A HISTORICAL HURRICANE DATABASE FOR COASTAL LOUISIANA.

Development and population of a historical hurricane database, to validate a rapid surge forecasting model.

Bachelor Thesis
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SUMMARY

Since hurricane Katrina (2005) flooded large parts of New Orleans and coastal Louisiana, a high demand for fast and accurate hurricane surge forecasting models and tools has been developed. Van den Berg (2008) developed the beta version of a rapid hurricane surge forecasting model eSURF. Furthermore, during hurricane Ike in 2008 eSURF predicted lower maximum water levels then were actually observed in coastal Louisiana. Therefore Lin (2009) adjusted eSURF by adding the Integrated Kinetic Energy parameter to improve eSURF predictions for hurricanes with a large wind span.

The main objective of this thesis was to develop an organized historical hurricane database that can give quick insight in maximum water levels that occurred during historical hurricanes. Another objective of this thesis was to validate the rapid hurricane surge forecasting model eSURF with the water level observations stored in the historical hurricane database. The main research question of this thesis is: *How accurate are the predicted maximum water levels of eSURF for historical hurricanes passing coastal Louisiana or near coastal Louisiana?*

The first result of this thesis is a historical hurricane database that contains meteorological and water level data for coastal Louisiana observed during hurricanes. The hurricanes included in the database: *Lili (2002), Ivan (2004), Cindy (2005), Dennis (2005), Katrina (2005), Rita (2005), Humberto (2007), Gustav (2008), Ike (2008 and Ida (2009).* The following hurricanes are selected based upon criteria: (1) *a hurricane should have at least category 1 strength on the Saffir-Simpson-Hurricane-Windscale,* (2) *have a track within 200 Nautical Miles of the state Louisiana* and (3) *occurred between 1999 and 2009*. The basic hurricane characteristics, water level observations, total daily precipitation and wind speed vector grids have been stored. The data quality of information stored in the historical hurricane database is discussed in this report.

The second result of this thesis is that the maximum water levels predicted by eSURF have a mean relative error of 37.2%. This error exceeds the mean error of the SLOSH model with 17.2%. The report includes validation of the historical hurricanes: *Ida* (2009), *Ike* (2008), *Gustav* (2008), *Rita* (2005) and *Katrina* (2005). eSURF has been validated based on 25 eSURF prediction points and 25 observations stations. Table 0-1 illustrates the overview on eSURF's accuracy. eSURF best predicted hurricane Ike (28.2%) and Ida (29.8%), based upon mean error. The most in-accurate predictions were made for hurricane Rita (48.7%). Although, Katrina (44.8%) and Gustav had similar mean relative errors (45.4%).

Only 2.4% of the stations of eSURF are validated, due to limited amount of available maximum water level observations. When using the results of this validation, some care has to be taken into account as the results may not be representative for eSURF's general accuracy. The results of this thesis are only representative for the available and suitable 2.4% of the prediction points.

TABLE 0-1: OVERVIEW ON ESURF'S ACCURACY

	[ft]	[%]
Maximum error	6.48	166.7
Mean error	2.03	37.2
Minimum error	0.04	1.4

PREFACE

A high need for fast and accurate hurricane surge forecasting models and tools has been developed, since the deadly hurricane Katrina (2005) flooded large parts of New Orleans and coastal Louisiana. Therefore Van den Berg (2008) and Lin (2009) developed a rapid hurricane surge forecasting model eSURF. A validation of the model was needed to evaluate eSURF maximum surge level prediction capabilities.

This report describes the development and filling of a historical hurricane database. Furthermore, it describes the method and results of the validation of the model eSURF. Both the database and the validation method and results are discussed.

This thesis is written in order to complete my bachelor program Civil Engineering at the University of Twente. Furthermore, this thesis supports Haskoning Inc.'s hydraulic engineers and future interns at Royal Haskoning with the further development of eSURF or other surge forecasting models for coastal Louisiana. The research has taken place at the department Coastal & Rivers of Royal Haskoning at Nijmegen from the 5th of July till the 5th of October 2010.

I would like to thank Ries Kluskens (Haskoning Inc, New Orleans) for his guidance and supervision during this bachelor assignment. Although I have never met him in person, he provided me with useful feedback by phone and e-mails. Next, I would like to thank Kathelijne Wijnberg. She provided me with useful feedback during the research proposal and interim report. Furthermore, for assisting me in the visa application process I would like to thank: Maartje Wise and Mathijs van Ledden.

I hope this database and validation aids future interns at Royal Haskoning in the process of improving eSURF and developing models for rapid storm surge prediction.

Rinse Joustra

Nijmegen, 10th of October 2010

CONTENTS

1 INTRODUCTION

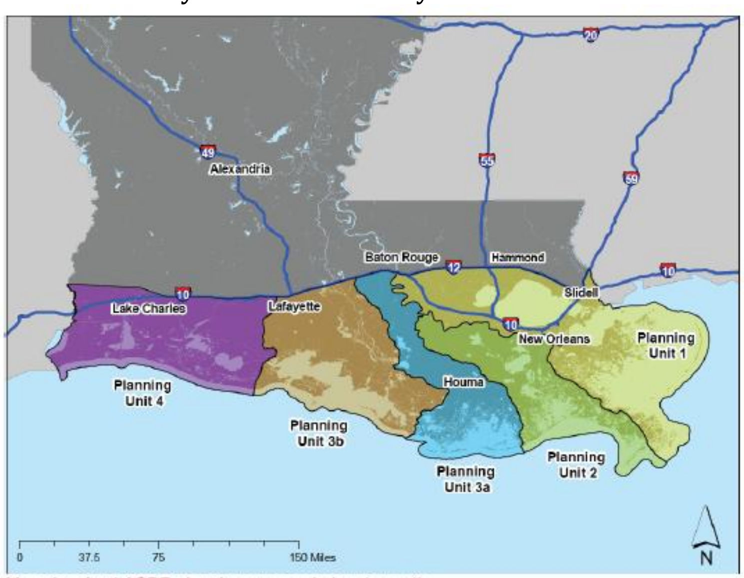
1.1 BACKGROUND

New Orleans is the largest city in the state of Louisiana in the U.S.A. The city is located on the south-east coast of this state. In the vicinity of the city flows the Mississippi river, the largest river in the U.S.A. The river passes the city to the west and meets the Gulf of Mexico to the south east of the city. New Orleans and coastal Louisiana have been exposed to hurricanes for centuries. There are two main reasons why New Orleans is vulnerable to hurricanes.

1. Coastal Louisiana (including New Orleans) is subsiding (or sinking). The settlement of the ground level occurs due to consolidation of soils and groundwater pumping. The natural counterbalancing effect of the subsidence is the supply of new sediment due to flooding of the Mississippi river. However, this supply is prevented by the major flood control structures build upstream of the river. Therefore some parts of the city are already situated below mean sea level and continue to subside (American Society of Civil Engineers Hurricane Katrina External Review Panel, 2007).

2. The Mississippi river discharge can strongly increase, when a hurricane passes its 3,1 million square kilometer total area of drainage.

The most recent devastating hurricane was on 29th of Augustus 2005. It crossed the southeast coast of Louisiana with a hurricane force of category three. The high surge levels (in Lake Borgne and Lake Pontchartrain) and the subsequent failure of the New Orleans Levee system caused a 80% flooding of the city of New Orleans. At this moment the United States Army Corps of Engineers (USACE) is rebuilding the levees and floodwalls around New Orleans. The 600 km long system needs to be ready before the 2011 hurricane system and will provide the greater New Orleans area protection against a storm that may occur one in 100 year.



Map showing LACPR planning area and planning units

FIGURE 1-1: LACPR PLANNING AREAS (UNITED STATES ARMY CORPS OF ENGINEERS (CORPS) NEW ORLEANS DISTRICT, 2009-2010)

The Louisiana Coastal Protection and Restoration Planning area (LACPR) is defined by the USACE to their coastal zone for restoration and protections purposes against hurricanes. Figure 1-1 illustrates the LACPR areas.

Overall, the USACE is responsible for the safety and protection of the people and buildings in the greater New Orleans area and has to operate several storm surge barriers during storm events. The closing and opening of these surge barriers mainly depends on the development of water levels and wave heights over time. In the United States the National Hurricane Center (NHC) monitors all storm developments on the Atlantic Ocean during Hurricane season (1 June to 30 November). After a tropical storm develops, the NHC issues every 6 hours forecasts of air pressure, storm size (diameter), forward speed, wind speeds and the expected storm track. About 24 to 36 hours prior to landfall, the National Weather Service (NWS) uses these parameters in their SLOSH (Sea, Lake and Overland Surges from Hurricanes) computer model to forecast maximum water levels. Besides SLOSH the USACE also uses the results of a modified version of the advanced circulation model (ADCIRC) SL15 grid. This numeric model computes water levels based on predicted wind speeds, air pressure, bathymetry and surface roughness of an area.

In 2008 Royal Haskoning developed and introduced the use of a storm atlas. This atlas was developed by using more than 300 different “Hypothetical” Hurricanes that make landfall in the State of Louisiana. This Hurricane Surge Atlas is a useful tool during emergency operations. The data which is presented in the atlas shows the surge for hurricanes with different tracks, sizes, intensities and speeds. Looking up the hurricane that most resembles the approaching hurricane will give a quick first estimate of the surge levels that can be expected in the area of interest. Parallel to the development of the storm atlas, eSurf (experimental Surge Forecast) was developed. The beta version of eSURF has been developed by Van den Berg (2008) and improved by Lin (2009) in 2009. eSURF predicts the maximum surge levels based on the interpolation of surge levels from 152 hypothetical storms computed by Advanced Circulation model (ADCIRC). eSURF is basically a search engine and is used for fast maximum water level prediction during actual hurricanes. Both the storm Atlas and eSurf can be defined as rapid surge forecasting tools that help to provide quick insight in maximum surge levels caused by an approaching hurricane.

1.2 PROBLEM DEFINITION

At the moment there are only few tools available that can be used for fast and relatively accurate prediction of maximum water levels for coastal Louisiana. The model ADCIRC is a highly detailed numerical model, but has a long calculation time (+/- 6 hours). This calculation time is not favorable, because the hurricane parameters (for example; radius, maximum winds and pressure) can change rapidly over time. The model SLOSH is used for determining the location of the potential of flooding, instead of determining detailed inundation depths and water levels in specific regions.

The model eSURF has a short calculation time and uses 152 synthetically generated hurricanes by ADCIRC (eSURF). However, to better know the accuracy of eSURF’s maximum surge level predictions and for further development of the model, a validation of eSURF with historical hurricanes is required. In July 2010 eSURF has only been validated with maximum water levels observed during 5 historical storms, but Van den Berg (2008) and Lin (2009) have not used many observations stations in their validation steps. In addition, three of these five storms have been validated with maximum water level prediction calculated by another model ADCIRC.

At the moment the required data for validation is dispersed at many information sources and presented in a disorderly format. Therefore, an easy to access database with historical meteorological and water level data for coastal Louisiana is required to validate eSURF.

1.3 RESEARCH OBJECTIVE

The main objective of this research is to validate the maximum surge level forecasting model eSURF. However, an organized dataset is needed to validate the model. The outcome of this validation could contribute in improving eSURF. The specific objectives are:

- Development and population of a historical hurricane database (HHD) with meteorological and observed water levels during hurricanes;
- Using historical meteorological and maximum observed water level data measured during hurricanes, to validate the rapid hurricane surge forecasting model eSURF.

1.4 RESEARCH QUESTIONS

The development and population of the historical hurricane database is essential to validate eSURF. Therefore question 1, question 2, question 3 and question 4 assist in the process of database development. Question 5 addresses the second specific research objective.

Main question: How accurate are the maximum water levels predictions by eSURF for historical hurricanes passing coastal Louisiana or in its vicinity?

Question 1: What kind of meteorological and water level information is, next to time and location, required for the validation of the model eSURF?

Question 2: What kind of meteorological and water level information is available?

Question 3: How can the historical meteorological and water level data best be organized to easily be accessed and used during the validation process?

Question 4: What is the quality of the observed meteorological and water level data used in the validation process?

Question 5: How accurate does eSURF predict the maximum water levels in coastal Louisiana for historical hurricanes?

Coastal Louisiana is defined as the LACPR Area (visualized in figure 1-1). The USACE defined this area as the main zone of Louisiana influenced by storm surge. In addition, the eSURF prediction points are located within this area.

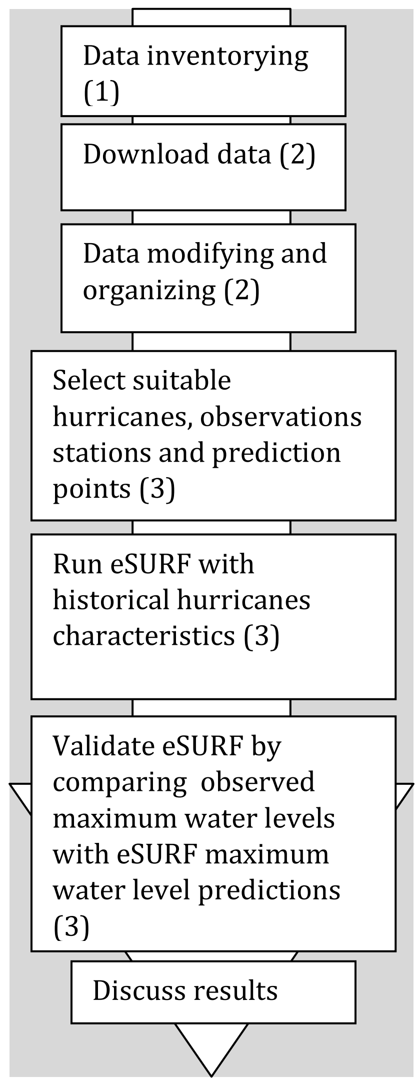
1.5 RESEARCH APPROACH

This research consists of three main parts.

1. Inventorying the required data for the validation of eSURF. (Q1,Q2)
2. Download and storage of this data in the Historical Hurricane Database. (Q3)
3. Validation of eSURF(Q4,Q5).

1. In order to know what needs to be stored in the database a literature review was executed to determine the minimum data requirements for the validation of eSURF. The data required for validation was written in the report of Berg v.d. (2008), Lin (2009). Next, hurricanes have been selected to be used for validation of eSURF. The hurricanes included in this thesis have been selected based upon the following criteria:

FIGURE 1-2: RESEARCH APPROACH.



- **Categorized as a hurricane category 1 on the Saffir Simpson Hurricane Wind Scale**. In general, lower intensity storms cause relatively small storm surge compared with the hurricane force winds.
- **Made landfall within a 200 Nautical miles of the Louisiana state boundary.** Hurricane Ike did not made landfall in Louisiana. However, due to its large span of wind it caused a storm surge at a large distance from the hurricane center. To also include hurricane Ike in the dataset this criteria has been used.
- **Occurred between 1999 and 2009.** Due to the amount of meteorological and water level data available and the accuracy of the observed water levels, only hurricanes within this time frame have been used to store in the hurricane database.

Many governmental organizations publish hurricane and observed water level information their websites. Through telephone conversations and emails with various engineers of Royal Haskoning in New Orleans and a thoroughly search on the internet the sources of data were identified. For all the found sources and observations stations a data inventory has been made.

2. The data collection process started once this inventory for each source of data was completed. Data was collected by simply downloading the information from the websites and by doing requests by email to the various organizations that had data available for the time period of the selected hurricane. The data was restructured and organized in such a way that all information was stored in the same format in order to easily compare and analyze the available information. Because all information has a spatial component (location along the Louisiana coastline) some of the information was mapped in order to visualize any spatial relationships between the data.

3. The final phase of this research is the validation of eSURF with the data stored in the HHD (Historical Hurricane Database). To validate eSURF; first, suitable hurricanes observation stations and prediction points have been selected out of the dataset based upon spatial and temporal criteria. For each observations station, a nearby eSURF prediction point has been selected based on its spatial component. The criteria is a 9000 feet distance between both locations. The hurricanes have been selected based upon the maximum amount of water level observations available and the landfall location of the hurricane. Next, a dataset with maximum surge levels predictions has been establish by running eSURF for all selected hurricanes. Comparing the maximum observed water levels during the time of a hurricane event with predicted maximum water levels by eSURF will give insight in the prediction capabilities of eSURF. However, the quality of the used meteorological and observed water level data for validation of eSURF can cause differences between the eSURF maximum water level predictions and maximum observed water levels. Therefore the accuracy of the water level measurements, the completeness of this dataset, influence of subsidence on maximum water level observations, and local terrain influences have been investigated.

The accuracy of the water level measurements has been investigated by searching the organizations website on their view on the quality of their measurements. The influence of missing data on the validation of eSURF has been reduced by examining the historical hurricane database on missing water level observations during the hurricane landfall. By use of a literature review the influence of subsidence on coastal Louisiana has been estimated. After a first validation run, the locations of the both the prediction point and observations station have been closely examined with a relatively high resolution map of coastal Louisiana for those eSURF prediction points that had an error exceeding 2.00 feet. Due to the limited amount of time of this thesis, the prediction points with an error less than 2.00 feet have not been examined. The observations station that did not represent the eSURF prediction points have been excluded from list of stations used for the final validation of eSURF. The results of this last validation have been visualized in this report.

The accuracy of eSURF is defined as the overall accuracy for all selected hurricanes and as the accuracy for the individual hurricanes. In this research accuracy is defined by the mean overall error (absolute and relative).In addition, under- or over-estimation is investigated with the use of a scatter plot. This scatter plot visualizes the relationship between the observed maximum water levels and eSURF maximum water level predictions. A regression line in this scatter plot will illustrate if eSURF over- or underestimates the maximum water levels. The coefficient of determination (R^2) determines how good the regression line fits the maximum observed water levels. Furthermore, the errors (in feet) for each prediction point have been visualized in histograms for the individual hurricanes.

1.6 OUTLINE

Chapter 2 introduces the model eSURF. This chapter briefly describes the model input parameters, an overview on the model processes and a view on the graphical user interface of the model. For more detailed information see also the thesis of (Lin, 2009) and (Van den Berg, 2008).

Chapter 3 describes the Historical Hurricane Database (HHD) development and population. In addition, it describes how it will benefit the main research objective of the historical hurricane database. The scope, and data requirements of the data within HHD is outlined in Section 3.1. The various sources and data formats that are included in the HHD are discussed in next section. Section 3.3 addresses data processing and the various issues with vertical datum's in the coastal region. The data visualization and data quality are discussed in the last two sections.

Chapter 4 describes the validation process, results and discussion. Section 4.1 describes the method used for validation. Selection process of the suitable stations, located near eSURF prediction points, and hurricane characteristics is described in this section. Furthermore, section 4.2 illustrates the result of the validation. An overview of eSURF accuracy and the accuracy for the individual hurricanes is stated in this section. Finally, the results are discussed in section4.3. The conclusion and recommendation of this thesis are written in chapter 5 and chapter 6.

2 ESURF

The rapid hurricane surge forecasting model eSURF predicts the *maximum surge level*, also called the *storm tide* or *maximum water level*[1] for locations in coastal Louisiana. The beta version of eSURF has been developed by Van den Berg (2008) and improved by Lin (2009). Lin (2009) improved the model because it lacked the capability to predict surge levels at points further away from the hurricanes track. This limitation was revealed when eSURF was used during hurricane Ike (2008). Hurricane Ike had a large span of wind. Lin (2008) integrated the Integrated Kinetic Energy (IKE) value. The IKE value takes into account the kinetic energy resulted from a large span of the wind field.

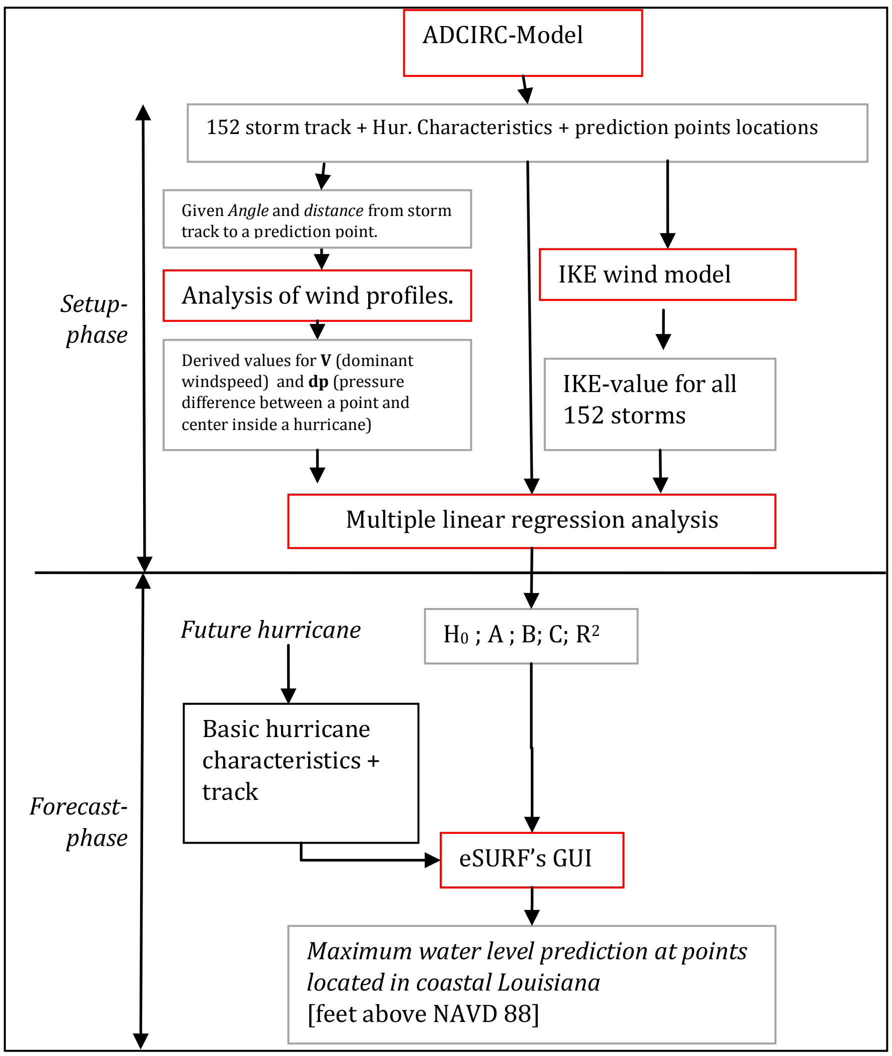


FIGURE 2-1: FLOW CHART OF ESURF

[1] Keep in mind that *Storm surge* is not the same as *maximum surge level.* For an explanation, see appendix B.

eSURF is basically a fast search engine. It can provide maximum water level estimation for a set of locations in coastal Louisiana. To predict the maximum water levels for a hurricane, the model searches in a dataset of pre-calculated (by ADCIRC) maximum water levels for locations in coastal Louisiana. However, as this dataset is extremely large this dataset needs to be prepared to reduce calculation time of eSURF. eSURF has two main phases; the Set-up phase and the *Forecast-phase*. The preparation of data is called the *Set-up phase*. The end user of the model only uses the Forecast-phase. A flow chart of the model is displayed in figure 2-1.

