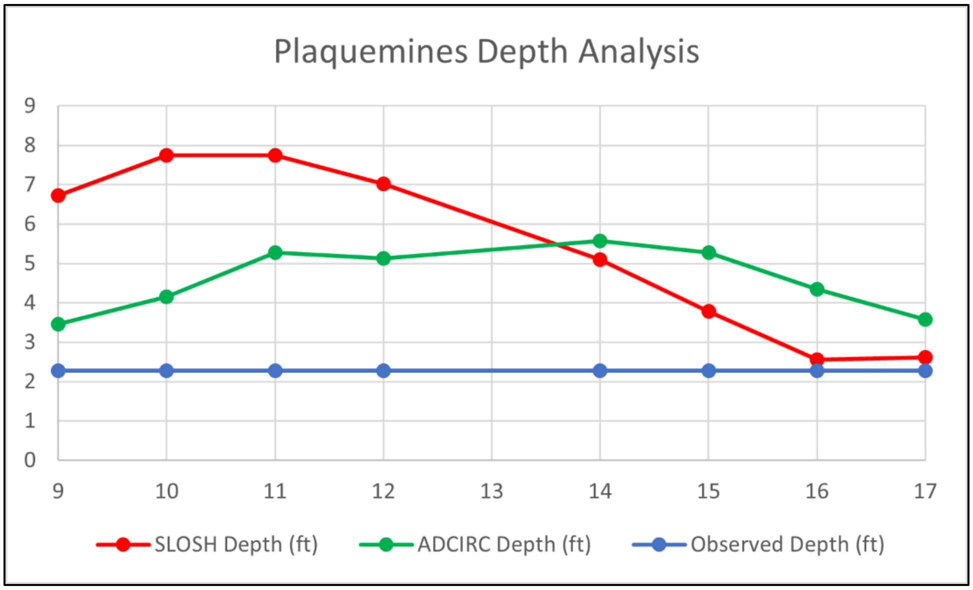

Figure 49. Plaquemines Parish Depth Analysis

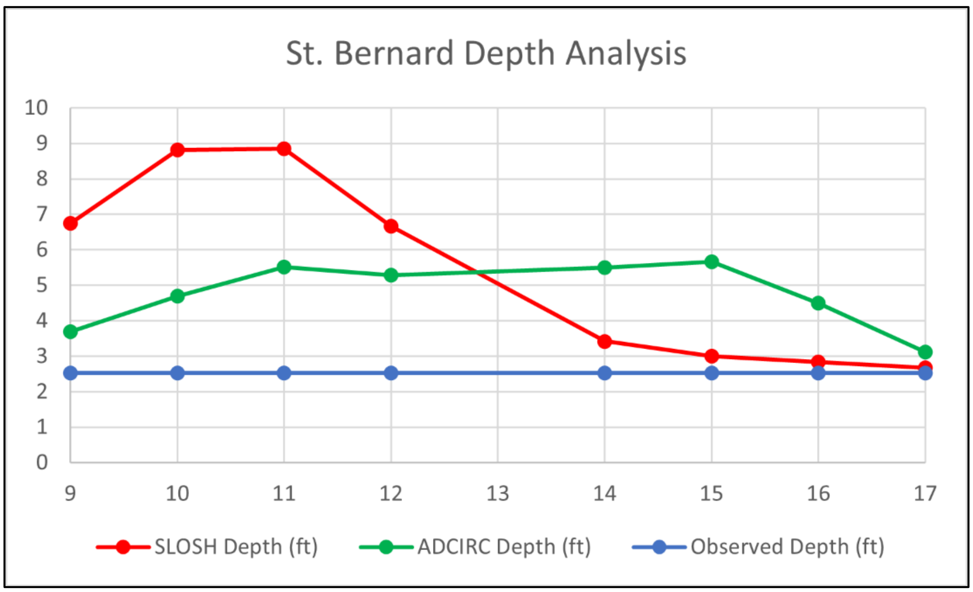

Figure 50. St. Bernard Parish Depth Analysis