***Set-up* phase**

The first phase of eSURF is called the *set-up phase.* In this phase a dataset is prepared to be used to calculate the maximum surge level for a future hurricane in the second phase. This dataset is named the *prepared dataset* and is derived from the *preliminary dataset*. The *preliminary dataset* consists of four sub-data sets derived from the meteorological and water level data from the ADCIRC pre-calculated 152 hurricanes.

- The coordinates of the prediction points for which a maximum water level has been predicted by ADCIRC. The prediction points are located in coastal Louisiana.
- The theoretical hurricanes with their basic hurricane characteristics (tracks, minimum pressure, radius to maximum winds, central speed and Holland-B parameter) and the associated pre-calculated maximum water levels at the prediction points.
- The third set contains distance and angle values. The distance values represent the distance between the hurricane center and a prediction point. The angle values represent the angle between the track and a line between hurricane center and the prediction point.
- The final dataset contains the IKE values derived from the hurricane characteristics of the 152 synthetically hurricanes of ADCIRC.

$$H_{\max\ surge\ level} = H_0 + A \cdot V^2 + B \cdot dp + C \cdot IKE \cdot Log(r) \qquad (1)$$

Next to the preliminary dataset, equation 1 is used in this phase. $H_{\max\ surge\ level}$ represents the maximum water level at a prediction point of one of the 152 hurricanes calculated by ADCIRC. H_0 represents the stationary water level at a prediction point. The increase in water level due to wind shear is represented by $A \cdot V^2$. Where A is a calibrations parameter (like H_0) and the V represents dominant wind speed at a prediction point. Furthermore the influence of air pressure on storm surge is represented by $B \cdot dp$. B is a calibration parameter and dP represents the pressure difference between normal pressure at sea level (1013mBar) and the pressure at the center of the hurricane. The last part ($C \cdot IKE \cdot Log(r)$) is added by Lin (2009) to take the hurricane span of wind influence on storm surge into account. C is a calibration parameter, IKE represents the kinetic energy resulting from a moving air mass of a hurricane and r is the distance between the hurricane center and the prediction point.

Furthermore, the *preliminary* dataset and equation 1 are used to calculate the 4 coefficients H0, A, B, and C using the method of multiple-linear-regression. The coefficients with the highest R2 are defined for every prediction point and stored in the *prepared dataset*.

***Forecast* phase**

The second phase is the *Forecast-phase*. The basic hurricane characteristics can be imported in the Graphical User Interface (GUI) of eSURF. Figure 2-2 shows the GUI of eSURF. Next, eSURF calculates the maximum water level H_{model} for the prediction points with these hurricane characteristics and the *prepared dataset*. Hereby equation 2 is used. The black parameters are known (as they are stored in the prepared dataset). The blue parameters are the input parameters derived from the basic hurricane characteristics of a future hurricane. The green parameter is the output parameter, the maximum water level at a prediction point. The Holland B eSURF input parameter is required for the equation of calculation of dP. More detailed information about this equation can be found in the thesis of Lin (2009).

$$H_{model} = H_0 + A \cdot V^2 + B \cdot dp + C \cdot (IKE \cdot Log(r)) \qquad (2)$$

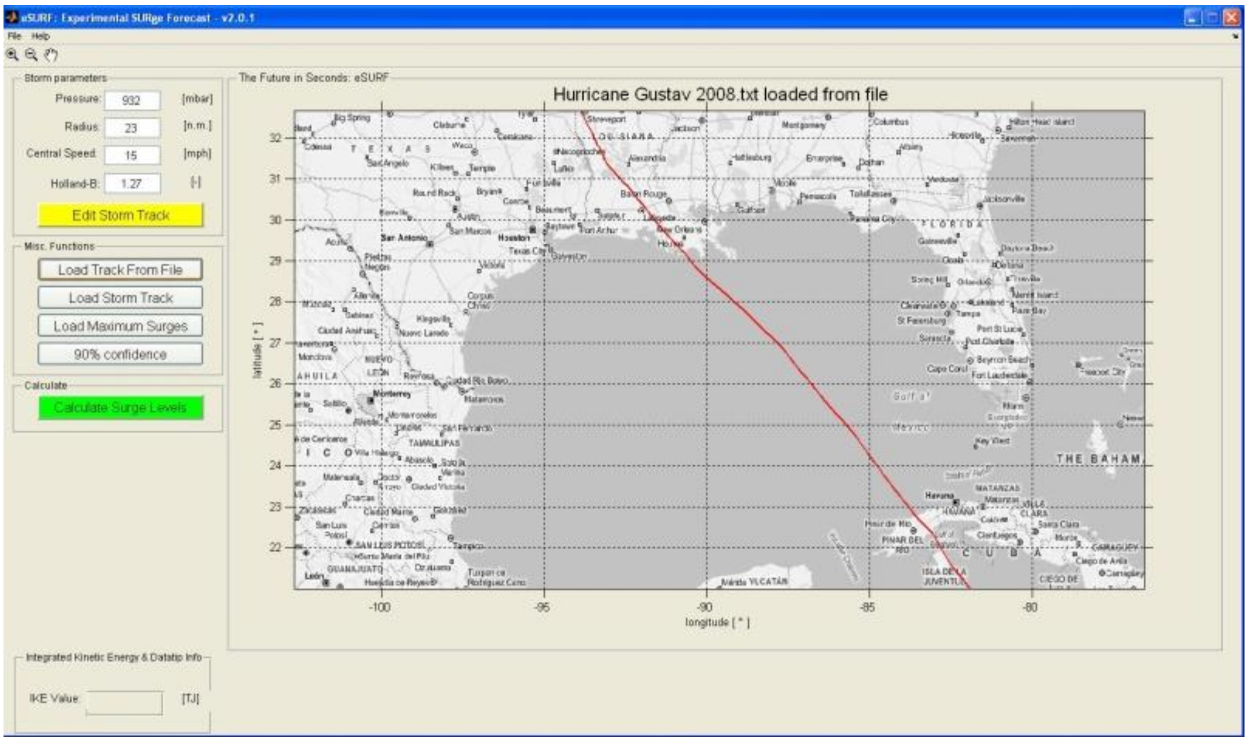


FIGURE 2-2: THE GRAPHICAL USER INTERFACE OF ESURF

3 HISTORICAL HURRICANE DATABASE

The main objective of this thesis is the validation of the model eSURF. However, meteorological and water level data observed during historical hurricanes is required for this validation. Therefore a historical hurricane database is developed and populated. This chapter describes and illustrates the process of HHD development and population and how it will benefit the main research objective. The scope, and data requirements of the data within HHD is outlined in Section 3.1. The various sources and data formats that are included in the HHD are discussed in next section. Section 3.3 addresses data processing and the various issues with vertical datum's in the coastal region. The data visualization and data quality are discussed in the last two sections.

3.1 DATA REQUIREMENTS AND SCOPE

First eSURF's input parameters are required to run eSURF and obtain maximum water level predictions. Next, the actual observed maximum water levels that have the same dimensions are defined. Finally, the time period considered in this research is set and discussed.

eSURF input requirements
In order to predict the maximum water levels in coastal Louisiana, eSURF's input parameters are required. These parameters are the basic hurricane characteristics. Table 3-1 illustrates the eSURF's input parameters, units and parameter boundaries.

TABLE 3-1: ESURF INPUT PARAMETERS (LIN, 2009)

Parameter	**Unit**	**Boundaries**
Hurricane track (Locations of hurricane)	[DMS] (Degree-Minute-Seconds)	No defined boundaries.
The minimum air pressure	[mBar]	850-1013 mBar.
The radius to maximum winds(RMW)	[Nmi]	5-35 Nmi
The central (foreword) speed	[mph]	6-18 mph
The Holland-B parameter.	[-]	0.7-1.5

The track is the location (latitude, longitude) of the hurricanes center at a six hourly interval during its lifetime. The minimum pressure is the pressure in the hurricane center. The central speed is the speed of which the center of the hurricane moves forward. The RMW is the radius to maximum winds or distance between the hurricanes center and the location of maximum observed wind speeds inside a hurricane.

The dimensionless Holland-B parameter characterizes the pressure profile of a hurricane at surface level. Figure 3-1 visualizes the pressure profiles of a hurricane for three values of Holland B. A lower Holland-B parameter results in a wider pressure profile and lower pressure differences. As stated in section appendix B (*Storm surge*), pressure is represents the amount of air pushing the water level down. If pressure drops, surface water level rises.

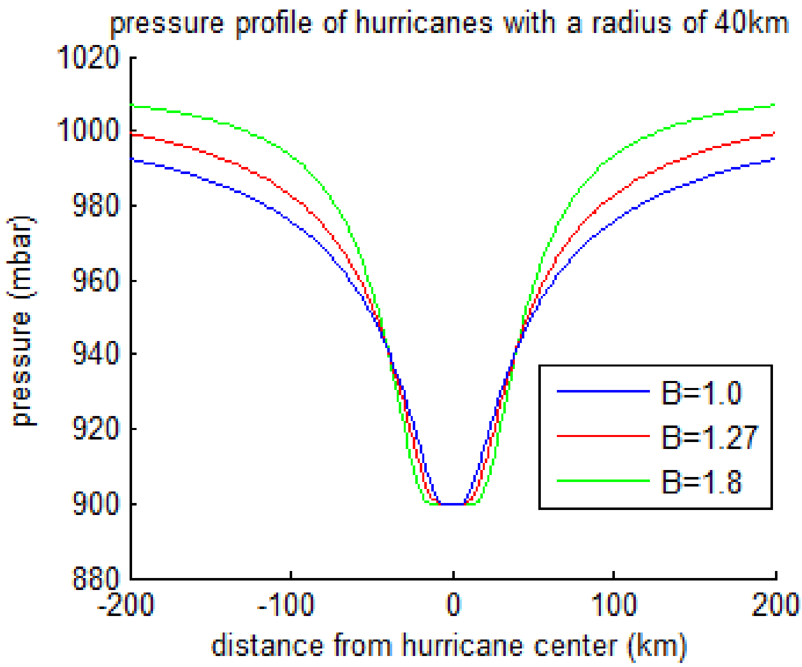


FIGURE 3-1: PRESSURE PROFILE VISUALIZED FOR THREE VALUES OF THE HOLLAND B PARAMETER. (SOURCE (VAN DEN BERG, 2008))

Maximum observed water levels

eSURF predicts the maximum water levels in feet above the North American Vertical Datum of 1988 (NAVD 88). eSURF prediction points are all located in the Louisiana Coastal Protection and Restoration Planning area (LACPR). So water levels in feet above NAVD 88 of nearby observations stations is required for validation of these prediction points of eSURF. Therefore the spatial extent for which the maximum water levels would need to be collected was defined as the LACPR area.

Time Period

The time period considered within this research project is set to the years between 1999 and 2009. Only hurricanes that occurred within this timeframe were selected to be included in the HHD. The underlying reason for choosing this time period was mainly the amount of the meteorological and water level data available. In addition, due to subsidence of the coastal zone and the monitoring of subsidence, water level observations are more accurate for the years 2004 till 2009. Subsidence issues are discussed in section 3.4.

In total there were about 85 hurricanes in the Hurricane Database (HURDAT) of the National Hurricane Center available within the timeframe. These hurricanes are visualized in figure 3-2.

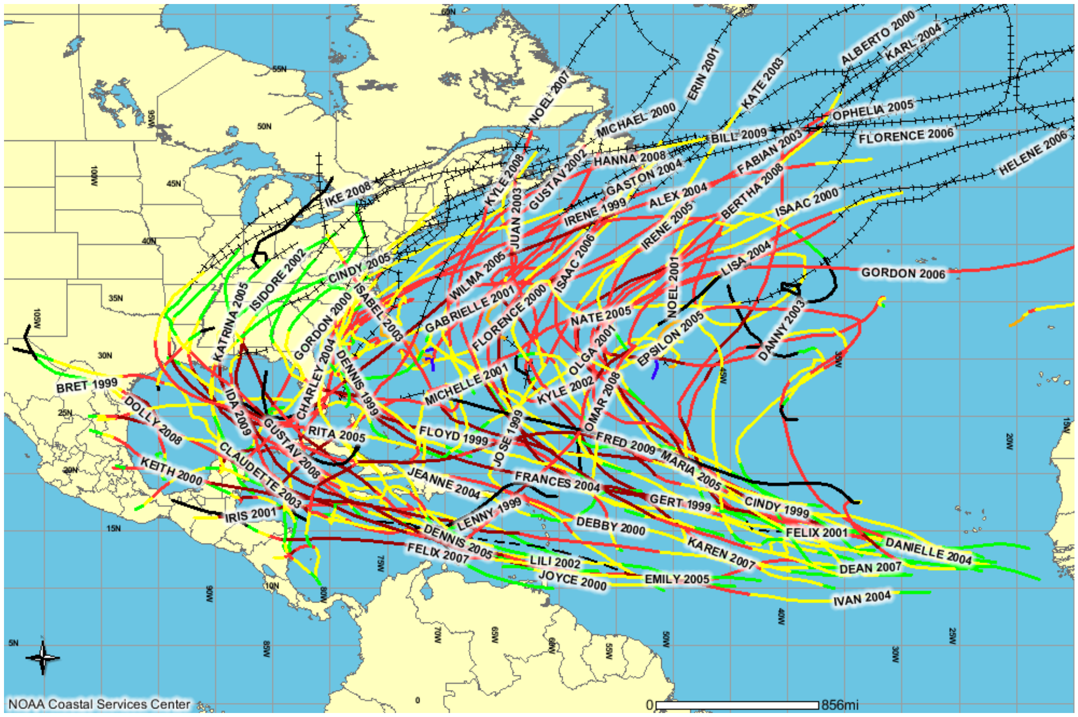


FIGURE 3-2: ALL HURRICANES DURING 1999-2009 TIME PERIOD (NOAA COASTAL SERVICES CENTER, 2010)

The number of hurricanes was narrowed down to a total of 11 hurricanes of at least category 1 strength that made landfall within 200 Nautical Miles from the Louisiana State border. Table 3-2 visualizes the selected hurricanes for storage in the historical hurricane database. For each hurricane name its start-, end- and landfall date is displayed.

TABLE 3-2: HURRICANE INVENTORY (DERIVED FROM TROPICAL CYCLONE REPORTS)

Name	Start date	End date	Landfall
LILI	20020921	20021004	October 3rd; 13:00h UTC
CLAUDETTE	20030707	20030717	July 15th; 1530 UTC
IVAN	20040902	20040924	September 16th ;0650h UTC
CINDY	20050703	20050711	July 6th ; 0300h UTC
DENNIS	20050704	20050718	July 10th ; 1930h UTC
KATRINA	20050823	20050831	August 29th ; 1110h UTC
RITA	20050918	20050926	September 24th ; 0740h UTC
HUMBERTO	20070912	20070914	September 13th; 0700h UTC
GUSTAV	20080825	20080905	September 1st ; 0000h UTC
IKE	20080901	20080915	September 13th; 0600h UTC.
IDA	20091104	20091111	No landfall in Louisiana

3.2 DATABASE SOURCES AND FORMATS

Much historical hurricane information is publicly available, however it is dispersed and not all information is available in the same data format. Based on the data requirements set out in section 3.1 a checklist was created of the types of data that would need to be collected to validate eSURF. In the next step the sources for these data were identified and documented[2]. The sources that are used gather the required data will be evaluated in this section. First the source and format of the basic hurricane characteristics will be described. Next, the sources and formats of the maximum observed water levels are evaluated.

Basic hurricane characteristics

The National Hurricane Center (NHC) monitors en stores the track, minimum pressure and the central foreword speed in the Hurricane Database HURDAT. This information has the format of a tab-delimited-file (.txt) and the track, minimum pressure and foreword speed required to run eSURF can easily be extracted from this database. The information is also provided in shape-file[3] format, and therefore easy to use in maps.

The RMW can be found on the website of the Hurricane Research Division of the Atlantic Oceanographic and Meteorological Laboratory (AOML). This division estimates the RMW at various times during historical hurricanes in their H-winds (or surface winds) analysis products. (Powell, et al., 2010 (37)). This scientific organization publishes the H-winds analysis products of historical hurricanes for scientific purposes.

The Holland-B parameter has not been found for the selected hurricanes and is therefore not stored in the HHD. The assumed value used for validation is discussed in chapter 4.

Maximum observed water levels

The water levels along the coast of Louisiana are measured and published by mainly three organizations (1) the United States Army Corps of Engineers (USACE), (2) United States Geological Survey (USGS) and (3) the National Oceanic and Atmospheric Administration (NOAA). Each organization gathers this data for their own purposes. USACE gathers this to make for example river stage forecasts or make decisions on the operation of their numerous flood control structures. The multidisciplinary federal science organization USGS gathers water level data for scientific evaluation of the United States natural resources. It measures all types of parameters, including sampled or continually measured gage heights. NOAA gathers this data for supporting safe and efficient maritime commerce, sound coastal management and recreation. NOAA assists in the Coastal Hazard Mitigation by monitoring and publishing time-critical storm tide information. . The Center of Operational Oceanographic Products and Services (CO-OPS) is the component of NOAA that publishes the water level data and tide level predictions.

Because these organizations gather these data for their own purposes, the formats and systems in which these data are stored are not necessarily 1 on 1 compatible. This means that data formats may be different and are not directly comparable with each other without any data processing. For example, NOAA provides *Storm Quick looks* on the internet. These *Storm Quick looks* only visualize

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[2] A full documentation of historical hurricane information sources and formats has not been included in this thesis, as it was not used to validate eSURF. This data inventory has been stored on an ftp-server of Royal Haskoning for future development of eSURF.

[3] A shape-file is an easy to read format for using in a geographical information system program, like ArcGIS.

the water levels in the format of graphs. But this format is unusable for validation. By means of a data inventory an overview is created of all available data and locations within each of these three organizations.

Additional data
Precipitation grids, Wind vector grids and astronomical tide levels are also stored in the historical hurricane database for future research to eSURF. Since these data was not used in the validation of eSURF, the data sources, formats, processing and output is further described in appendix C.

Data dimensions
All the data that is being collected has a certain dimension and it is very important to document what these are before data is being compared with each other. The main dimensions for each dataset in the historical hurricane database are:

- **Units**: the observation has a certain unit. For example, water level is measured in feet above, a for each station specific, *station datum*; rainfall is for example the daily total radar estimated rainfall in inches.

- **Spatial dimension:** coordinate system or projection that is used to describe the location of the observation. The spatial dimension may refer to either horizontal as well as a vertical coordinate or reference system.

- **Temporal dimension:** when was the observation made and what is the frequency in which the observation was made. The NOAA stations measure water levels at an hourly interval. Many of the USGS stations have a daily mean water level observation. Some do even measure daily minimum and daily maximum water levels. All these stations water level observations have been stored in the HHD, but only those who measure daily maximum water levels, can be used for the validation of eSURF.

Knowing the dimensions of the observation at hand will enable easy conversion into another dimension. Hence it will help in the creation of a consistent and directly comparable dataset.

In addition to the sources of data, the types of data and their dimensions the data inventory also details of where water level data is available. For each organization, for each hurricane the data inventory shows at which stations these organizations have water level data.

3.3 DATA PROCESSING

This section briefly describes the data modifications made to fit the purpose of the historical hurricane database. More specifically, this section describes the modification made to the observed water level data. The water level data needed most modification, compared to hurricane characteristics, precipitation and the hurricane wind field grids. A description of modification made to the hurricane characteristics, precipitation and wind field grids can be found in appendix C.