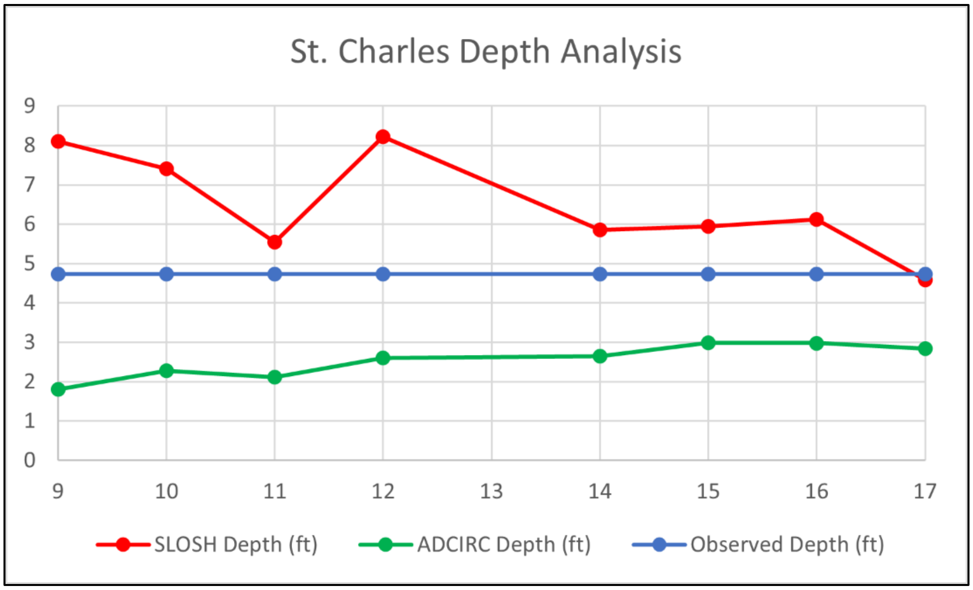

Figure 51. St. Charles Parish Depth Analysis

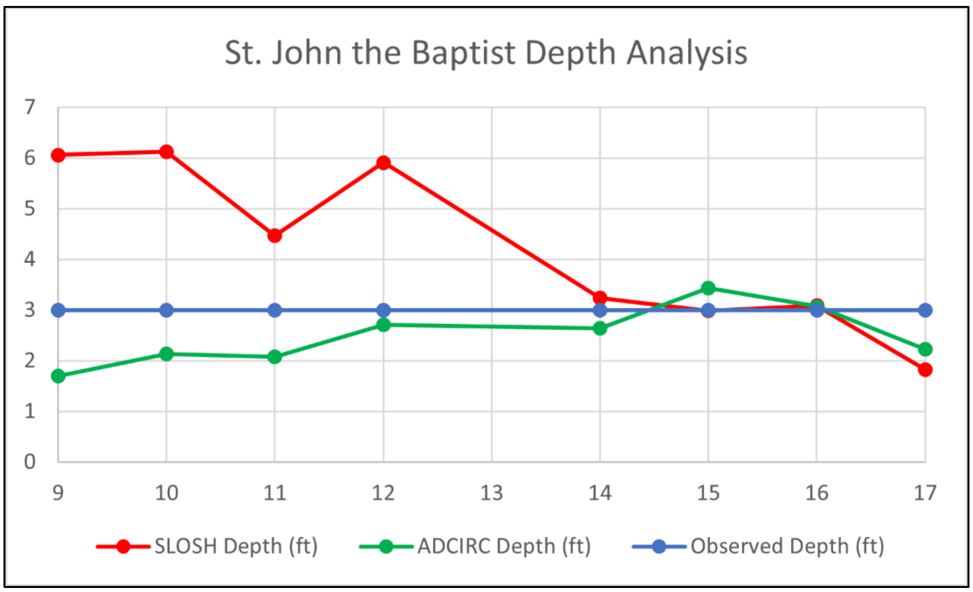

Figure 52. St. John the Baptist Parish Depth Analysis