First the usable USGS, NOAA and USACE stations have been selected based on their spatial dimension and temporal dimension. The stations of interest are those located in the LACPR planning area and have water level data for the time period of interest. In total 86 water level observations stations have been stored in the HHD. It contains 19 NOAA, 49 USGS stations and 18 USACE stations. Next, all water levels data could be downloaded into Excel files and .txt files.

This data had to be re-organized and modified so it could be used for validation of eSURF. Next to deleting comment rows and unnecessary meta data, the following labels have been attached to the water levels: The station identity number, station name, its location (latitude and longitude in decimal degrees), the vertical datum used, the unit of observation, time of the observation (UTC[4]) and hurricane name.

eSURF uses the vertical referce datum NAVD 88. However, not all downloaded data is referenced to this vertical datum. Some of them are referenced to the datum NGVD 29 or to a station unique vertical reference level. Therefore these water levels needed to be converted to NAVD 88 in order to get a consistent dataset. For conversion of the vertical datum, an additional station specific conversion value has been attached to each water level observation and used to convert observed water levels to the vertical datum NAVD 88. The observed water levels referenced to *station datum* have first been converted to Mean Sea Level and then to NAVD 88.

After the data has been modified, the maximum observed water levels during hurricanes have been visualized into maps. Maps do better visualize the observed water levels over coastal Louisiana. An example is displayed in appendix C. More of these maps could be made to provide a quick look in the spatial relations of the maximum observed water levels during a hurricane. This could be useful in future development of the model eSURF.

3.4 DATABASE OUTPUT

The historical hurricane database is visualized in three main data formats, in this thesis named the database output. The formats are an organized table format of the water levels and hurricane characteristics, maps visualizing this information and pictures containing radius to maximum winds. An overview on the structure of the directory of the historical hurricane database is shown in table 3-3. The database contains two main sections.

[4] Coordinated Universal Time: Time standard set at Greenwich: England. The offset value for mid United States is – six hours in summer.

TABLE 3-3: DIRECTORY STRUCTURE

	Map/file name
1	**Overview** - FTP_structure.xlsx - Overview_database.xlsx

2	**Historical hurricane database**
	- Hurricane characteristics
	  - HURDAT_18512009.txt
	  - Hurricane1999-2009.shp
	  - "*YYYY_NAME" (.shp-files)*
	
	- Water level
	  - NOAA_Database.xls
	  - USGS_Database.xls
	  - USACE_Database.xls
	- Wave data
	  - Not included
	- Meteorological
	  - Winddata
	    - "RMW_*NAME*".png
	    - "*YYYY_NAME" (.shp-files)*
	  - Precipitation
	    - "*YYYY_NAME" (.shp-files)*

Directory 1 of the historical hurricane database contains an overview on all hurricane data and sources available, which were found during this research. It contains a list USGS, USACE and NOAA stations with for each station a data inventory and its vertical datum.

Directory 2 of the historical hurricane database contains the basic hurricane characteristics in a tab separated file (.txt). In addition, this chapter also contains shape-files of the basic hurricane characteristics for every hurricane. These characteristics can be easily imported in ArcGIS to visualize them on a map. Furthermore, water level data has been organized in a database for each organization. These databases contain two sheets, one with all data and one with a summary of all data by hurricane. The column labels of the sheet with all data is; YYYY (year), MM (month), DD,(day), HH:MM (hour:minutes), Station ID, Station Name, Latitude (decimal degrees), Longitude (decimal degrees), Tide level NAVD 88 (if available; feet above NAVD 88), Water level (feet above NAVD 88), Storm surge (feet above tide level), Tide level (feet above MSL) and Water level (feet above MSL) and Hurricane name.

Three examples of visualizations made from the data stored in HHD are a map of maximum water levels observed in the LACPR planning areas, a map of the total precipitation at the hurricane landfall for Louisiana or a map of gridded wind speed and wind direction. These maps can be useful in future development of the model eSURF. Appendix C contains example maps for hurricane Ike (2008). The Microsoft excel formatted database is too large be visualized in this thesis, therefore these are not attached in the appendices.

3.5 HHD DISCUSSION

It is important to know the limitations and accuracy of the data that are stored in the HHD. These may have a certain impact on the results of the validation of eSURF. Therefore the data quality of the observed water levels and the accuracy of the used vertical datum's will be discussed in this section. At the end of this section possible improvements to the historical hurricane database will be recommended.

Data quality of observed water levels
The number of stations included, the accuracy of water level measurement and the accuracy of the datum estimations could limit the usability of the historical hurricane database for the validation of eSURF.

The measurement errors in the water level data of the three organizations, could influence the validation results. In addition, the measurement method could provide less accurate water levels. CO-OPS (A component of NOAA) monitors the quality of the data of the NOAA stations, for example filtering unusual water levels out of the dataset. Twenty-four hours a day and 7 days a week NOAA's employees check the quality of the measurements and published real-time water levels as preliminary observations. After about 2 weeks till 4 weeks, the data is being verified and published as verified water levels on the NOAA website. Water level measurements with measurement errors could assess the reality wrongly, but for this thesis it is assumed to be of inferior to errors associated with the main area of this research: Hurricanes.

During hurricanes extreme wind velocities and waves impact the stations. It influences the quality of the observations. Several stations stopped measuring water levels during a hurricane because they were partly or completely destroyed. This results in gaps between observations. If stations had gaps during hurricane landfall, it could be that not the actual maximum water level is derived from the database. An example, as hurricane Katrina (2005) made landfall, all of the selected USACE stations stopped measuring and therefore the maximum water level derived from the dataset could wrongly display the actual occurred water level.

Accuracy of vertical datum
The maximum water levels calculated by eSURF are referenced to NAVD 88(2004.65). The best suitable stations for validation of this model are those stations using this datum.

The accuracy of the vertical datum establishment of each station directly influences the quality of the water level observations, hence this can impact the eSURF validation results. This section will discuss the accuracy of the vertical datum used throughout this study.

The water levels are measured relative to a reference level, or also called vertical datum. Since 1991 the North American Vertical Datum of 1988 (NAVD 88) has been replacing the old vertical datum; the National Geodetic Vertical datum of 1929 (NGVD 29). On the 65th day of 2004, a reestablishment of to the vertical datum has been made for a various location dispersed over coastal Louisiana. This correction to the datum is to reduce error, associated with the subsidence of this part of Louisiana.

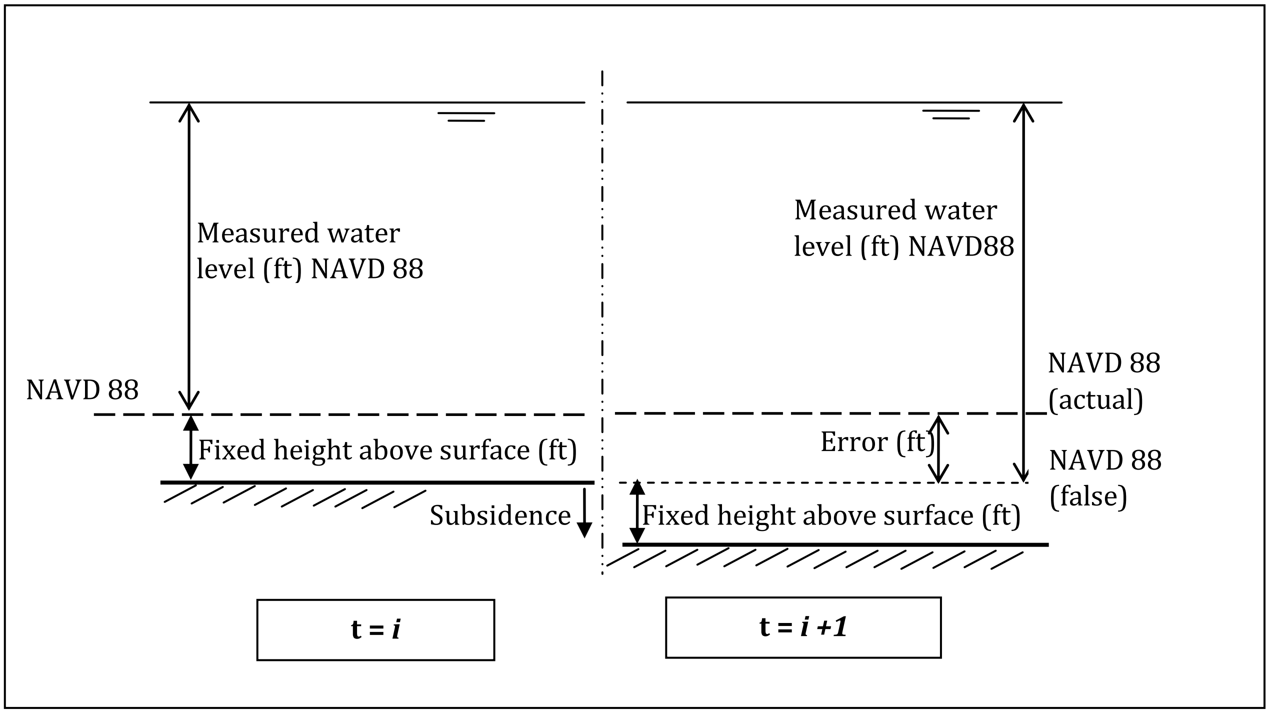

FIGURE 3-3: EXPLAINATION OF ERRORS OCCURING DUE TO SUBSIDENCE. t=TIME OR DATE, i=FIXED VALUE, FOR EXAMPLE JANUARY 1ST 1995.

"The land-surface altitude data collected in the levied areas of New Orleans metropolitan region during five survey epochs between 1951 and 1995 indicated mean annual subsidence of 5 millimeters or 0.016 feet per year. Preliminary results of other studies detecting regional movement of the north-central Gulf coast indicate that the rate maybe as much as 1 centimeter or 0.033 feet per year." (Burkett, Zilkoski, & Hart, 2003). If this subsidence value is extrapolated, the measured water level to the NAVD 88[6] during hurricane IDA (2009) could have included an error of 0.3 to 0.6 feet due to this datum issue. Therefore some of the observed water levels could be overestimations of the true water levels.

[6] and referenced to the in 1991 established water level.

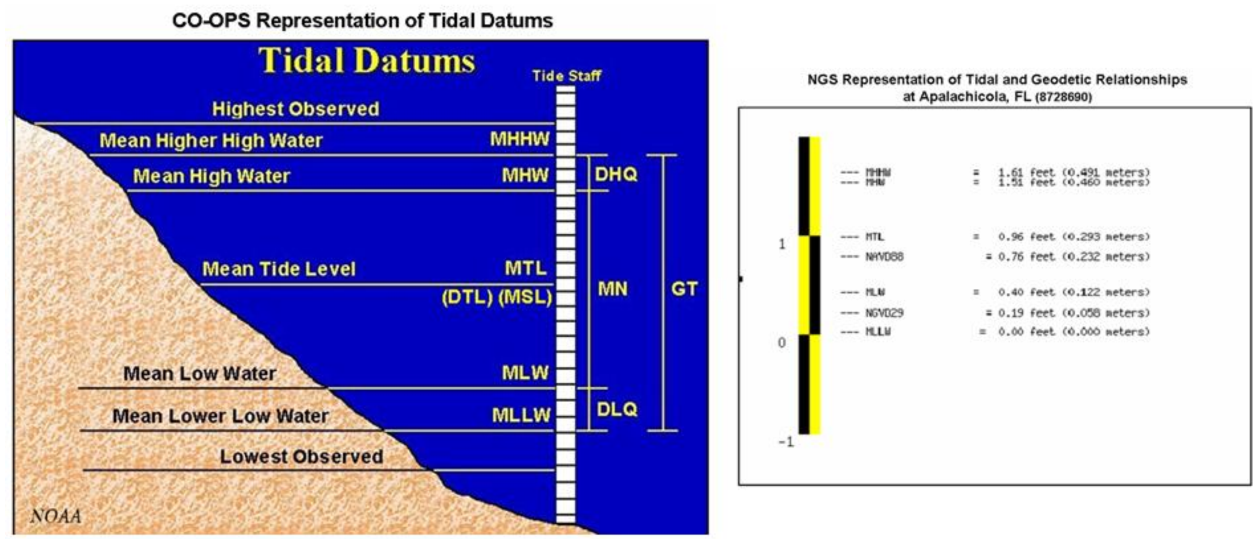

FIGURE 3-4: TIDAL DATUMS. NOTE THAT MSL=MTL. RIGHT SIDE: AN EXAMPLE FOR A STATION IN FLORIDA. (NOAA - CENTER FOR OPERATIONAL OCEANOGRAPHIC PRODUCTS AND SERVICES, 2010)

USACE report on their website, that their datum has been corrected to NAVD 88 (2004.65). It is unknown if the USGS has corrected their NAVD 88 values to NAVD 88 (2004.65). Finally, there are some other datum issues. Some USGS and USACE stations use the old NGVD 29 datum. If conversion values from NGVD 29 to NAVD 88 were unavailable for a station, the water levels have been stored in the HHD using NGVD 29. Other alternative conversion tools like VERTCON, for converting the old NGVD 29 datum to NAVD 88 could not be used. VERTCON is strongly disapproved by the USACE to be used for coastal restoration and engineering purposes. One reason for not using this tool is that uses the conversion values from the year 1991.

The NOAA stations measure the water levels to a unique station datum. For most stations the accurate datum conversion values for converting *Station datum* to *Mean Sea Level* have been published. For coastal Louisiana, accurate conversion values for MSL to NAVD 88 are not available due to subsidence errors. For most other parts of the United States, the relevant and most accurate available conversion values are published by the National Geodetic Survey in tidal benchmark reports. Therefore, a program called VDATUM has been used to convert water levels from MSL to NAVD 88. There are three main reason why using VDATUM for converting datum’s decreases the accuracy of the observed water levels., it does not include the new NAVD 88(2004.65) corrected datum. Furthermore, VDATUM uses conversion values generalized for areas. This means that it matches the inputted location to the appropriate area and returns the conversion value for that area. Finally, not all of the inputted station locations had conversion values returned. Figure 3-5 visualizes these conversion values for coastal Louisiana. Stations with the value -99999 have no MSL to NAVD 88 conversion values. Therefore, it is assumed that conversion values from ‘nearby’ station are suitable for these stations. The converting values from MSL to NAVD are approximately between 0.7 ft and 1.3 ft.

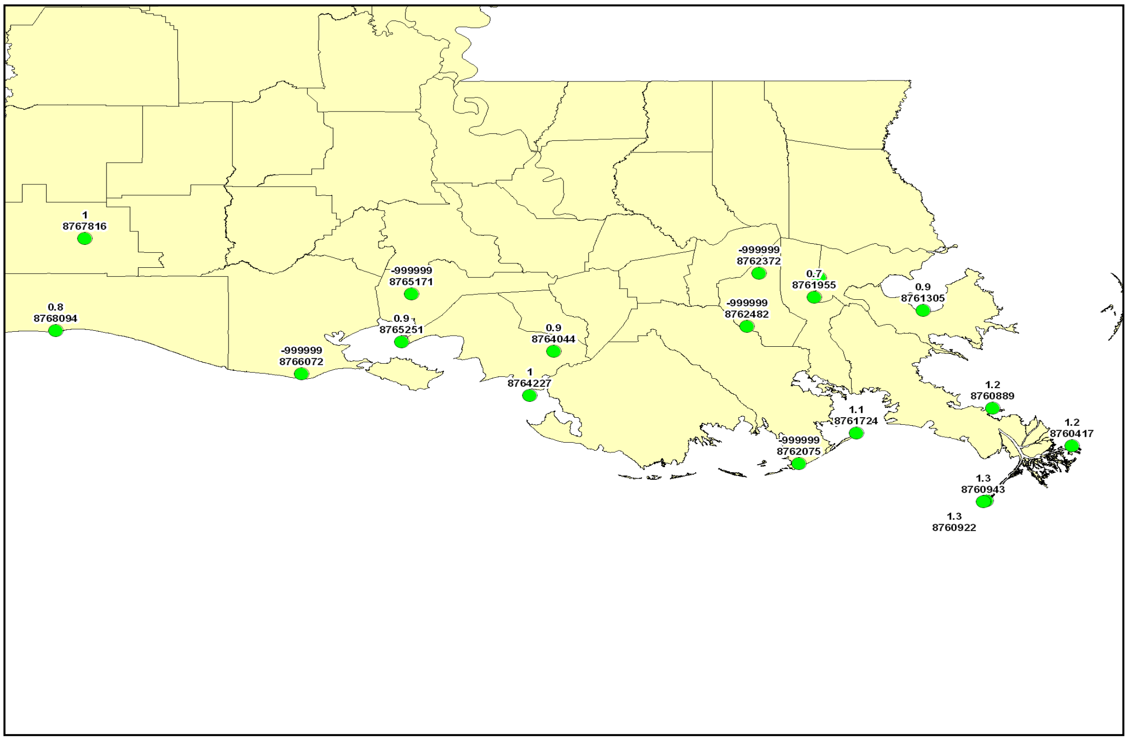

FIGURE 3-5: MSL TO NAVD 88 CONVERSION VALUES FOR NOAA STATIONS

Future improvements of the HHD

At the moment the historical hurricane database could be further improved. The following additional information should be added to the HHD. Adding the below stated data to the database could provide a better basis for future validation.

- Water level data of hurricanes before 1999.
- Including hurricane Isidore (2002)
- Maps of flooded areas of coastal Louisiana.

eSURF predicted predicted a storm surge of 8.3 feet at Rigolets Louisiana for hurricane Isadore (2002), however this hurricane has not been included in the historical hurricane database. This is because of the used method of defining the hurricanes of interest. Only those storms with a hurricane classification in a range of 200 Nautical Miles from the state Louisiana have been included in the Historical *Hurricane* Database. Isidore had a tropical storm classification within this range.

Furthermore, maps of flooded areas of Louisiana should be included to check the quality of the observed water levels of USGS, NOAA and USACE.

Along with storm surge, the waves can also overtop levees during a storm. Another feature of eSURF can be used to predict wave heights during a storm. Therefore, adding wave height data would add to the quality of the database and validation of eSURF. The format and extracting method issues regarding the wave height data are discussed in appendix C.

Additional, precipitation grids during hurricane landfall of hurricanes before 2007 could be used for future research to the relationship between total observed precipitation and rise of water level at a river observation station.

4 ESURF VALIDATION

eSURF has been validated with the information stored in the historical hurricane database. This chapter describes the validation process, results and discussion. Section 4.1 describes the method used for validation. Selecting process of the suitable stations, located near eSURF prediction points, and hurricane characteristics is described in this section. Furthermore, section 4.2 illustrates the result of the validation. An overview of eSURF accuracy and the accuracy by hurricane is stated in this section. Finally, the results are discussed in section 4.3.

4.1 METHOD OF VALIDATION

Selection of hurricanes
For the validation of eSURF 5 hurricanes have been selected. The selection criteria were:

1. The locations of lands fall are spread over Louisiana.

2. Hurricanes preferably occurred in the period between 2005 and 2009. The observations stations have been set to the new vertical datum NAVD 88(2004.65) in this period. Therefore using stations with these datum's should reduce the amount error related to datum conversion and increase the number of available stations with NAVD 88 (2004.65).

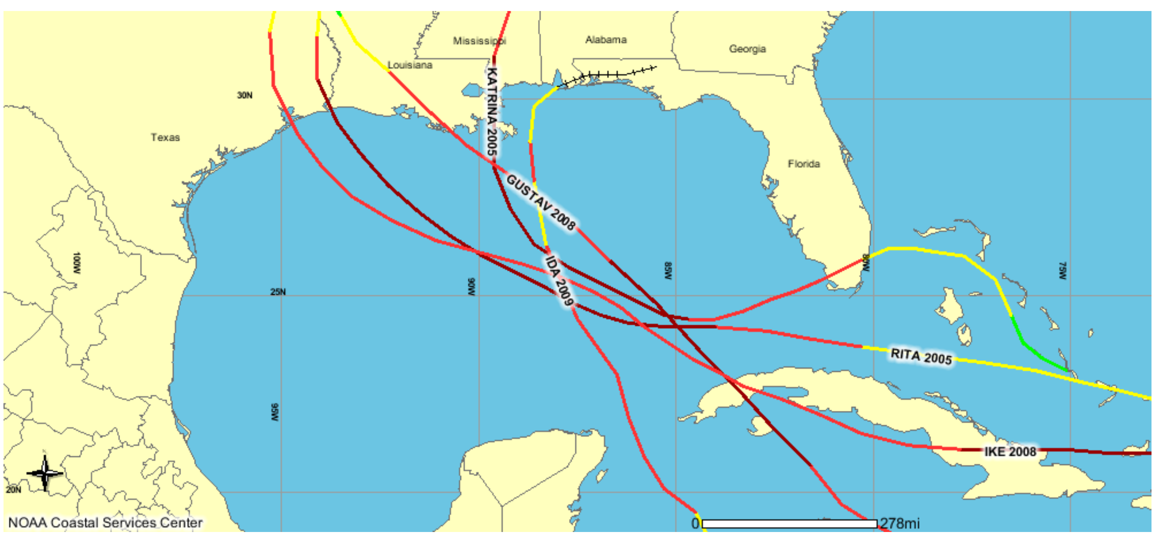

FIGURE 4-1: HURRICANES TRACKS OF HURRICANES USED FOR VALIDATION (SOURCE: NOAA COASTAL SERVICES CENTER)

Selection of observations stations
Next, suitable USGS, USACE and NOAA stations have been selected. Suitable stations have at least maximum daily water level observations or hourly water level observations (daily maximum water levels can be extracted from this). In addition, suitable stations also have observations at the moment of landfall of the hurricane (this means there are no gaps in the measurements and

therefore the maximum water level during the hurricane event is captured by the dataset). Furthermore, the referenced datum has to be NAVD 88 (2004.65) or NAVD 88. After the suitable stations have been filtered from the total list of stations to meet these requirements, a *station-input-list* is created.

The locations of the selected stations on the map of Louisiana have been used to estimate the nearest eSURF predictions points. The closest prediction points were chosen, however in some cases the closest prediction point was quite far away. Prediction points with a distance up to a maximum of 9000 ft[7] were selected. For some NOAA stations, multiple eSURF prediction points have been combined to interpolate the predicted maximum surge level on the location of the NOAA station.

eSURF model predictions

When the eSURF prediction points and the NOAA stations were selected, the maximum predicted water levels for hurricane Ida (2009), Ike (2008), Gustav (2008), Rita (2007), Katrina (2005) were calculated by eSURF. These calculated maximum water levels were than compared with the actual observed water levels at the USGS, NOAA and the USACE stations.

First validation round

Next, the prediction points that had a maximum error (ft) of more than 2.00 feet have been further examined in order to determine what caused this error. Based upon the location of the stations and the type of environment the station was located in, a *station-final-list* has been created. Those stations that could not represent the prediction points have been excluded from this list. More information of this selection of suitable stations and prediction points can be found in appendix F. The final list of stations and eSURF prediction points has been used to provide a final validation of eSURF.

An alternative criterion to select points for further examination could be the accuracy of the SLOSH-model. This model has also been validated with historical hurricane maximum water levels. The validation of SLOSH proved that model had an overall accuracy of +/- 20 % (if the historical hurricanes were described adequately in tropical cyclone reports) (Jelesnianski, Chen, & Shaffer, 1992).The 20% mean error has not been used, because it would result in a closer examination of almost all the eSURF points. In addition, this is the overall accuracy of the model and not the (for this thesis preferable) accuracy of the model for the specific region of coastal Louisiana. Due to the limit of time of this thesis, the criterion has been set to 2.0 feet.

Final validation round

The accuracy of eSURF is defined as the overall accuracy for all selected hurricanes and as the accuracy for the individual hurricanes. Accuracy is defined by the mean overall error (absolute and relative). In addition, under- or overestimation of the model prediction is determined with the use of a scatter plot. The scatter plot visualizes the relationship between the observed maximum water levels and eSURF maximum water level predictions. The coefficient of determination compares the predicted maximum water level with observed maximum water level. The value range of R^2 is 0.00-1.00. If $R^2 = 1$, than the regression line best represents the observed maximum water levels for all

[7] 9000 feet = 2.743 kilometer.

selected prediction points. Furthermore, the outcome of the validation for the individual hurricanes can be found in appendix G. This appendix contains also the absolute errors (feet) for each prediction point, visualized in histograms.

The number of stations used in this final step is displayed in 4-1.

TABLE 4-1: NUMBER OF OBSERVATIONS STATIONS AND PREDICTION POINTS USED

Total # observations stations used	=	*25*
Total # eSURF prediction points validated	=	*25*

4.2 RESULTS

This section illustrates an overview on eSURF accuracy for all 5 selected hurricanes. In addition, a brief review on eSURF accuracy for the individual hurricanes has been described in this section.

4.2.1 OVERVIEW

This subsection illustrates the overview of eSURF prediction capabilities. The maximum, mean and minimum overall error (absolute and relative) are being evaluated. Furthermore, a scatter plot will illustrate if eSURF has significantly over- or underestimated the maximum water levels.

Maximum, Minimum and Mean error
The absolute and relative maximum, minimum and mean error are visualized in Table 4-2. Keep in mind that a prediction point that contained the maximum absolute error does not also contain the maximum relative error for a hurricane.

The mean overall error of eSURF is +/- 37.2 %. This mean error is 17.2 % more than the accuracy of the widely developed SLOSH model. However, the SLOSH accuracy is the overall accuracy and not the accuracy of the model predictions for coastal Louisiana[8].

TABLE 4-2: OVERVIEW ON ESURF'S ACCURACY

	Absolute error [ft]	**Relative error[%]**
Maximum error	6.48	166.7
Mean error	2.03	37.2
Minimum error	0.04	1.4

[8] This accuracy of the model predictions for Louisiana has not been taken into account in this thesis. Only the overall accuracy of the model predictions has been found. This accuracy is based upon 13 hurricanes and 9 different area grids. (Jelesnianski, Chen, & Shaffer, 1992)

The maximumrelative error (%)
The maximum relative error (%) occurred at station *Lake Pontchartrain at Bonnet Carre Spillway* (USACE 85555). The associated eSURF prediction point is D1468. eSURF overestimated the maximum water level by 5.0 feet. After locating both on a map, it seems that station and prediction point are located along the coast. A high resolution map is used to check if local factors caused the amount of error had. However the resolution was not high enough. Therefore, a field trip to the site is needed to check for possible local terrain condition causing the error. This error occurred during hurricane Gustav.

The maximum absolute error (ft)
The maximum absolute error (feet) occurred at station *Pilots Station East, SW Pass* (NOAA 8760922). The associated eSURF prediction point is Q167. eSURF underestimated the maximum water level. After locating both on a map, it seems that almost no terrain differences between point and station could result in an error in prediction. This error occurred during hurricane Katrina.

Minimum absolute and relative error (ft en %)
The minimum error (absolute and relative) in the model's predictions occurred at prediction point Q564 during hurricane Ida. USACE station 85420, *Pass Manchac near Pontchatoula* was located at a distance of 4162 feet from this eSURF point. This is eSURF's most accurate prediction. Remarkable is that the eSURF point that had the best accurate prediction is not located near the observations station. Therefore, it could be pure luck that the water levels were the same. No investigation to the cause of this accurate prediction point was done.

Over- or underestimated
The regression line in Figure 4-2 (page 29) visualizes how well the model predictions fit to the actual observed water levels. It illustrates that eSURF maximum water levels are slightly underestimated. The coefficient of determination R^2 is 0.73[9].

[9] The R^2 value, or the coefficient of determination, explains us to what extent the points are situated along the regression line (black). The model would perfectly predict the maximum water levels if the R^2 value is 1.0 and all dots are on the dotted line.

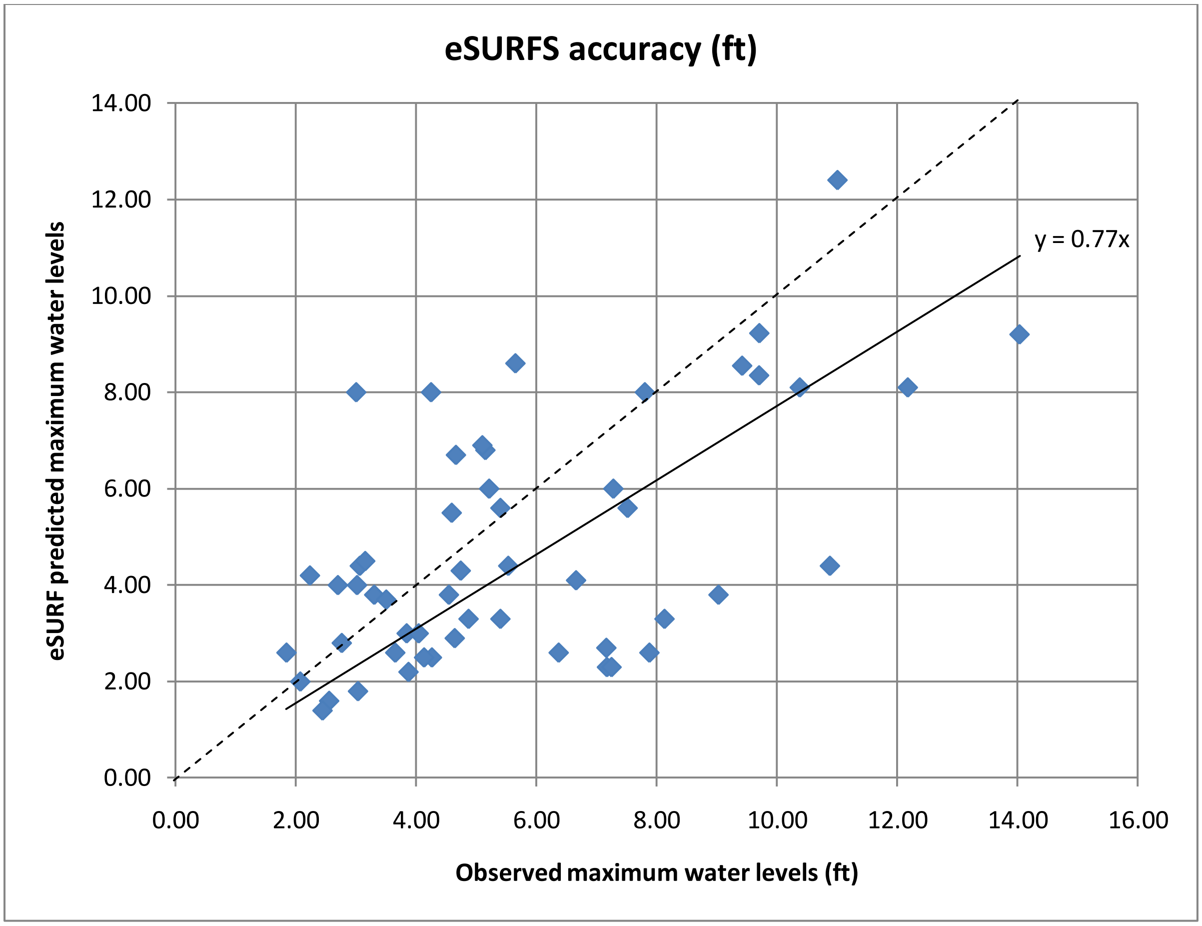

FIGURE 4-2: ESURF ACCURACY VISUALIZED IN A SCATTERPLOT. THE DOTTED LINE VISUALIZES WHAT WOULD BE THE BEST POSSIBLE PREDICTIONS OF ESURF.

4.2.2 INDIVIDUAL HURRICANES

This subsection describes eSURF prediction accuracy for the individual hurricanes. Appendix G contains the final results for each hurricane. All the stations and prediction points with an error exceeding 2.0 feet have been checked on influence due to terrain differences. The maximum, mean and minimum overall error (in feet and percentage) are displayed in Table 4-3.

TABLE 4-3: OVERVIEW ON ESURFS ACCURACY

	Maximum		Minimum		Mean	
Hurricane name	**[ft]**	**[%]**	**[ft]**	**[%]**	**[ft]**	**[%]**
KATRINA	6.48	88.3	0.20	2.5	2.00	44.8
RITA	4.95	68.3	1.05	28.8	2.89	48.7
GUSTAV	5.00	166.7	0.48	5.0	2.21	45.4
IKE	5.28	67.0	0.20	3.7	2.05	28.2
IDA	5.23	67.9	0.04	1.4	1.44	29.8

Best hurricane prediction

eSURF best predicted hurricane Ida and hurricane Ike. Hurricane Ida has the lowest absolute mean error (feet). Hurricane Ike had the lowest mean error in percentage. Both their mean relative errors (%) significantly differ from hurricane Katrina, Rita and Gustav.

Worst hurricane prediction

The highest mean error (absolute and relative) occurred when eSURF predicted the maximum water levels for hurricane Rita. Rita had the lowest coefficient of determination 0.69 and the maximum water levels were under estimated by eSURF. However, the mean relative error (%) does not significantly differ from the mean errors of Katrina and Gustav.

TABLE 4-4: NUMBER OF MEASUREMENTS USED

Hurricane name	# observations stations
IDA	15
IKE	13
GUSTAV	11
RITA	8
KATRINA	6

Number of observations stations

Table 4-4 illustrates that Ida and Ike had the most used observations stations for validation. But if compared with Gustav, it seems that this does not cause their relatively low mean relative error (%).

Hurricane characteristics

Furthermore, it could be that the hurricane characteristics have caused the low amount of relative error (%). Both hurricanes made landfall outside Louisiana. Ike made landfall near the western border of the state Louisiana, Ida near the coast of south-east Louisiana. The hurricane category of Ike and Ida were both small compared to Gustav, Rita and Katrina. Ida was a category 1 hurricane near Louisiana and Ike a category 2 hurricane. Ida had a small RMW of 19 nautical miles, Ike had a large RMW of 37 Nautical miles.

The results indicate that:

- eSURF prediction of maximum water levels has a mean relative error of 37.2 %.
- eSURF slightly underestimates the maximum water levels when considering all used historical hurricanes: *Ida (2009), Ike (2008), Gustav (2008), Katrina(2005), Rita (2005).*
- The best predicted hurricane was a hurricane category 1 with a small radius to maximum winds close to southeast Louisiana, but did not made landfall there. This was hurricane Ida. Hurricane Ike had the second best mean relative error (%). Hurricane Ike had a large radius to maximum winds. Lin (2009) improved eSURF with the IKE-value to better predict hurricanes with a large span of wind, such as hurricane Ike.
- The worst predicted hurricane was hurricane Rita. However Gustav and Katrina had also a high absolute and relative error. Although the highest mean error (%) did occur when eSURF predicted maximum water levels for hurricane Rita, hence hurricane Gustav and hurricane Katrina had also a high mean error (%).

4.3 DISCUSSION

The results in the previous section show quite significant differences between what maximum water level predicted by eSURF and that observed in the field. The question is: are these errors mainly caused by the data that is being used for the validation or are these caused by the way eSURF interpolates and predicts the water levels? With this in mind the following can be said:

1) It seems unlikely that vertical datum differences between observed and predicted water levels are the main factor contributing to large errors. Measured water levels are relatively low compared to the peaks in errors occurred at some eSURF prediction points. Differences vertical datum cannot explain those high observed errors.

2) Also stations that had missing water level data during hurricane landfall were excluded from the validation. Only stations that captured a peak water level during the full course of a hurricane are included. Therefore missing data (or missing peak water level data) cannot be used as an explanation for errors.

3) Only 2.4 % of the eSURF prediction points have been used in the final validation. This is mainly caused by the limit number of observation stations that performed measurements during a specific hurricane.

4) In some cases there is quite a distance between the station location and the prediction point. Some of the errors may be explained because of this reason.

5) More water level data for more hurricanes would provide better insight in relation between hurricane characteristics and the observed water levels.

6) Overestimated prediction of the maximum water level by eSURF could be caused by a low tide at a station. Some errors may be caused because of this reason. A rough estimation of the range of astronomical tide results in a 0 to 3 feet range.

7) eSURF has also been validated by Lin (2009). Lin validated eSURF with hurricanes *Betsy(1965), Andrew(1992), Katrina(2005), Gustav(2008) and Ike(2008).* For *Betsy, Andrew* and *Katrina* Lin (2009) used maximum water level prediction by the numerical model ADCIRC. For Gustav and Ike water level observations from observations stations were used. Lin (2009) concluded that the maximum water levels predicted by eSURF for hurricane Gustav were generally overestimated. From this validation in this thesis, no such conclusion can be made from the regression line in the scatter plot of hurricane Gustav. This could be caused by the input parameters used by Lin(2009) and the observations stations used for validation. The differences between Lin (2009) parameters and this validation are described in appendix D. The result of the validation of Lin (2009) and this thesis both conclude an underestimation for hurricane Ike. Furthermore, both validations conclude that there is no over- or underestimation of the eSURF's maximum water level predictions for hurricane Katrina.

5 CONCLUSION

The main objective of this thesis was to develop an organized historical hurricane database that can give quick insight in maximum water levels that occurred during historical hurricanes. Another main objective of this thesis was to validate the rapid hurricane surge forecasting model eSURF.

The historical hurricane database contains meteorological (wind speed and precipitation) and water level data for coastal Louisiana observed during hurricanes: *Lili (2002), Ivan (2004), Cindy (2005), Dennis (2005), Katrina (2005), Rita (2005), Humberto (2007), Gustav (2008), Ike (2008 and, Ida (2009).* At least the maximum observed water level data and the basic hurricane characteristics were needed to validate eSURF. The HURDAT database provided the necessary hurricane characteristics. The USGS, NOAA and USACE provided the water level observations, needed for suitable station to extract maximum water levels during a hurricane. For quick access to the database for validation of eSURF the data has been labeled and if possible corrected to the vertical datum NAVD 88.

Suitable stations were selected to limit the error in the validation due to non-eSURF related causes. The stations and prediction points have been selected based upon the criteria: distance between prediction point and station, vertical datum of water level, no missing water level observations during hurricane landfall, less influence due to terrain differences between prediction point and station. As a result 2.4 % of all eSURF prediction points have been selected for validation of eSURF.

The model eSURF has been validated with hurricane *Ida* (2009), *Ike* (2008), *Gustav* (2008), *Rita* (2005) and *Katrina* (2005). The overall mean relative error is 37.2 %. This mean relative error exceeds the mean relative error of the slosh model with 17.2%. It seems that eSURF best predicted hurricane Ida and Ike. Overall, eSURF slightly underestimated the maximum water levels. More specifically, the predictions by eSURF for hurricane Ike, Ida and Rita are slightly underestimated. When using the outcome of this validation some care has to be taken into account, due to the few suitable eSURF prediction points used in this validation.

6 RECOMMENDATIONS

For future validations of eSURF and improving eSURF the following is recommended from this thesis:

1. **Perform a sensitivity analysis**, to investigate the amount of uncertainty in the output of eSURF if input characteristics are uncertain.

2. **Include more water level observations by adding maps of flooded areas and high water marks**. By increasing the number of water level observations, more eSURF points can be used for validation and therefore more insight in possible causes could be revealed.

3. **Add more hurricanes to the validation set**. Data is available in the historical hurricane database for the use of the remainder hurricanes for the validation. The hurricanes should be selected based upon track and category. This would improve the level of insight in the relation between track or category storm and eSURF's accuracy. It also would improve the level of insight in the relation between hurricane category and eSURF's accuracy.

4. **The prediction points exceeding 2.0 feet should be further evaluated**. Therefore, possible terrain characteristics causing the errors can be excluded. Bathymetry and elevation maps and/or a site visit to the location of the station and prediction point could be used.

5. **Further research to the influence of predicted tide levels on errors occurred in this validation.** The ADCIRC model calculated for 152 hypothetical storms the maximum water levels for the prediction points in coastal Louisiana. eSURF uses these values in the *set-up* phase. However, in this thesis it is assumed that ADCIRC included spring tide levels in their maximum water levels. The tide levels at the prediction points and observations stations should be verified to check if this was a cause for over-estimation of the maximum water levels by some of eSURF prediction points for hurricane Gustav.

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Tempe?qvq=q:hurricane+katrina;lc:NVA2~32~32,NVA2~31~31,NVA2~63~63,NVA2~30~30,NVA2~62~62,NVA2~61~61,NVA2~60~60,nasaNAS~22~22,NVA2~19~19,nasaNAS~20~20,NVA2~18~

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8 APPENDICES

List of appendices:

A. List of abbreviations

B. Theory of

- Hurricane development
- Saffir-Simpson-Hurricane-Wind-Scale.
- Storms surge
- SLOSH-model and ADCIRC-model.

C. Historical hurricane database

- Database inventory
- Data process details
- Example maps of Ike

D. eSURF input parameters.
This are the hurricane characteristics used in the validation of eSURF.

E. Holland B parameter influence on error.

F. Terrain influence on errors.
An evaluation of geographical location of prediction points and observations stations with errors exceeding 2.0 feet after the first validation round.

G. Individual hurricanes validation results.

A. LIST OF ABBREVIATIONS

USACE	United States Army Corps of Engineers
HHD	Historical Hurricane Database
NHC	National Hurricane Center
NOAA	National Oceanic and atmospheric Administration
USGS	United States Geological Survey
NDBC	National Data Buoy Center
NGS	National Geodic Survey
NAD 83	North American Datum (1983)
NAVD 88	North American Vertical Datum (1988)
NAVD 88 (2004.65)	North American Vertical Datum (1988) Vertical reference level measured for subsiding coastal Louisiana at 2004 (on 65th day).
SLOSH MODEL	Sea, Lake and Overland Surges from Hurricanes model.
ADCIRC MODEL	Advance Circulation model
eSURF model	Experimental SURge Forecasting model
NGVD 23	National Geodetic Vertical Datum 1923
LACPR	Louisiana Coastal Protection & Restoration
AOML	Atlantic Oceanographic and Meteorological Laboratory
mph	Miles per hour
Nmi	Nautical miles

B. HURRICANE AND STORM SURGE

One of the objectives of this research focuses on improving the prediction capabilities of eSURF's maximum surge levels during hurricane events. Therefore it is important to understand the basic theory of hurricanes and their general impacts on coastal regions.

THE HURRICANE

A hurricane is a cyclonic storm, with hurricane degree wind velocities, a low pressure center and originating in the tropical zone. This phenomenon has a variety of names. In the western part of the pacific it is called a *Typhoon*, and in the Indian Ocean it is called a *Tropical cyclone* (R.H. Simpson, 1981). Furthermore, the Atlantic hurricane season takes place in the period of the 1st of June till 30th of November.