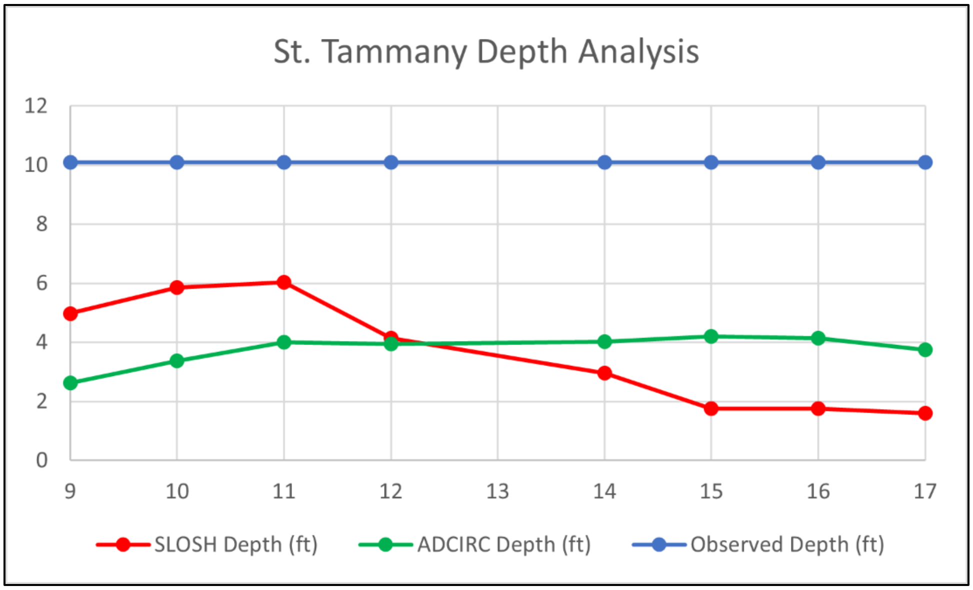

Figure 53. St. Tammany Parish Depth Analysis

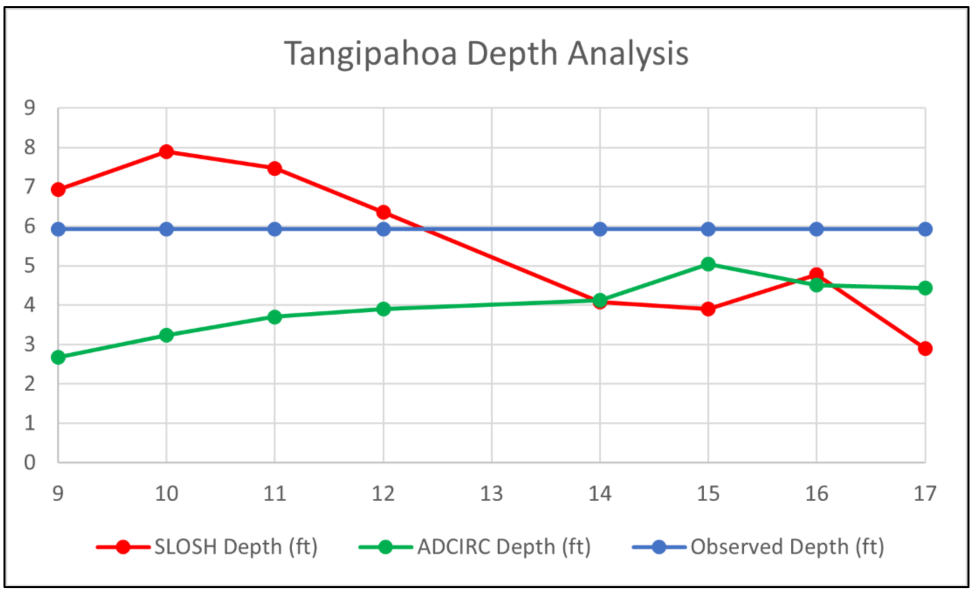

Figure 54. Tangipahoa Parish Depth Analysis

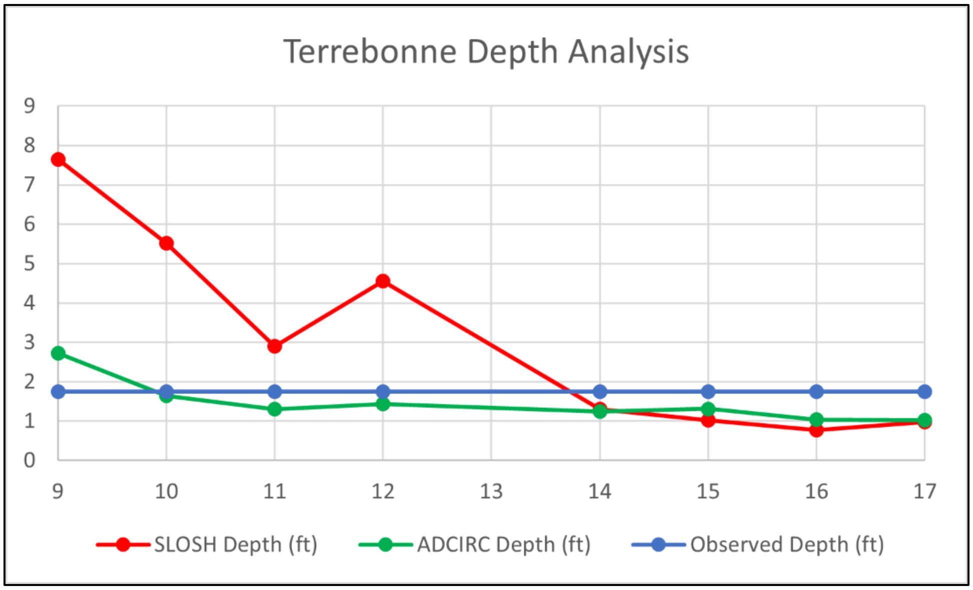

Figure 55. Terrebonne Parish Depth Analysis

Appendix C Surge Depth by Advisory

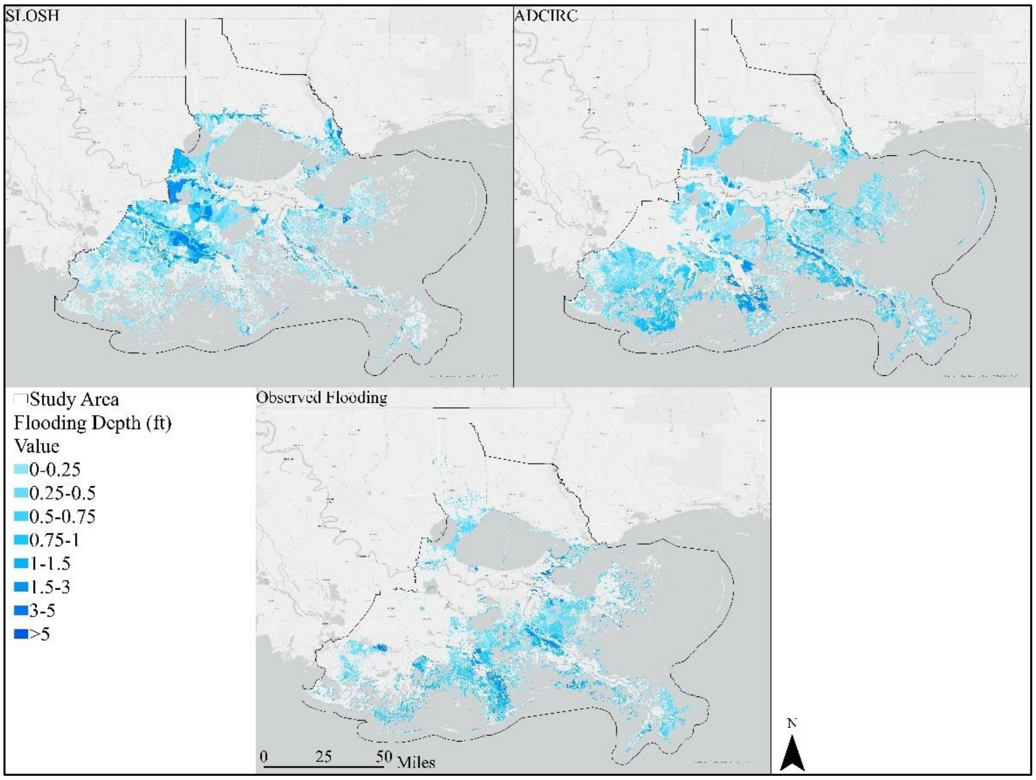