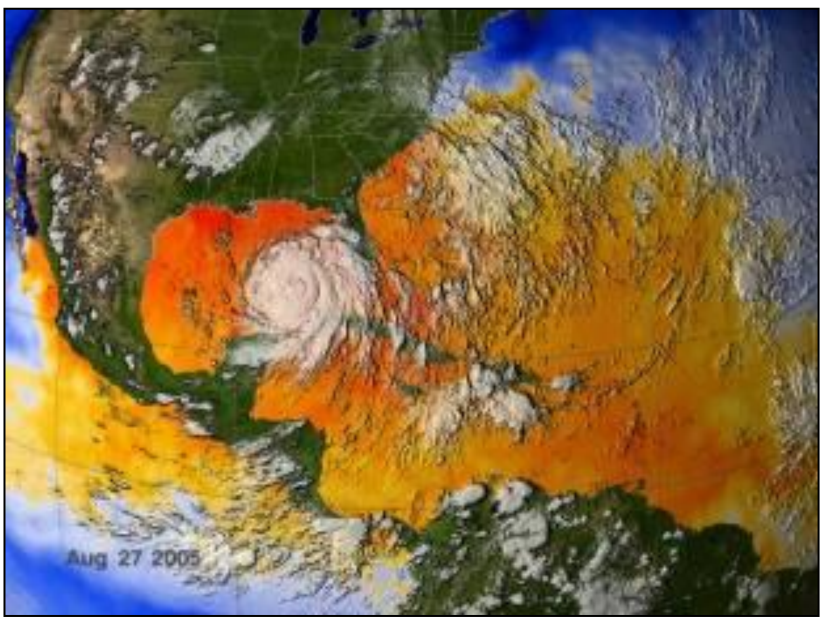


FIGURE 8-1: SATELLITE IMAGE OF HURRICANE KATRINA (2005) . WARM WATER IS INDICATED BY RED OR ORANGE, COLD WATER BY BLUE. THE USED TEMPERATURE RANGE WAS NOT AVAILABLE. (NASA/COURTESY OF NASAIMAGES.ORG.))

What are the factors that contribute to the initiation and development of a hurricane?

The reason for the development of (most) hurricanes in the tropical zone is, because of the warm and humid climate. The first important factor is a water temperature of at least 27 °C. If the temperature of the water is below 27°C, it won't generate enough heat and humidity to create and fuel the hurricane (National Weather Service, 2010). Figure 8-1 represents a quick view of the ocean temperature at arrival of hurricane Katrina in the Gulf of Mexico.

Secondly, the rotation of the earth along with its spherical shape results in a Coriolis force. This force increases at higher latitudes and at a minimum distance of 480 km of the equator it is large enough to generate the cyclonic motion of the depression. This cyclonic motion is important for the supply of warm humid air to the depressions environment. There are some other factors that contribute to the development of a hurricane. A relatively small wind velocity gradient with altitude increase, an atmospheric disturbance at sea level and a high humidity level at 4,9 km altitude. An example of disturbance at sea level can be a local turbulence or a local change in temperature. (National Weather Service, 2010)

Hurricanes are classified by the *Saffir-Simpson Hurricane Wind Scale.* This scale distinguishes hurricanes in five different categories. It is based on measured intensity of wind velocities and expected wind caused damage. For example, if the wind velocity exceeds 120 km/h (74 mph) it is classified as a category 1 hurricane. The high wind velocities in hurricane are caused by the pressure gradient between centre and outer layers of the hurricane. (National Hurricane Center, 2010)

TABLE 8-1: SAFFIR SIMPSON HURRICANE WINDSCALE. (AMERICAN SOCIETY OF CIVIL ENGINEERS HURRICANE KATRINA EXTERNAL REVIEW PANEL, 2007)

Category hurricane	Wind speed [mph]
1	74 - 95
2	96 - 110
3	111 - 130
4	131 - 155
5	> 155

As the hurricane moves through the North Atlantic basin, several of the hurricane characteristics are published by the National Hurricane Center at a six hourly interval. These hurricane characteristics are being used as important input parameters by many storm surge models that estimate the coastal water levels. The National Oceanic and Atmospheric Administration (NOAA) stores these parameters in the HURDAT. HURDAT is the Atlantic basin hurricane database (Hurricane Research Division). Table 8-2 illustrates these parameters.

TABLE 8-2: NHC BASIC HURRICANE CHARACTERISTICS PUBLISHED AT A 6 HOURLY INTERVAL.

Location (Latitude, Longitude);
Direction (degrees);
Speed (mph);
Maximum 1-minute sustained wind velocity ;
Lowest observed pressure;
Storm category;
Expected track of hurricane;

STORM SURGE

Storm surge is defined as the rise in water level above normal astronomical tide level. Storm surge is mainly caused by the friction of the wind on the sea surface water and the low air pressure within a hurricane. If the storm surge is combined with a spring tide, it can result in a unusual high water level. (National hurricane Center, 2010)

Storm surge [ft] = Storm tide (or observed water level) [ft] - normal astronomical tide level [ft]

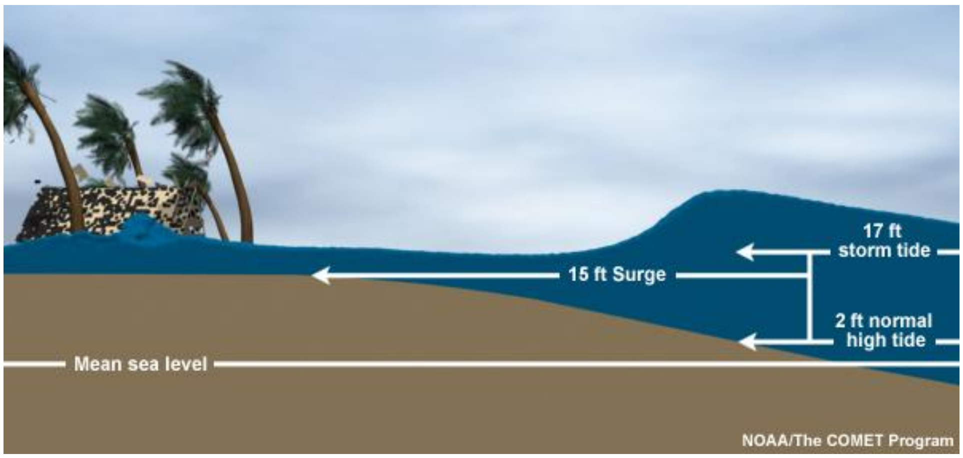


FIGURE 8-2: STORMSURGE, STORM TIDE AND NORMAL ASTRONOMICAL TIDE. (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / COMET PROGRAM)

Other important factors that influence the magnitude of storm surge along the coast of Louisiana are: local bathymetry, coastal geometry, the river Mississippi discharge and precipitation. For example, a funneling shape of coastline squeezes water to a location. As the water column is pushed forward by the hurricane winds, the funneling shape of both the coast line and bathymetry forces the water level to rise.

OTHER SURGE FORECASTING MODELS.

SLOSH – Model

The Sea, Lake and Overland Surges from Hurricanes model (SLOSH-model) is being used by the National Hurricane center (NHC), for prediction of the storm surge caused by an approaching hurricane. These storm surge predictions are mainly being used for the estimation of evacuation zones. The SLOSH-model predictions are based on parameters such as air pressure, size, propagation speed, track (bearing), wind velocities. (Federal Emergency Management Agency, 2009).

ADCIRC – Model

"ADCIRC is a highly developed computer program for solving the equations of motion for a moving fluid on a rotating earth. These equations have been formulated using the traditional hydrostatic pressure and Boussinesq approximations and have been discretized in space using the finite element method and in time using the finite difference method." (ADCIRC.ORG, 2010). ADCIRC stands for Advanced Circulation Model. This tool predicts seawater currents and water levels for coastal and estuarine areas. A supercomputer of the Texas University takes about six hours to make a detailed prediction (Waart, Februari 2009). It calculates for each hurricane of the maximum surge level at a variety of locations within the coastal zone. U.S. Army Corps of Engineers (USACE) uses this model, because it is specifically design for the coastal zone of New Orleans.

C. DATABASE DEVELOPMENT

This appendix describes additional information regarding the historical hurricane database development. First, a more detailed data inventory is visualized in a table. Next, database processing issues are evaluated. Finally, an example of the output of the database is visualized for hurricane Ike.

DATABASE INVENTORY

TABLE 8-3: LIST OF PARAMETERS

8.1 Parameter	Format	Unit	Source
Track/location hurricane	.txt and shape-files	Decimal degrees	NOAA_National Hurricane Center & NOAA Coastal Services Centre
Minimum pressure	.txt and shape-files	mbar	NOAA_National Hurricane Center & NOAA Coastal Services Centre
Storm category	.txt and shape-files		NOAA_National Hurricane Center & NOAA Coastal Services Centre
Central (Foreword) speed	.txt	mph	NOAA_National Hurricane Center & NOAA Coastal Services Centre
Central (Foreword) direction	.txt	Degrees from true North	NOAA_National Hurricane Center & NOAA Coastal Services Centre
Max sustained windspeeds 1-minute	shape-files	mph	NOAA_National Hurricane Center & NOAA Coastal Services Centre
Radius to maximum winds	.xls	mph	Atlantic and oceanographic meteorological laboratory - Hurricane research division.
Daily total precipitation	shape-files	inch	NOAA_ National Weather Service
Wind direction and speed	shape-files	mph, degrees from true North	Atlantic and oceanographic meteorological laboratory - Hurricane research division.
Tide level	.xls	meters and foot	NOAA_Center of Operational Oceanographic Products and Services
Water level (1)	.xls	meters and foot	NOAA_Center of Operational Oceanographic Products and Services
Water level (2)	.xls	foot	USGS_Surface water daily data
Water level (3)	.xls	foot	USACE_Rivergages, and USACE New Orleans district
List of hurricanes	.xls		National hurricane center
List of stations with each statoins data inventory	.xls		NOAA, USGS, USACE

Tide levels and Storm surge

NOAA also publishes the predicted tide levels. Combined with the observed water levels, it is possible to calculate the storm surge. The tide level predictions have been downloaded from the NOAA website for those coastal stations that had this information available. This information could provide insight in occurred storm surge[10] along the coast during historical hurricanes. Therefore it could aid in future improvements or validations of eSURF.

Wave data

Wave data was not included to the eSURF database as it was out of the scope of this thesis. However, in future the HHD could be improved by adding these wave height observations during hurricanes. Waves during a storm can build up and cause overtopping of levees. During hurricane Katrina, overtopping caused erosion behind the levees which resulted in levee failure.

One of the possible sources is the National Data Buoy Center. Its database can be accessed using the above stated OPeNDAP clients. OPeNDAP databases are being used by a variety of governmental agencies to distribute meteorological and hydrological information to the society. During this thesis, one of the OPeNDAP disadvantages was encountered. To access the information stored in the database, some skills of how to query this information are required. After spending some time on learning and on downloading database-clients, this process has been halted to reduce the chance on delay of this thesis. Another possible source would be WAVCIS. WAVCIS is a wave-current and surge information system for coastal Louisiana. Also the NOAA Marine environmental Buoy Database could be used for downloading wave data. It contains wave height, wave period and spectra data. However this data is presented in a disorderly format.

Wind speed vector data

NOAA's Wind data can be found on the website of the Hurricane Research Division of the Atlantic Oceanographic and Meteorological Laboratory. This is a scientific organization that researches hurricanes and publishes H-wind analysis products of historical hurricanes for scientific purposes.

Precipitation grids

Precipitation NOAA's National Weather Service is as the source. The precipitation grids are estimated by the NWS. These grids were only available for Humberto (2007), Gustav (2008), Ike (2008), Ida (2009). The precipitation grids (in a shape-file format) measured by satellites for the United States are only available for years between 2005-2009.

All measured wind data of historical hurricanes has been analyzed by the National Hurricane Research division. The data has not been checked with USGS or NOAA meteorological observations in this thesis. The daily total precipitation and wind speed data has been stored in the historical hurricane database for future research on eSURF.

[10] See appendix B for explanation of storm surge

Precipitation and wind field grids

The total daily precipitation grids for hurricane Humberto (2007), Ike (2008), Gustav (2008) and Ida (2009) have been downloaded from the website of the NWS and modified with the geographical information program ArcGIS. The grids were modified to fit the Louisiana state. Combined with the hurricane characteristics, maps of the total precipitation of these hurricanes at landfall have been made and stored in the hurricane database.

VDATUM

VDATUM a freely available vertical datum conversion program published and developed by NOAA on their website. This program is used for converting the water levels of NOAA's stations from *MSL* to NAVD 88. (National Geodetic Survey (NGS); Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS)). A screenshot of the graphical user interface is visualized in Figure 8-3.

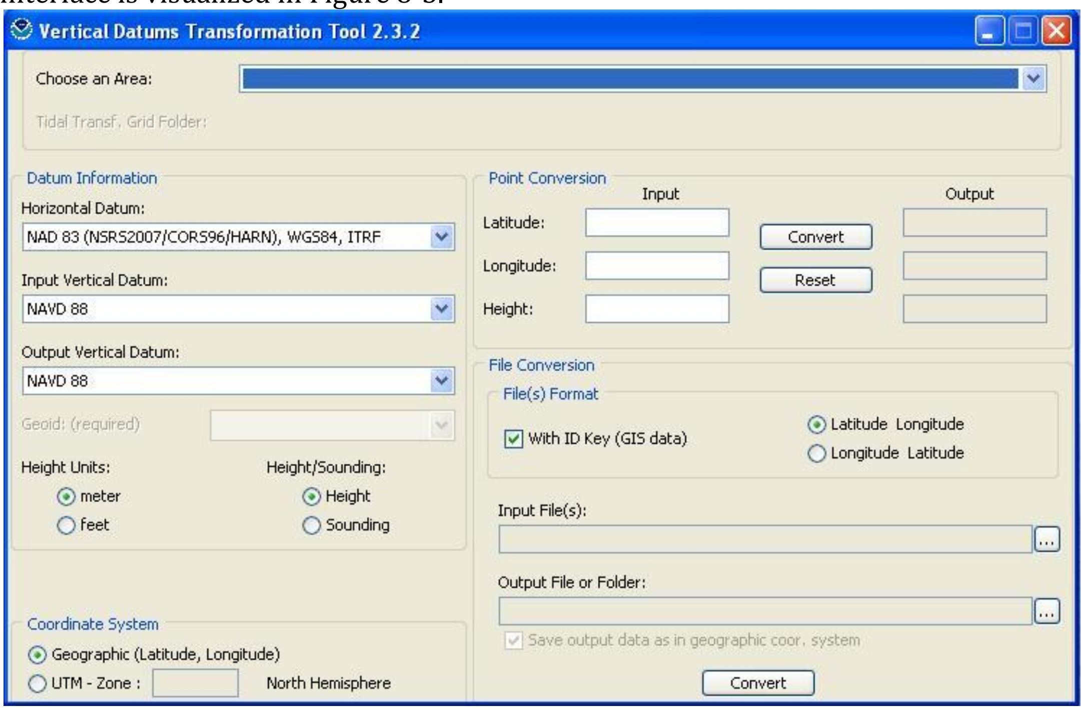
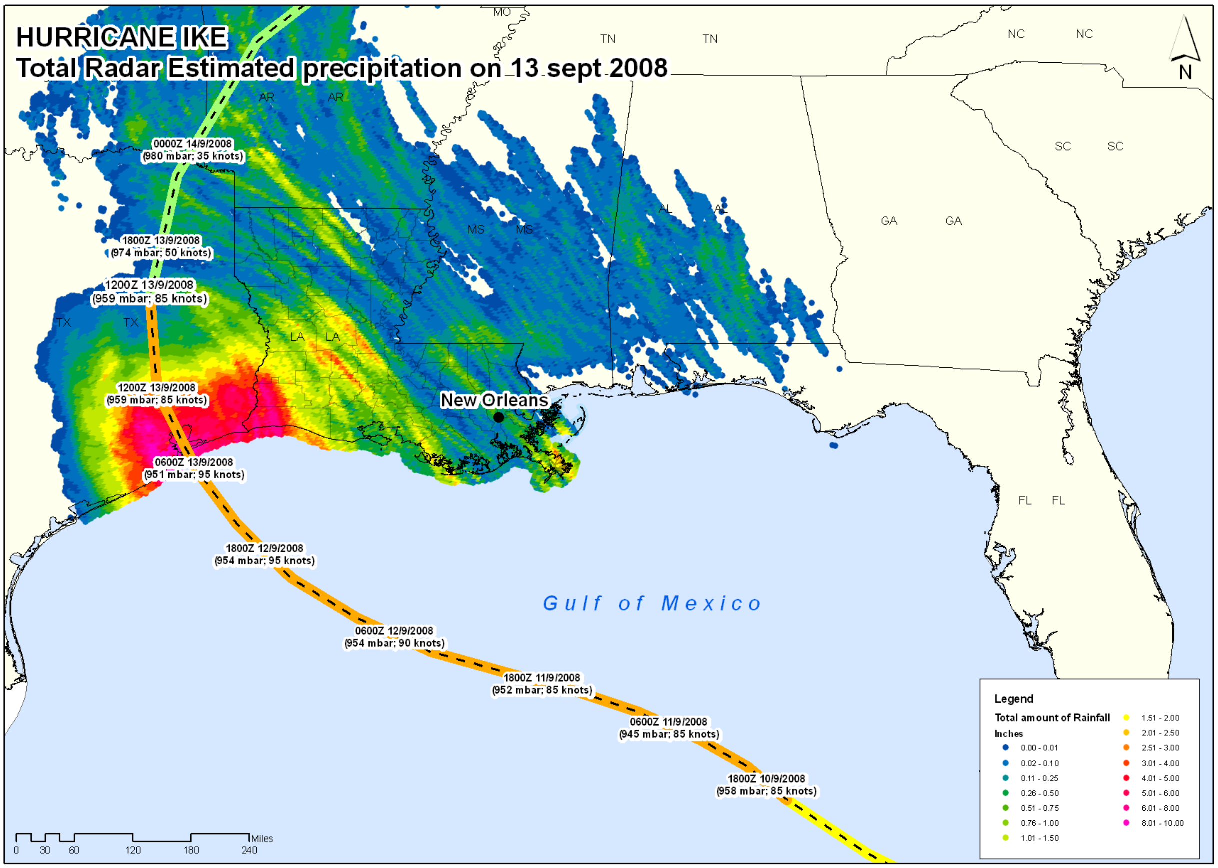


FIGURE 8-3: THE GRAPHICAL USER INTERFACE OF VDATUM

DATABASE OUTPUT IKE

This section provides some examples from the database for hurricane Ike and an example of how the dataset could be visualized. The daily precipitations grids are stored in the HHD. With the shape files provided by the AOML, quick insight in the wind vector grids of a historical hurricane can be provided. These grids have been downloaded modified with ArcGIS to provide maps of the wind field for various times during the hurricane. Finally, the maximum water levels can be visualized on a map as all the observed water levels have a spatial component.



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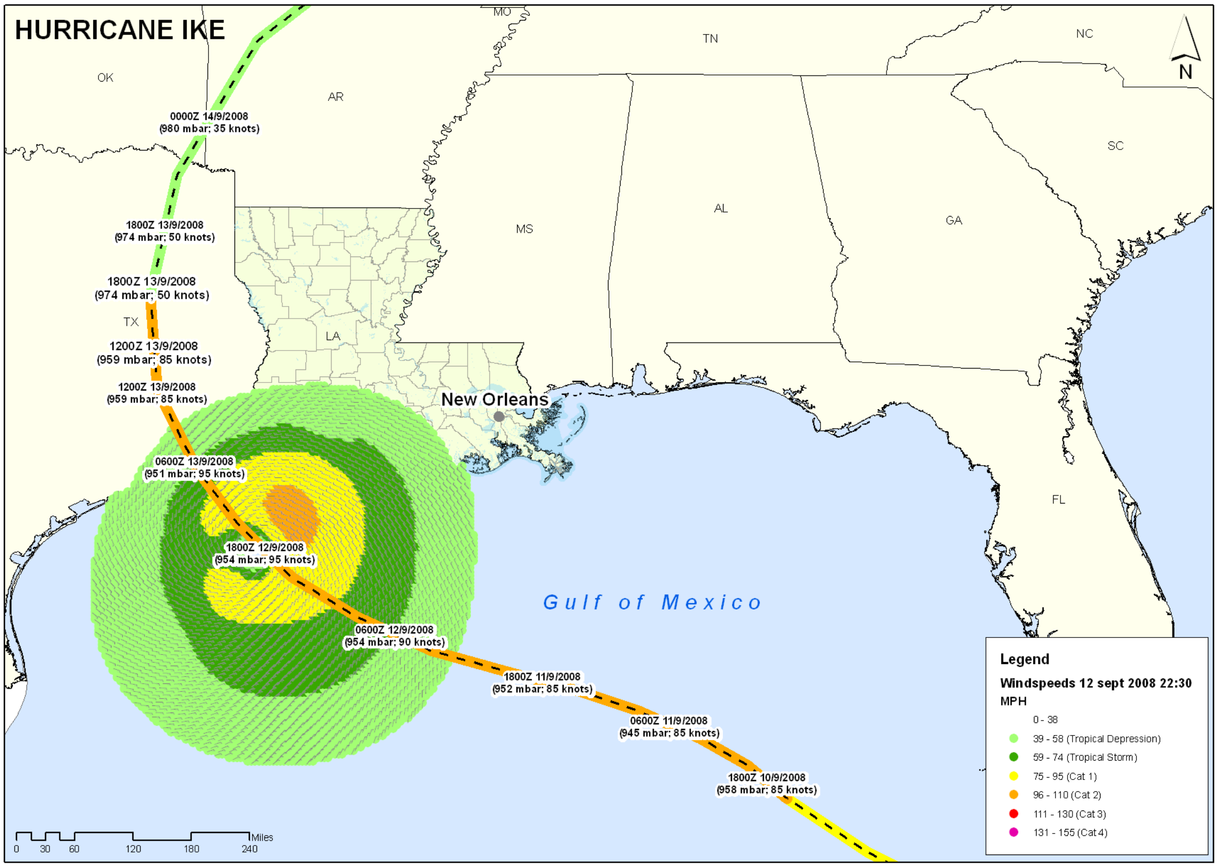
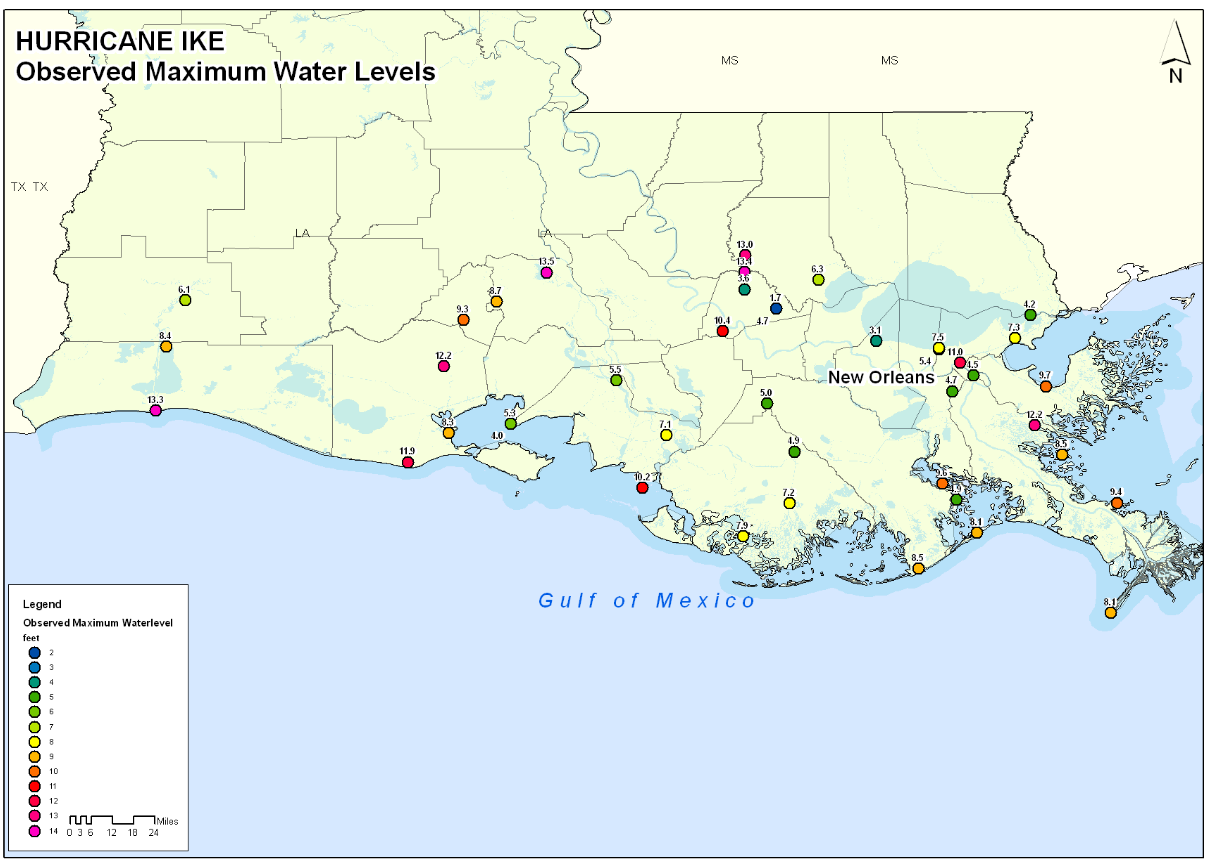




D. ESURF INPUT PARAMETERS

This appendix describes the basis hurricane characteristics used for validation. The track files are too large to display in this thesis.

	Pressure [mBAR]	Radius of Max Winds [Nmi]	Central Speed [mph]	Holland-B [-]
IDA (2009)	993	19	11	1,27
IKE (2008)	951	37	10	1,27
GUSTAV(2008)	959	26	14	1.27
RITA(2005)	937	16	10	1.27
KATRINA (2005)	920	35	13	1.27

	KATRINA (2005)			
	Lin(2009)	**Joustra(2010)**	**Difference**	**Unit**
Pressure	934	920	14	mBar
Radius of Max Winds	23	35	-12	Nmi
Central Speed	8	13	-5	mph
Holland-B	1.1	1.27	-0.17	[-]

	IKE (2008)			
	Lin(2009)	**Joustra(2010)**	**Difference**	**Unit**
Pressure	952	959	-7	mBar
Radius of Max Winds	34	26	8	Nmi
Central Speed	9	14	-5	mph
Holland-B	1.06	1.27	-0.21	[-]

Interesting is the difference between the used parameters at the validation of eSURF by (Lin (2009). This could influence the quality of a validation. The used parameters for the validation of eSURF stated in this report are based upon accurate tropical cyclone reports, the HURDAT database and post-hurricane wind analysis of the hurricane research division of the AOML.

E. HOLLAND-B PARAMETER INFLUENCE ON ERROR

Next, the Holland –B parameter influence on the amount of error for hurricane Gustav is estimated.

The Holland – B parameter is one of eSURF input parameters required for running the model. This parameter describes the pressure profile of the hurricane at surface level. This parameter is a result of a post-analysis of the of historical hurricanes pressure and wind profile. However, it has not been found on the internet for the selected hurricanes. Therefore Holland B has been set to the value 1.27. 1.27 is the most commonly used Holland B parameter. The value is used to avoid over- or under estimation of the pressure profile if the value is unavailable. Figure 8.4 illustrate the pressure profile related to the Holland-B parameter.

The impact of this assumption is estimated by comparing hurricane Gustav's input characteristics in eSURF, but the value of the Holland –B parameter has been set first to 0.7 then to 1.5. Table 2 summarizes the uncertainty maximum, minimum and average amount of error for hurricane Gustav's maximum water levels predicted by eSURF's nearby stations.

TABLE 8-4: HOLLAND B PARAMETER INFLUENCEON MAXIMUM SURGE LEVELS CALCULATED BY ESURF FOR HURRICANE GUSTAV.

	Absolute difference 0.70_1.27 (ft)	**Absolute difference 1.27_1.5 (ft)**
max	2.6	1.9
min	0.0	0.0
mean	0.7	0.5

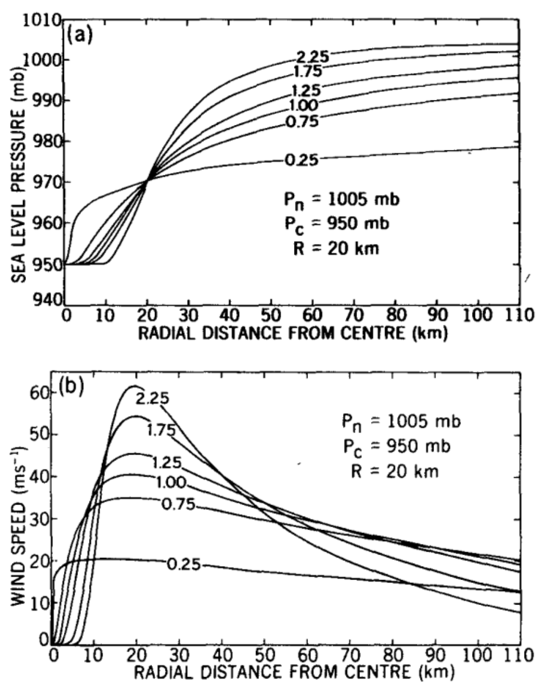
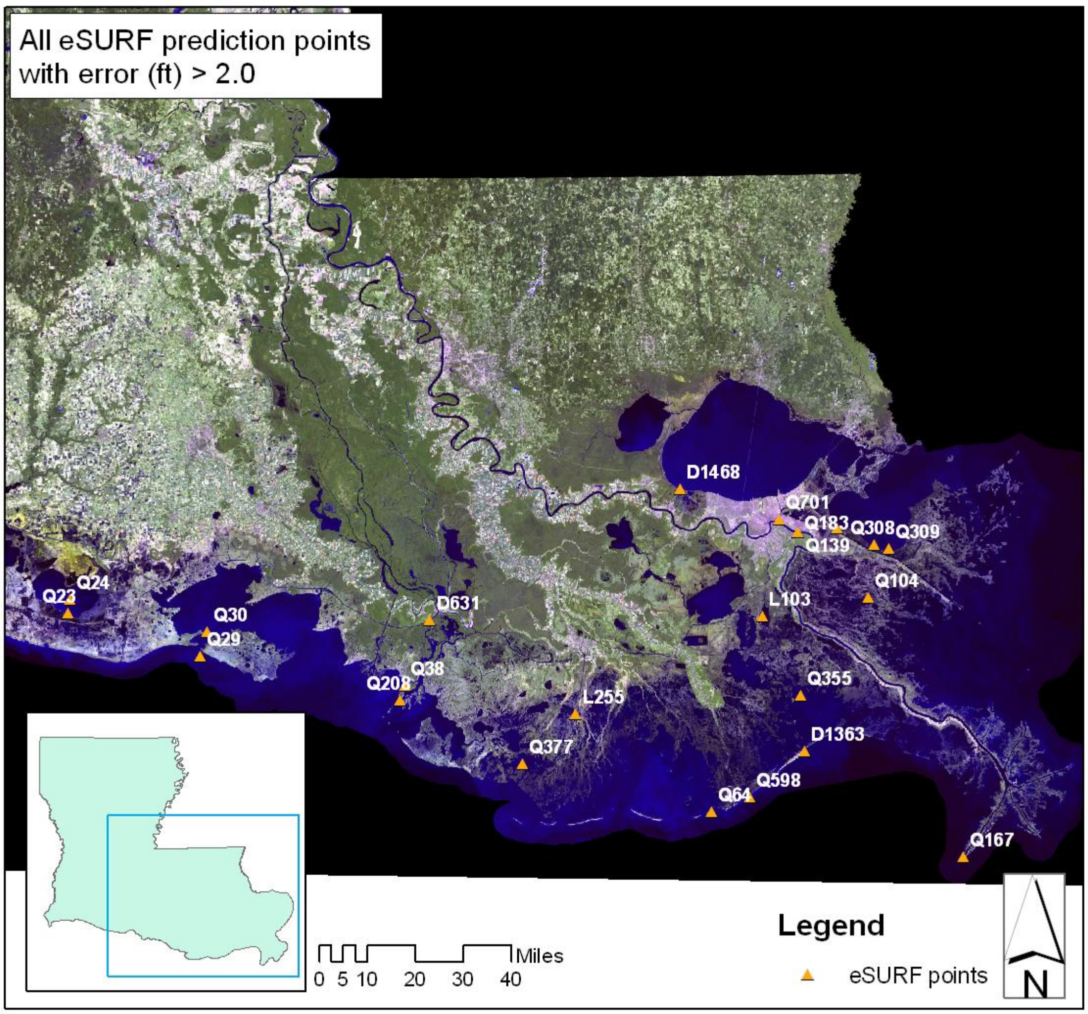


FIG. 2. The effect of varying the parameter *B* on (a) the sea level pressure profile and (b) the gradient wind profile.

FIGURE 8-4: (Holland, 1980)

F. TERRAIN INFLUENCE ON ERRORS

The selection of observations station for the preliminary validation has been based upon an assumption. It is assumed that a station with a maximum distance of 9000 feet to the prediction point is suitable for validation.
However, errors in eSURF validation might occur due to this assumption. Due to the different terrain characteristics of the prediction point and the observation station, some stations could not represent the prediction point. For example, a structure (dam or lock) could separate the prediction point and the observations station. Therefore; this appendix describes the selection of stations for the final validation. Figure 8-5 illustrates the location of the prediction points on the map of Louisiana.



8-5: ESURF PREDICTION POINTS WITH ERROR EXCEEDING 2.0 FEET

METHOD OF SELECTION

After the preliminary validation round, those eSURF prediction points that had an error exceeding 2.0 feet have been selected for a closer look (Figure 8-5).

Observation stations that did not have the same terrain characteristics (see below criteria for a definition of this word within this thesis) as the prediction point have been deleted. These stations have been deleted to improve the quality of the used station list for validation. In addition, excluding external errors provides a better view on eSURF related errors. The following criteria have been used for this cleaning process:

- An open water connection between station and prediction point.
- Relatively small distance between point and station.
- No structures, barriers or dams between station and prediction point.

After selecting suitable stations and prediction points, this list has been used in the final validation round. Please note that the stations with errors of less than 2.0 feet have not been checked based upon terrain differences, due to limited amount of time for this research.

RESULTS

ESURF point(s)	Observation Station	Suitable?	Remarks
D1363	NOAA (8761724)	No	This prediction point is not suitable. NOAA station is sheltered in a harbor north-west of the prediction point. The prediction point lies on the other side of an island (South coast). Island is separating point with observations station.
Q167	NOAA (8760922)	Yes	Prediction point is suitable. Small distance between station and prediction point. Furthermore, no natural or artificial barriers in between.
Q64,Q598	NOAA (8762075)	No	This prediction point is not suitable. eSURF points located on open sea. Station is located in a harbor land inland and sheltered.
Q104	USGS (73745257)	Yes	Prediction point seems suitable. Partly separated by land, but seems like both points are located in a swamp. Distance between station and prediction point is relatively small (approximately 800 feet). Therefore, this is a case of doubt.
Q38,Q208	NOAA (8764227)	No	This prediction point is not suitable. NOAA station lies between 2 islands and is sheltered. Has open water connection, but prediction points lie outside those islands. One is located in a river. Distance to each point is respectively 10.000ft and 7000ft. Therefore the points cannot be used.

Q23,Q29, Q24,Q30	NOAA (8766072)	No	This prediction points are not suitable. Used in the first place with the assumption that complete area might be easily flooded, due to same elevation. But Q23& Q29 are located in a lake. The points are isolated from point Q24&Q30. Q24&Q30 are located along the coast in the Gulf of Mexico. The NOAA station lies in a river mouth or channel.
Q377	USGS (7381349)	Yes	Prediction point is suitable. Although distance is approximately 8000feet. Both are located in open water. No land between station and point. Could be influenced by local bathymetry. Case of doubt.
Q183	USACE (76240)	No	This prediction points are not suitable. eSURF point located in Mississippi river. USACE station is located in a channel joining the river, at an unknown structure.
D1468_1	NOAA (8762372)	Yes	Prediction point seems suitable. Case of doubt. Prediction point at coast. NOAA station is located at a distance of 1800 ft in a channel. Distance is 1800ft.
D1468_2	USACE (85555)	Yes	Prediction point seems suitable. Case of doubt. The distance between prediction point and station is approximately 900ft. Resolution of used map not high enough. It seems that both are located along the coast.
Q308,Q309	NOAA (8761305)	Yes	Prediction point seems suitable. NOAA station is approximately located in the middle of the 2 eSURF points. The distance between both the prediction points and the coast is approximately 2700 feet. The distance between station and coast is 500 feet. Bathymetry could cause a difference between predicted maximum water level and observed maximum water level.
L255	USGS (7381328)	No	This prediction point is not suitable. Station and point separated by land. Distance is approximately 2700feet. It seems that station is located in stream or river.
D631	NOAA (8764044)	Yes	Prediction point is suitable. Small distance between station and prediction point. Furthermore, no natural or artificial barriers in between.
Q355	USGS (7380251)	Yes	Prediction point seems suitable. Case of doubt. The distance between point and station is approximately 4000 feet. But both are located in open water and there is no natural or artificial barrier separating the station and prediction point.
Q701	USACE (76160)	Yes	Prediction point seems suitable. Case of doubt. The distance between station and prediction point is small. Both station and point are located in a small channel joining the Mississippi river. Resolution of map to low to see if structure or dam is separating the points. It is assumed this is not the case. A site visit should provide more certainty in estimating suitability.

L103	USACE (82875)	No	This prediction point is not suitable. Distance between point and station is approximately 6500 feet. In addition, Station is located in stream or river. eSURF point located in nearby lake.

Total=	16
Suitable=	9
Excluded=	7

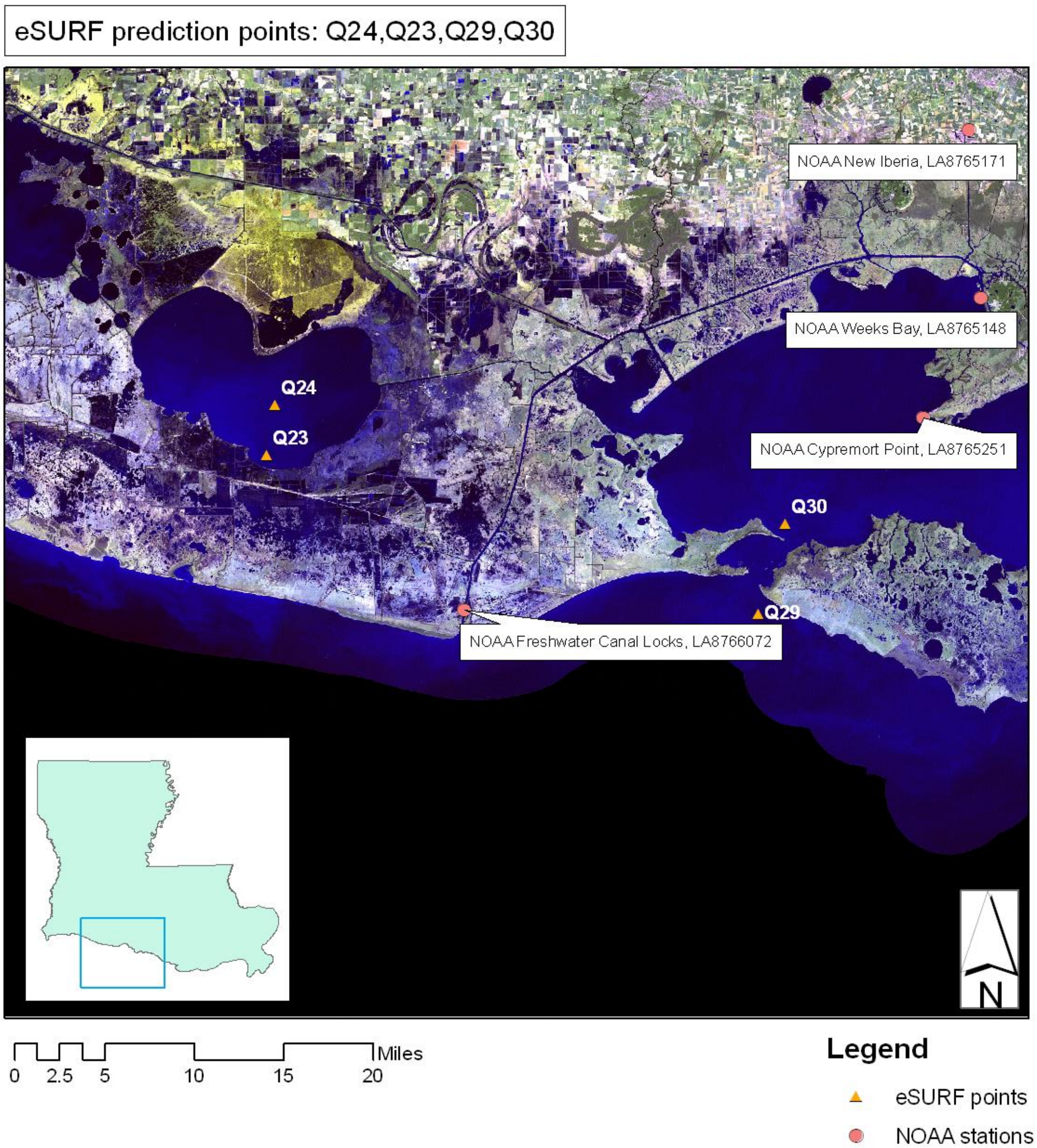


FIGURE 8-6: EXAMPLE OF STATIONS CHECKED FOR INFLUENCE OF LOCATION ON ERROR.

G. INDIVIDUAL HURRICANE RESULTS

This subsection will evaluate eSURF prediction capabilities for the individual hurricanes in chronological order. The hurricanes used for validation are *Ida (2005), Ike (2008), Gustav (2008), Rita (2005) and Katrina (2005).* For each hurricane:

- The character of the hurricane is described. The character includes: basic hurricane parameters, track and maximum storm surge above tide level for the state Louisiana.
- A histogram is displayed. This illustrates the amount of error in feet for each station.
- Number of prediction points and observation stations used for validation.
- A scatter plot is displayed. This scatter plot visualizes how eSURF maximum water level predictions related to the actual observed maximum water levels. The scatterplot could illustrate if a hurricanes maximum water level is underestimated or overestimated by eSURF.

Table 8-5 provides an overview of maximum, mean and minimum errors in eSURF maximum water level predictions (relative and absolute errors) for all 5 hurricanes.