Figure 56. Depth Analysis for NHC Advisory 10

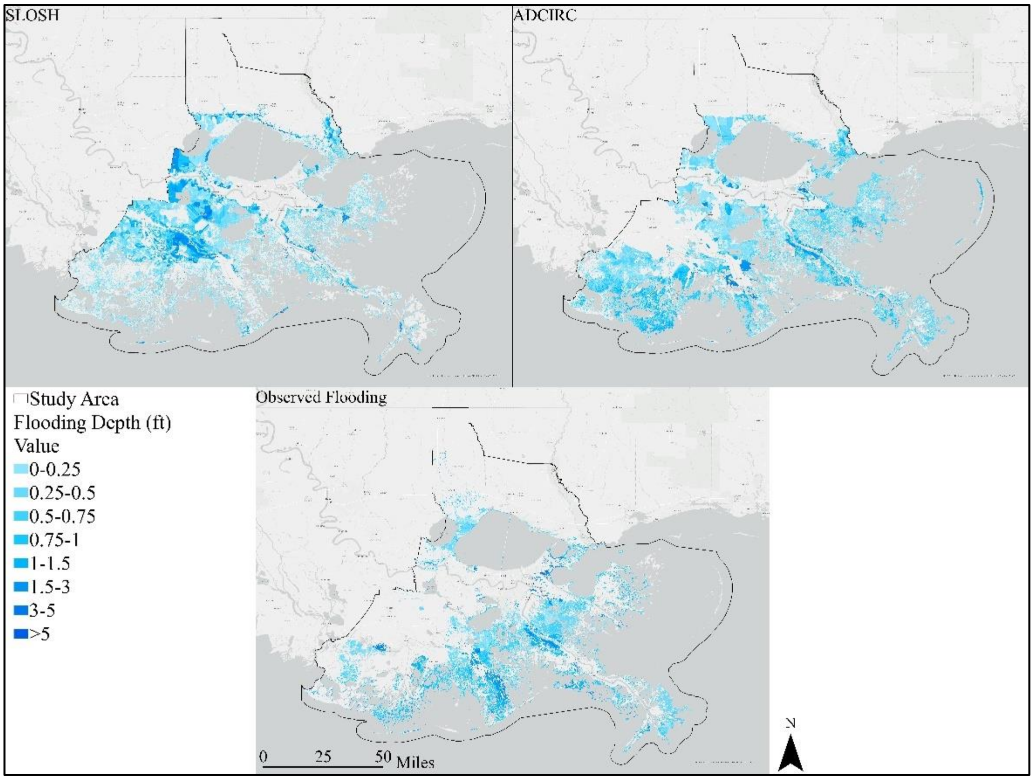

Figure 57. Depth Analysis for NHC Advisory 11