TABLE 8-5: OVERVIEW ON ERRORS IN FEET AND PERCENTAGE, WITHOUT SELECTION OF SUITABLE STATIONS BASED UPON TERRAIN CHARACTERISTICS.

	Maximum		**Minimum**		**Mean**	
Hurricane name	**[ft]**	**[%]**	**[ft]**	**[%]**	**[ft]**	**[%]**
KATRINA	6.48	88.3	0.20	2.5	2.00	44.8
RITA	4.95	68.3	1.05	28.8	2.89	48.7
GUSTAV	5.00	166.7	0.48	5.0	2.21	45.4
IKE	5.28	67.0	0.20	3.7	2.05	28.2
IDA	5.23	67.9	0.04	1.4	1.44	29.8

	[ft]	**[%]**
All Max	6.48	166.67
All Mean	2.03	37.2
All Min	0.04	1.4

IDA (2009)

Hurricane characteristics

Ida did not made landfall in the United States, but its track curved to the east near the south-east coast of the state Louisiana. The date and time used for determination of the eSURFS input parameters is 10th of November on 00:00 hour (UTC). Table 8-6 illustrates that Ida decreased in intensity at that time. This hurricane had a small radius to maximum winds, compared to the other hurricanes. The maximum storm surge (above predicted tide) in Louisiana described in the tropical cyclone report of Ida is 6.53 feet (Avila & Cangialosi, 2010). Figure 8-8 visualizes the track of hurricane Ike.

TABLE 8-7: HURRICANE CHARACTERISTICS OF IDA (HURRICANE RESEARCH DIVISION)

Ida	-06:00 hour	Landfall	+6:00 hour
Category	1	Tropical storm	Tropical storm
Maximum 1-minute sustained windspeeds (mph)	75	70	60
Minimum pressure (mbar)	990	993	998
Speed (mph)	18	11	10
Radius to maximum winds (Nmi)	-	19	-

FIGURE 8-7: TRACK OF HURRICANE IDA. RED INDICATES HURRICANE FORCE WINDS, YELLOW INDICATES TROPICAL STORM CATEGORY.

Maximum, minimum and mean error

Hurricane Ida had the lowest mean error (in feet). Hurricane Ida had the lowest mean error (in %) of 28.2%. In addition, hurricane Ida had also the most accurate prediction or lowest minimum error (ft & %) compared with the other hurricanes. The maximum, minimum and mean errors have been visualized in Table 8-8.

TABLE 8-8: ESURFS ACCURACY FOR HURRICANE IDA

	Error (ft)	Error (%)
Maximum	5.23	68.0
Minimum	0.04	1.4
Mean	1.44	29.8

Histogram of errors (ft)

For all stations having maximum water levels and prediction points available, a histogram has been made. This histogram in Figure 8-8 provides a clear overview on the amount of error for the prediction points in feet for this hurricane.

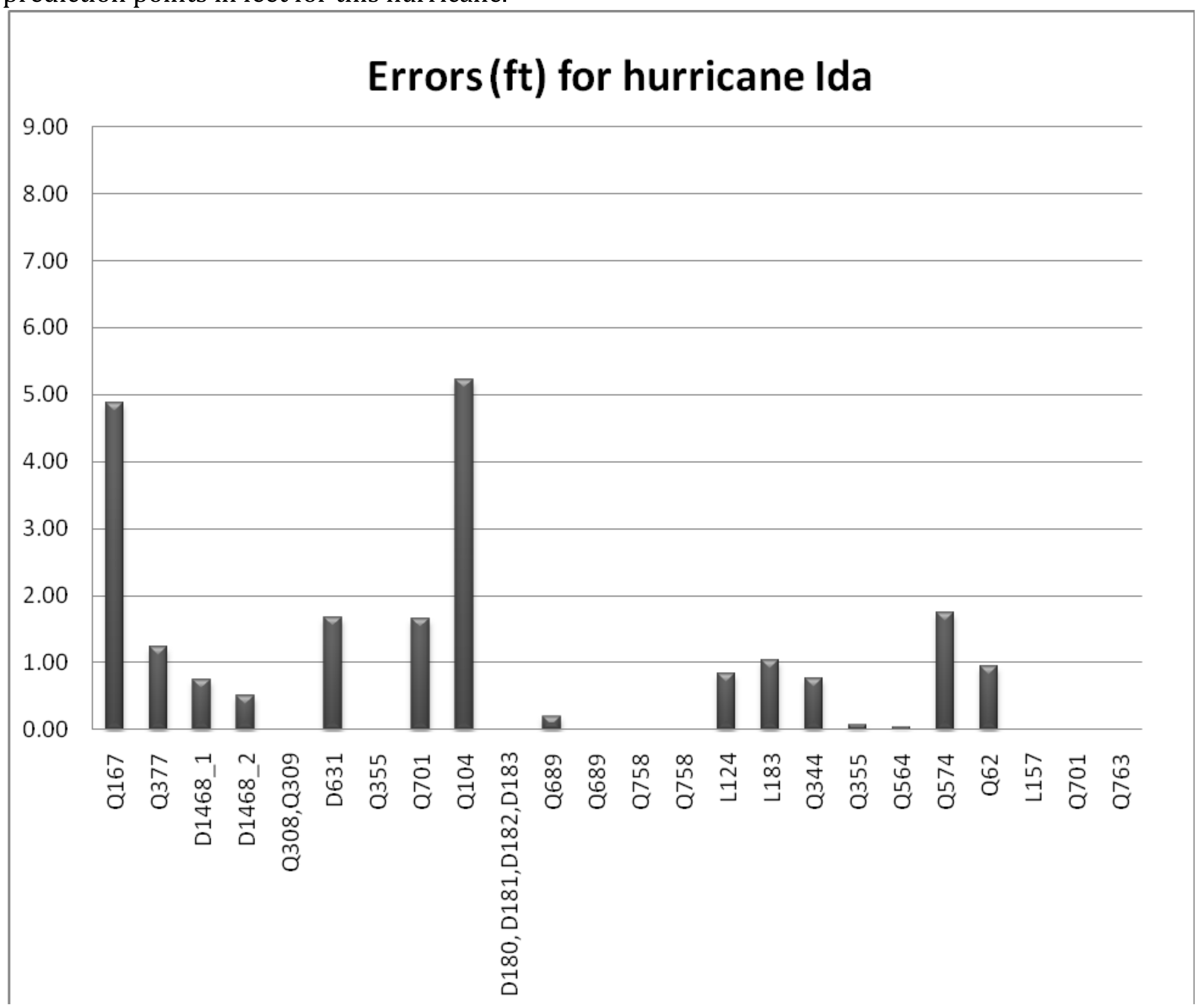


FIGURE 8-8: HURRICANE IDA ABSOLUTE ERRORS IN FEET BY PREDICTION POINT.

Errors exceeding 2.0 feet

Figure 8-8 shows 2 peaks at Q104 and Q167. These points have an error exceeding 2.0 feet. More details are stated in Table 8-9.

TABLE 8-9: ERRORS IN ESURF PREDICTIONS EXCEEDING 2.0 FEET FOR HURRICANE IDA.

nr	Station ID	Observed maximum water level (ft)	eSURF point	eSURF prediction (ft)	Error (ft)	Error (%)	Case of doubt?
1	8760922	7.17	Q167	2.30	4.87	67.9	no
2	73745257	9.03	Q104	3.80	5.23	57.9	yes

There are no artificial or natural barriers between eSURF prediction point Q167 and NOAA station 876092. Therefore it seems that the influence of terrain type characteristics could not be the cause of the high amount of error.

However, prediction point Q104 is a case of doubt. This means that there might be a possible terrain type difference causing the error. On the map the location seemed like a swamp and the points are partly separated by land. But the station and prediction point are both connected by water and distance is relatively small compared to the distance between other observations stations and prediction points. A sight visit to the NOAA station would provide the necessary details to exclude possible terrain type influence on the error.

Quantity of stations and prediction points

For hurricane Ida the most maximum water level data is used for validation, compared to the amount of observations used for validation of the other hurricanes. The total number of maximum water level observations is 15. The total number of eSURF prediction points validated is 14. The total number of eSURF prediction points is 1024.

Structerally over- or underestimated

The scatter plot in Figure 8-9 visualizes how accurate eSURF predicted the maximum water levels for hurricane Ida. The dotted line describes the best possible fit to the reality, if observations are correct. Interesting is the fact that most points are located on or below the dotted line. The goodness of fit; R^2 for hurricane Ida is 0.82. Hurricane Ida's maximum water level prediction are underestimated by eSURF.

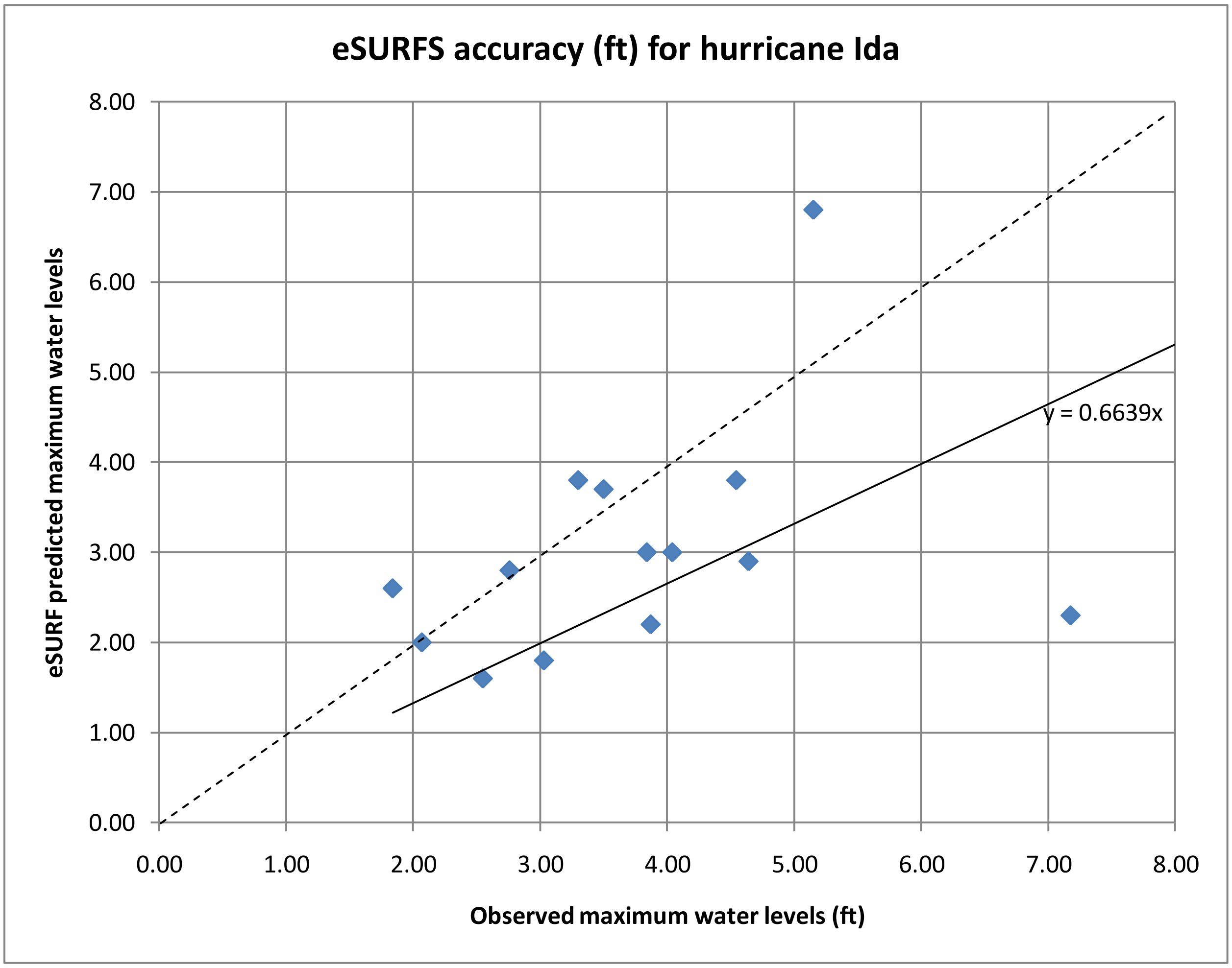


FIGURE 8-9: THE SCATTERPLOT, VISUALIZING THE ACCURACY OF ESURF'S MAXIMUM WATER LEVEL PREDICTIONS FOR HURRICANE IDA.

HURRICANE IKE

Hurricane characteristics

Ike made landfall to the west of Louisiana in the state Texas as category 2 hurricane. The date and time of landfall are September 13th and 06:00 hour (UTC). Hurricane Ike had the same hurricane characteristics from 12 hours before landfall until landfall. Table 8-10 illustrates this. This hurricane had a huge radius to maximum winds. The RMW used as an input parameter for eSURF exceeded the limit value of RMW. The maximum value is 35 Nmi (Lin, 2009). The maximum storm surge (above predicted tide) in Louisiana described in the tropical cyclone report of Ike is 10.40 feet (Berg R. , 2009). Figure 8-10 visualizes the track of hurricane Ike.

TABLE 8-10: HURRICANE CHARACTERISTICS OF IKE (HURRICANE RESEARCH DIVISION)

Ike	-12:00 hour	-06:00 hour	Landfall
Category	2	2	2
Maximum 1-minute sustained windspeeds (mph)	110	110	110
Minimum pressure (mbar)	954	952	951
Speed (mph)	11	11	10
Radius to maximum winds (Nmi)	-	-	37

FIGURE 8-10: TRACK OF HURRICANE IKE. RED INDICATES HURRICANE WIND VELOCITY. YELLOW INDICATES TROPICAL STORM WIND VELOCITY.

Maximum, minimum and mean error
Hurricane Ike had the lowest mean relative error of 28.2 %. In addition, hurricane Ike has a low mean absolute error (ft) relatively to the other hurricanes. The maximum, minimum and mean errors have been visualized in Table 8-11.

TABLE 8-11: ACCURACY OF ESURF FOR HURRICANE IKE

	Error (ft)	Error(%)
Maximum	5.28	67.0
Minimum	0.20	3.7
Mean	2.05	28.2

Histogram of errors (ft)
For all stations having maximum water levels and prediction points available, a histogram has been made. This histogram in Figure 8-11 provides a clear overview on the amount of error for prediction points in feet for this hurricane.

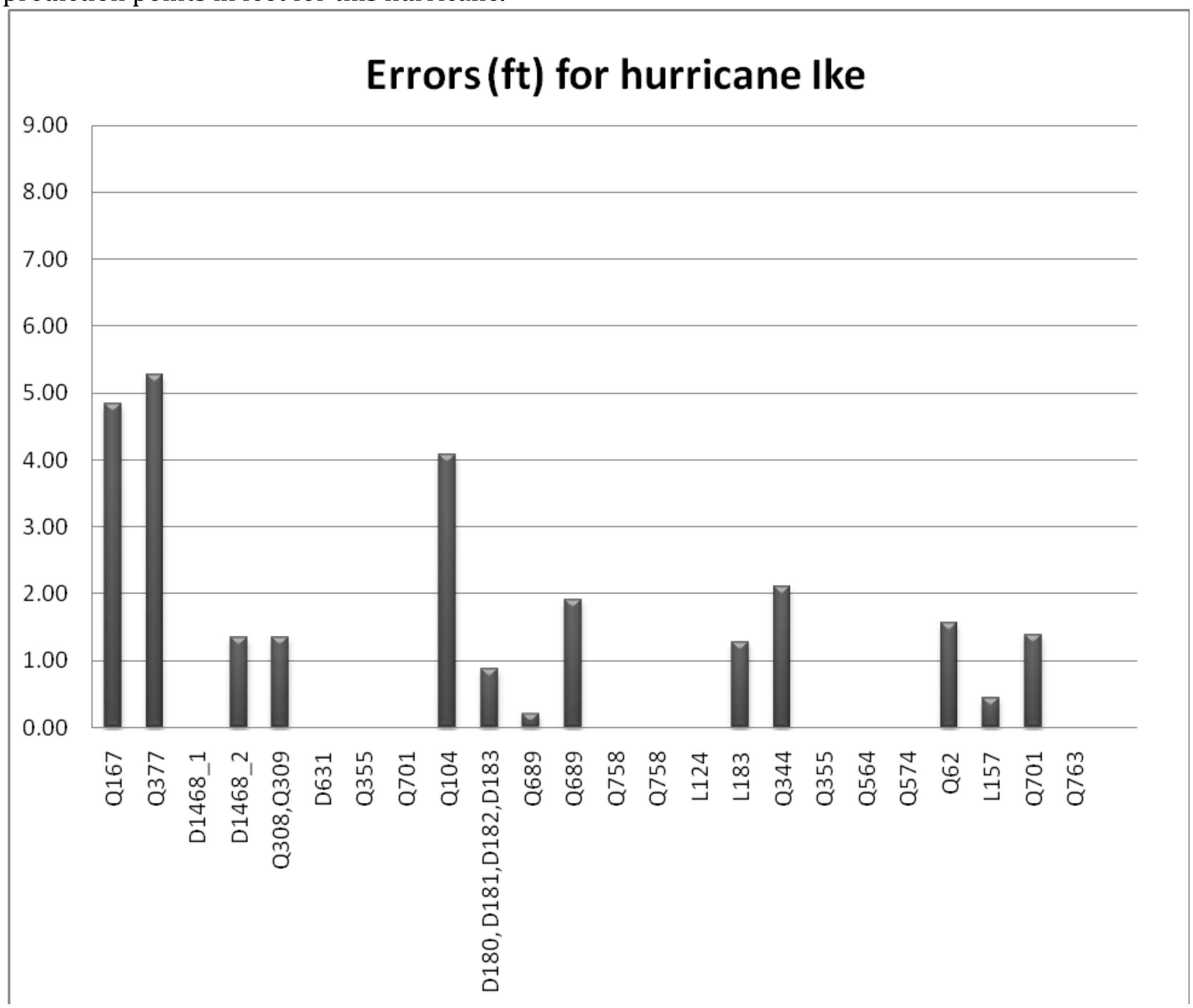


FIGURE 8-11: HURRICANE IKE ERROR IN FEET BY PREDICTION POINT.

Errors exceeding 2.0 feet
Figure 8-11 shows 3 error peaks with an error value exceeding 2.0 feet. The points are displayed in Table 8-12.

TABLE 8-12: ERRORS IN ESURF PREDICTIONS EXCEEDING 2.0 FEET FOR HURRICANE IKE.

nr	Station ID	Observed maximum water level (ft)	eSURF point	eSURF prediction (ft)	Error (ft)	Error (%)	Case of doubt?
1	8760922	8.13	Q167	3.30	4.83	59.4	no
2	7381349	7.88	Q377	2.60	5.28	67.0	yes
3	73745257	9.03	Q104	3.80	5.23	57.9	Yes

It seems that all three prediction points underestimated the maximum water levels. However, a closer look on the map is needed to exclude possible terrain type influence on the station and points.

There are no artificial or natural barriers between eSURF prediction point Q167 and NOAA station 876092. Therefore it seems that the influence of terrain type characteristics could possible not be the cause of the high amount of error.

Both prediction point Q377 and the station are located on open water and there is no land in between. But this is a case of doubt. The distance between prediction point and station is approximately 8000 feet. There might be a possible difference in terrain type causing the error. It seems that the local bathymetry could have caused the error. A site visit or checking a bathymetry map is recommended.

Prediction point Q104 is a case of doubt. On the map the location seemed like a swamp and the points are partly separated by land. But the station and prediction point are both connected by water and distance is relatively small compared to the distance between other observations stations and prediction points. A site visit to the NOAA station would provide the necessary details to exclude possible terrain type influence on the error.

Quantity of stations and prediction points
For hurricane Ike the second most maximum water level data is used for validation. The total number of maximum water level observations is 13. The total number of eSURF prediction points validated is 13. The total number of eSURF prediction points is 1024.

Structerally over- or underestimated
The scatter plot in Figure 8-9 visualizes how accurate eSURF predicted the maximum water levels for hurricane Ike. The dotted line describes the best possible fit to the reality, if observations are correct. Interesting is the fact that most points are located on or below the dotted line. The coefficient of determination R^2 for hurricane Ike is 0.75. eSURF underestimated the maximum water level for hurricane Ike.