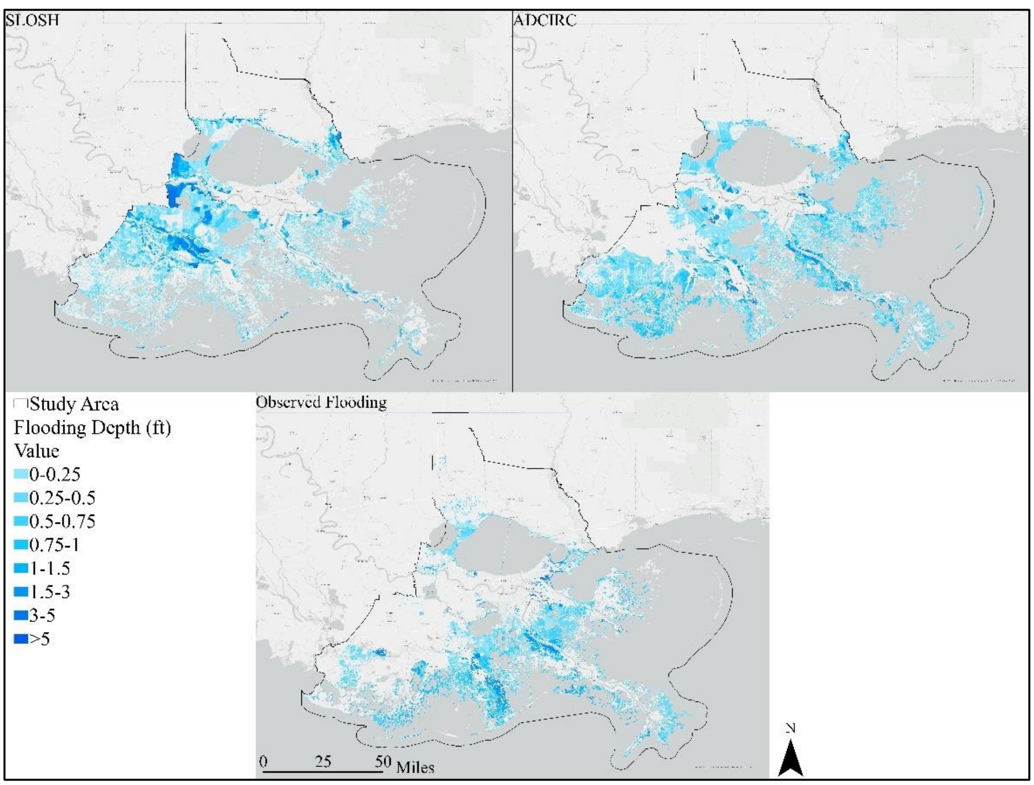

Figure 58. Depth Analysis for NHC Advisory 12

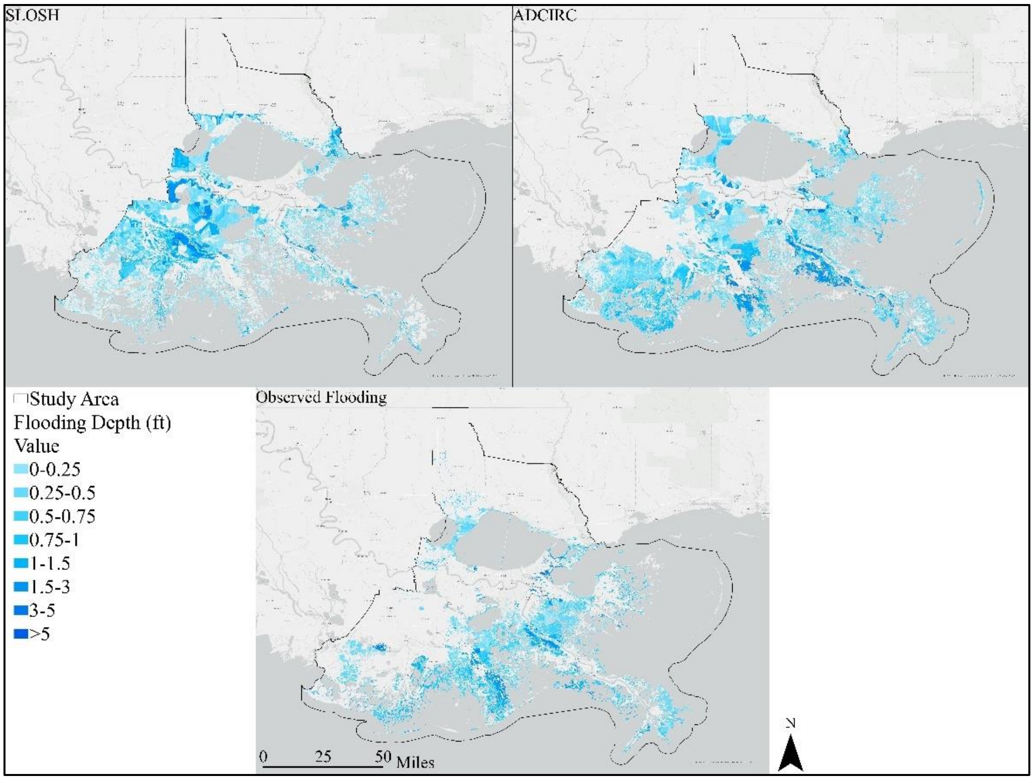

Figure 59. Depth Analysis for NHC Advisory 14

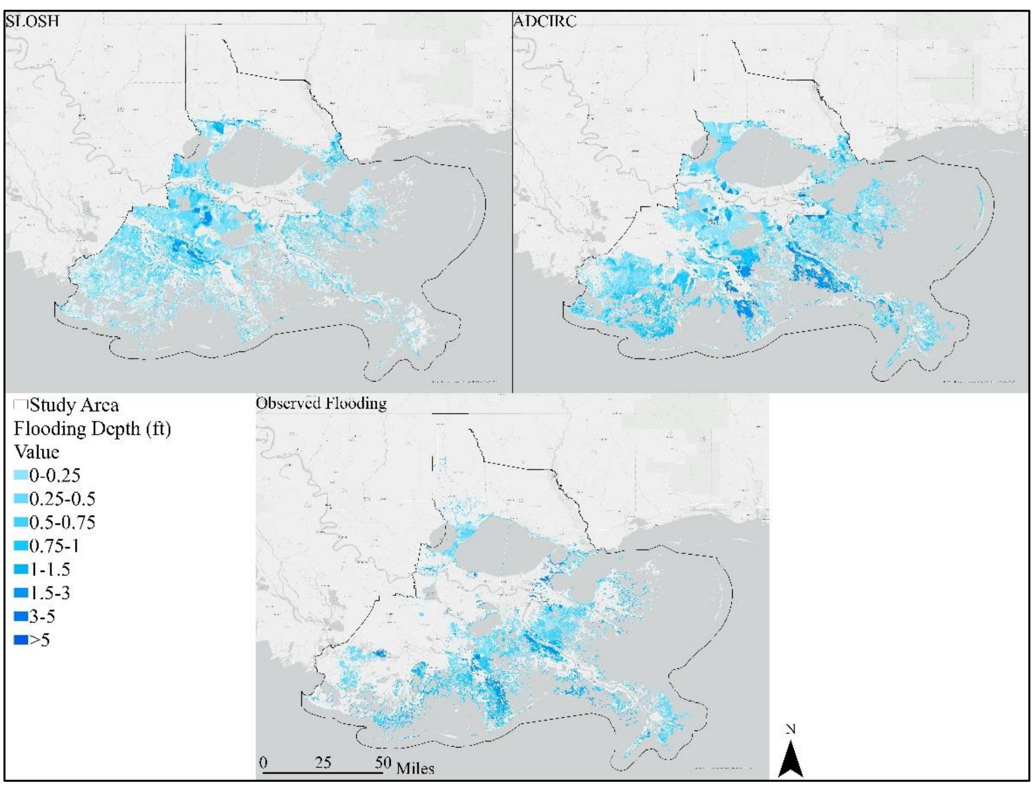

Figure 60. Depth Analysis for NHC Advisory 16

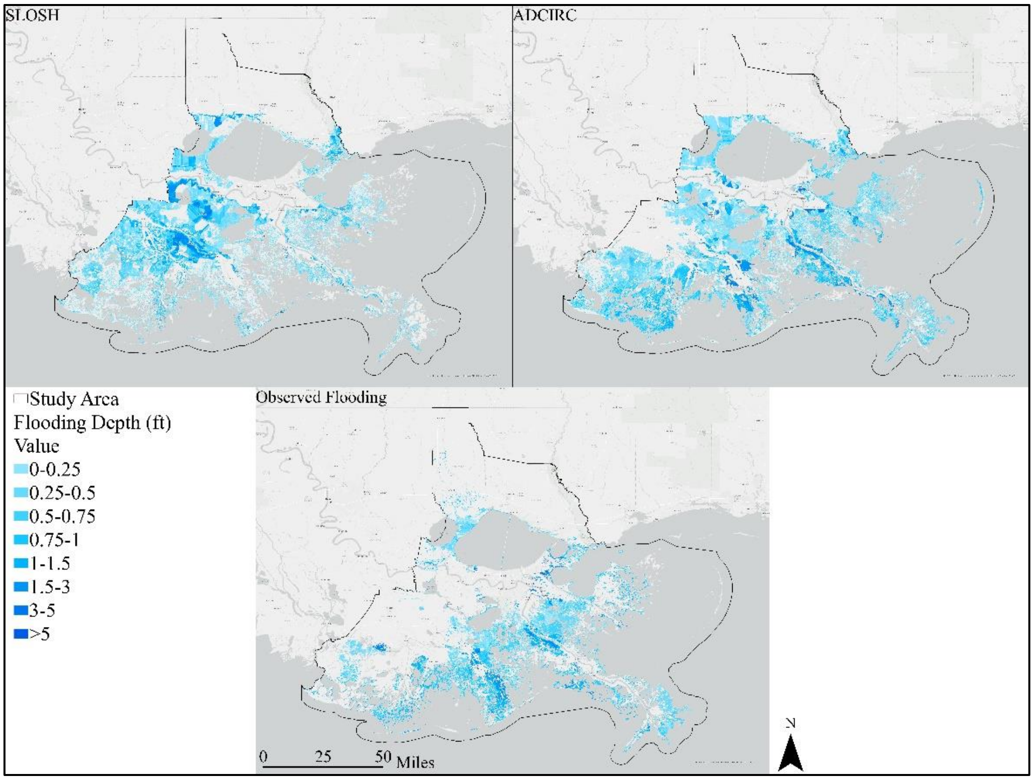

Figure 61. Depth Analysis for NHC Advisory 17