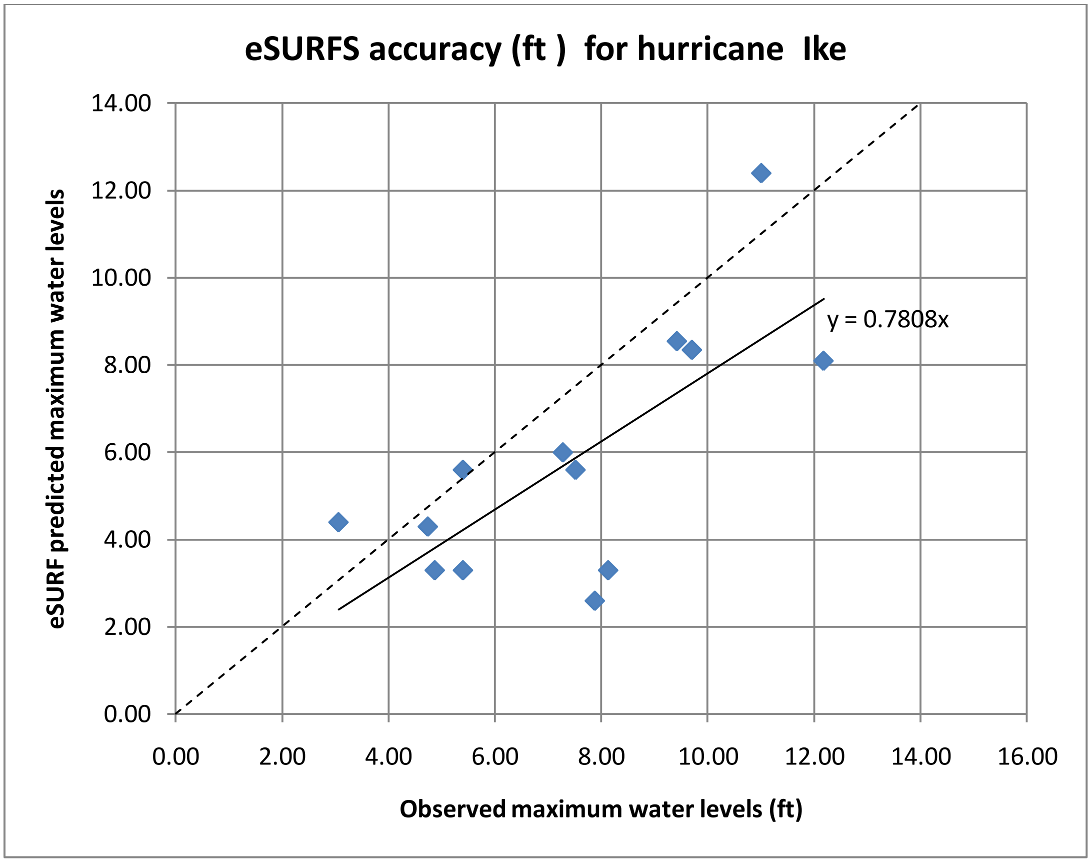


FIGURE 8-12: SCATTERPLOT FOR HURRICANE IKE

Hurricane characteristics

Gustav made landfall in south east Louisiana as a category 2 hurricane. The date and time of landfall are September 1th and 00:00 hour (UTC). Remarkable is the fact that maximum 1-minute sustained wind speeds decreases along with the minimum pressure. The RMW is smaller than the RMW of Katrina and Ike. Table 8-13 visualizes this. The maximum *observed* storm surge (above predicted tide) in Louisiana described in the tropical cyclone report of Gustav is 9.89 feet (Beven II & Kimberlain, 2009). The maximum *estimated* storm surge (above predicted tide) in Louisiana described in the tropical cyclone report of Gustav is 12.50 feet. Figure 8-16 visualizes the track of hurricane Gustav.

TABLE 8-14: HURRICANE CHARACTERISTICS OF GUSTAV (HURRICANE RESEARCH DIVISION)

Gustav	-12:00 hour	-06:00 hour	Landfall
Category	3	2	2
Maximum 1-minute sustained windspeeds (mph)	115	110	110
Minimum pressure (mbar)	961	960	953
Speed (mph)	17	17	14
Radius to maximum winds (Nmi)	-	-	26

FIGURE 8-13: TRACK OF HURRICANE GUSTAV

Maximum, minimum and mean error

Hurricane Gustav had not a remarkable mean error (in feet). However, it had one of the highest mean error (in %). Also hurricane Rita (48.8%) and Katrina (44.8%) had high mean error (%) compared to Ike and Ida. Furthermore, hurricane Gustav had the highest maximum error (%). The maximum, minimum and mean errors have been visualized in Table 8-15.

TABLE 8-15: MAXIMUM, MINIMUM AND MEAN ERROR FOR HURRICANE GUSTAV

	Error (ft)	Error (%)
Maximum	5.00	166.67
Minimum	0.48	4.99
Mean	2.21	45.40

Histogram of errors (ft)

For all stations having maximum water levels and prediction points available, a histogram has been made. This histogram in Figure 8-14 provides a clear overview on the amount of error for prediction points in feet.

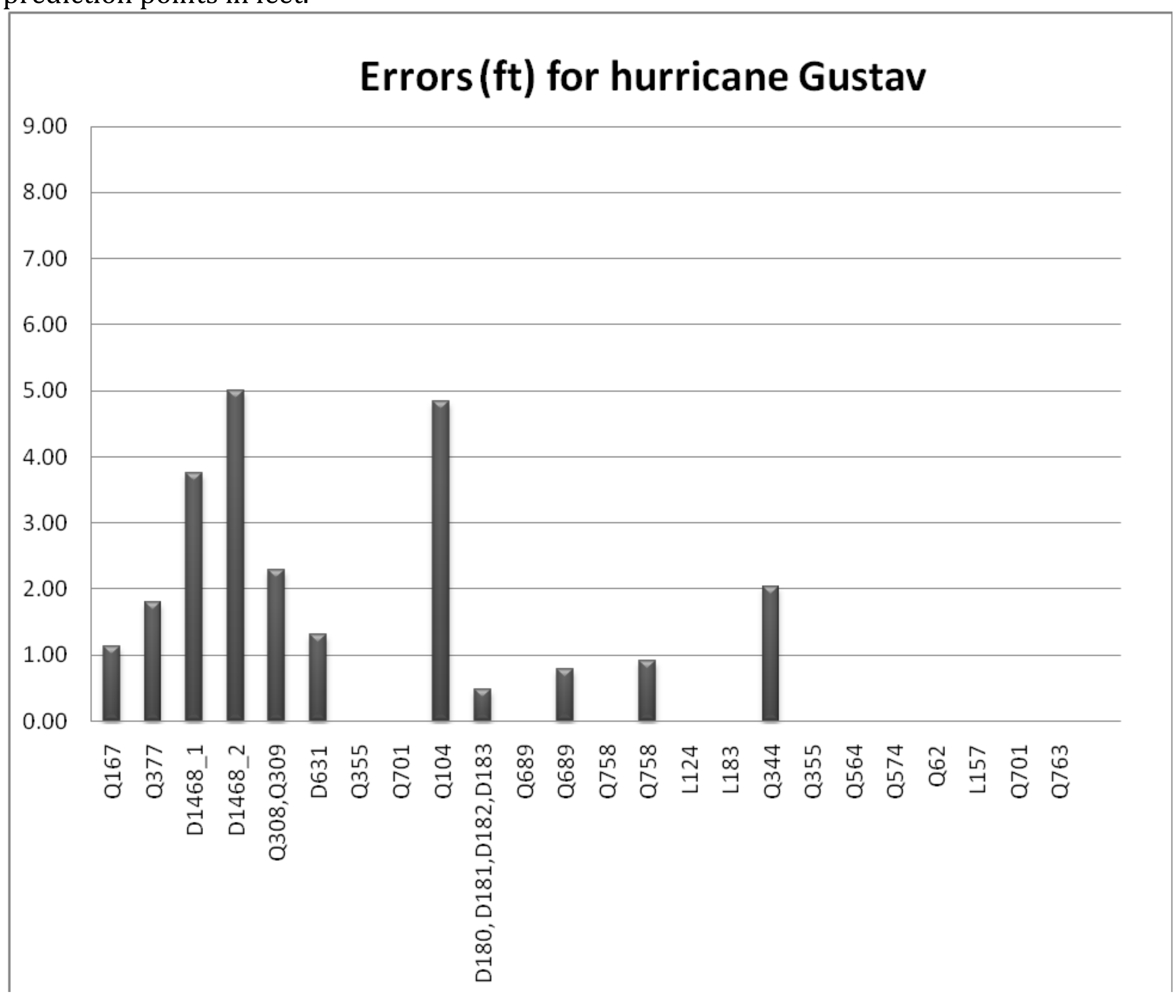


FIGURE 8-14: HURRICANE GUSTAV ERROR IN FEET BY PREDICTION POINT.

Errors exceeding 2.0 feet

Figure 8-14 shows 4 error peaks with an error value exceeding 2.0 feet. The points are displayed in Table 8-16.

TABLE 8-16: ERRORS IN ESURF PREDICTIONS EXCEEDING 2.0 FEET FOR HURRICANE GUSTAV.

nr	Station ID	Observed maximum water level (ft)	eSURF point	eSURF prediction (ft)	Error (ft)	Error (%)	Case of doubt?
1	8762372	4.25	D1468	8.00	3.75	88.4	Yes
2	85555	3.00	D1468	8.00	5.00	166.7	yes
3	8761305	10.38	Q308, Q309	8.10	2.28	22.0	no
4	73745257	14.04	Q104	9.20	4.84	34.5	Yes

It seems that no clear pattern of over- or underestimated maximum water levels for these points. The D1468 has over estimated the water levels for stations 85555 and 8762372. The prediction points (combination Q308 and Q309) and Q104 under estimated the water levels. A closer look on the map is needed to exclude possible terrain type influence on the station and points.

There are two observations that have been chosen to represent the eSURF prediction point D1468, based upon distance between point and station. Station 8762372 is located at a distance of 1800 feet in some kind of channel near coast. Station 85555 is located at a distance of 900 feet along the coast. A site visit is recommended for both stations.

Q308 and Q309 are located at a distance of 2700 feet to the coast. The observations station of NOAA is located at a distance of 500 feet off the coast. Although this is not set to be a case of doubt in the first place, it the bathymetry could have influenced the error.

Prediction point Q104 is a case of doubt. On the map the location seemed like a swamp and the points are partly separated by land. But the station and prediction point are both connected by water and distance is relatively small compared to the distance between other observations stations and prediction points. A site visit to the NOAA station would provide the necessary details to exclude possible terrain type influence on the error.

Quantity of stations and prediction points

The total number of maximum water level observations for hurricane Gustav is 13. The total number of eSURF prediction points validated is 13. The total number of eSURF prediction points is 1024.

Structerally over- or underestimated

The scatter plot in Figure 8-15 visualizes how accurate eSURF predicted the maximum water levels for hurricane Gustav. The dotted line describes the best possible fit to the reality, if observations are correct. Interesting is the fact that most points are located on the dotted line. The coefficient of determination R^2 for hurricane Gustav is 0.79. eSURF did not systematically over- or underestimated the maxim water level for this hurricane. However, some prediction points did overestimate the maximum water level.

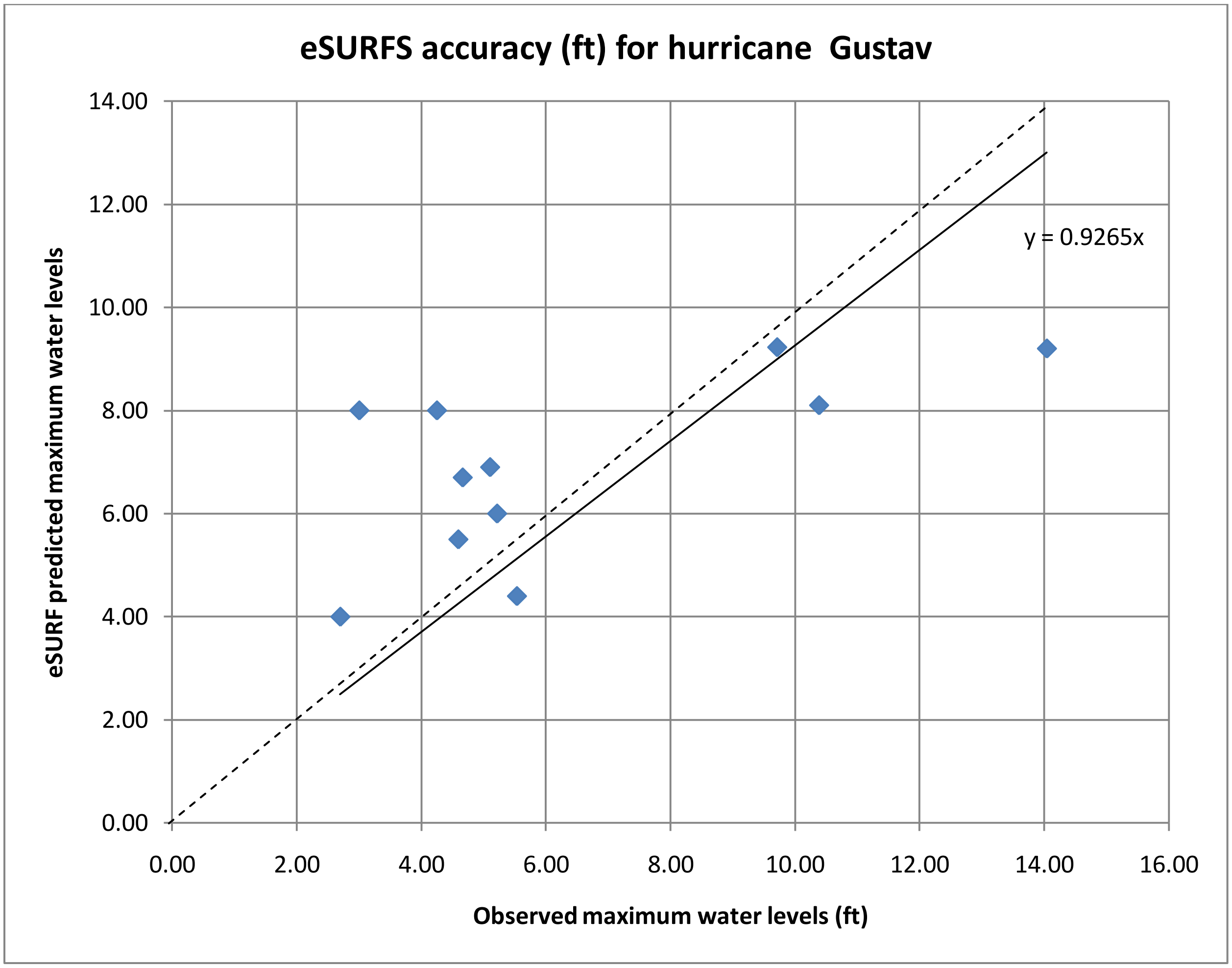


FIGURE 8-15: SCATTERPLOT FOR HURRICANE GUSTAV

Hurricane characteristics

Rita made landfall in south west Louisiana at the border of Louisiana with the state Texas. It made landfall as a major hurricane (category 3). The date and time of landfall are September 24th; 07:40 hour UTC. Remarkable is that the wind speeds slightly decrease, the pressure increases between 12 hours before and landfall. In addition, the radius to maximum winds has the smallest value compared to the other used hurricanes for validation. Hurricane Ida had RMW of 19 Nautical miles. Table 8-17 visualizes this. The maximum storm surge (above predicted tide) in Louisiana described in the tropical cyclone report of Rita is 9.89 feet (Knabb, Brown, & Rh, Tropical Cyclone Report: Hurricane Rita, 2006). The maximum *estimated* storm surge (above predicted tide) in Louisiana described in the tropical cyclone report of Gustav is 12.50 feet. Figure 8-16 visualizes the track of hurricane Gustav.

TABLE 8-18: HURRICANE CHARACTERISTICS OF RITA (HURRICANE RESEARCH DIVISION)

Rita	-12:00 hour	-06:00 hour	Landfall
Category	3	3	3
Maximum 1-minute sustained windspeeds (mph)	125	120	115
Minimum pressure (mbar)	930	931	935
Speed (mph)	10	11	10
Radius to maximum winds (Nmi)	-	-	16

FIGURE 8-16: TRACK OF HURRICANE RITA

Maximum, minimum and mean error

Hurricane Rita had the highest mean error (in feet and %). Also hurricane Gustav (45.4%) and Katrina (44.8%) had high mean error (%) compared to Ike and Ida. Furthermore, hurricane Rita has the highest minimum error (feet and %). The maximum, minimum and mean errors have been visualized in Table 8-19.

TABLE 8-19: ACCURACY OF ESURF FOR HURRICANE RITA

	Error (ft)	Error (%)
Maximum	4.95	68.3
Minimum	1.05	28.8
Mean	2.89	48.7

Histogram of errors (ft)

For all stations having maximum water levels and prediction points available, a histogram has been made. This histogram in Figure 8-17 provides a clear overview on the amount of error for the prediction points in feet.

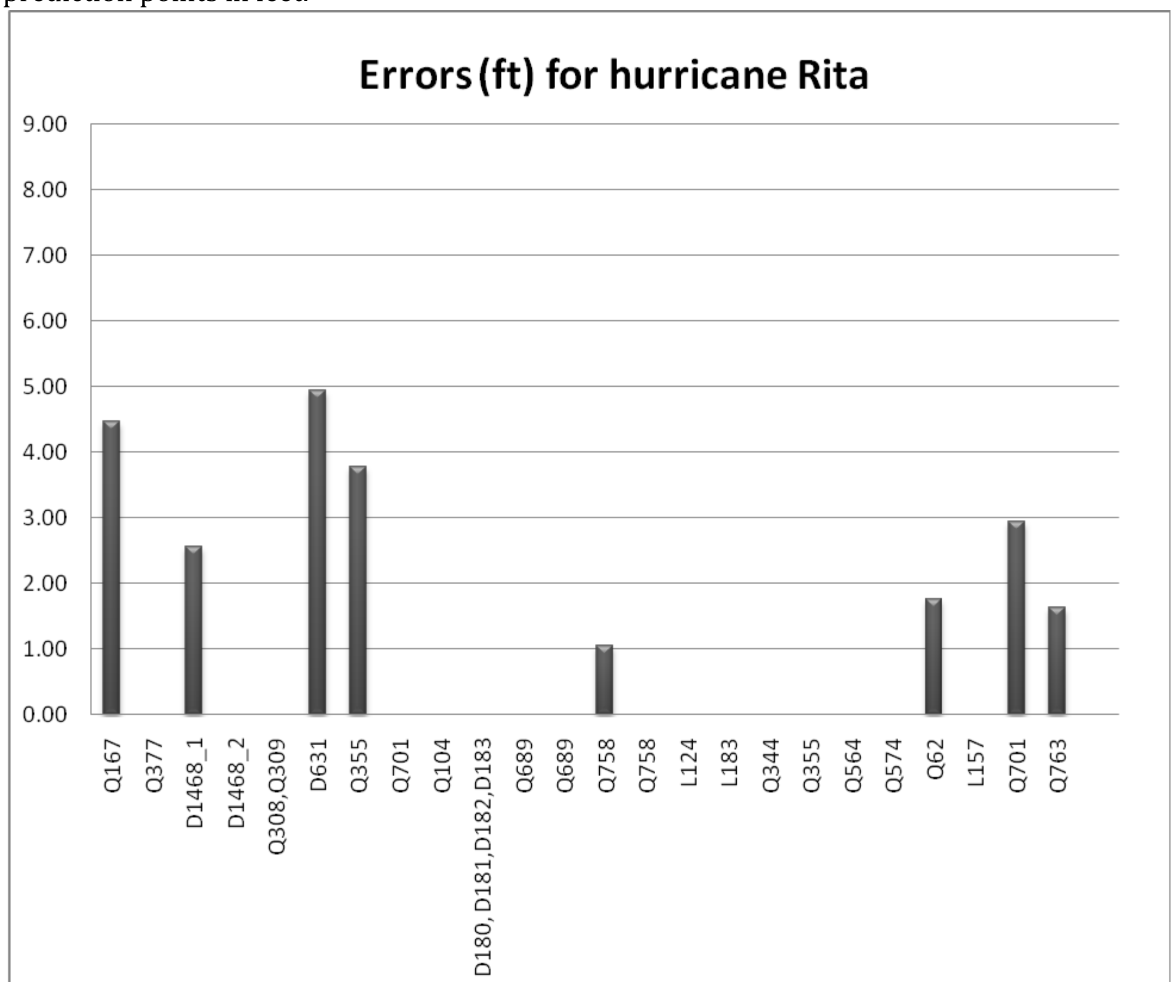


FIGURE 8-17: HURRICANE RITA ERROR IN FEET BY PREDICTION POINT.

Errors exceeding 2.0 feet
Figure 8-17 shows 5 error peaks with an error value exceeding 2.0 feet. The points are displayed in Table 8-20.

TABLE 8-20: ERRORS IN ESURF PREDICTIONS EXCEEDING 2.0 FEET FOR HURRICANE RITA.

nr	Station ID	Observed maximum water level (ft)	eSURF point	eSURF prediction (ft)	Error (ft)	Error (%)	Case of doubt?
1	8760922	7.16	Q167	2.70	4.46	62.3	no
2	8762372	6.66	D1468	4.10	2.56	38.4	Yes
3	8764044	7.25	D631	2.30	4.95	68.3	no
4	7380251	6.37	Q355	2.60	3.77	59.2	yes
5	76160	5.65	Q701	8.60	2.95	52.2	Yes

It seems that eSURF underestimated most maximum water levels for these prediction points. However, a closer look on the map is needed to exclude possible terrain type influence on the station and points.

There are no artificial or natural barriers between eSURF prediction point Q167 and NOAA station 876092. Therefore it seems that the influence of terrain type characteristics could possible not be the cause of the high amount of error.

There are two observations that have been chosen to represent the eSURF prediction point D1468, based upon distance between point and station. Only station 8762372 had observed water levels during the hurricane landfall. The station is located at a distance of 1800 feet in some kind of channel near coast. A site visit is recommended for this station.

There are no artificial or natural barriers between eSURF prediction point D631 and the NOAA observation station 8764044. Therefore it seems that the influence of terrain type characteristics could possible not be the cause of the high amount of error.

Prediction point Q355 is a case of doubt. The distance between the points is approximately 4000feet. However, both station and point have an open water connection. A closer look to the bathymetry of the area is needed to estimate the error due to depth differences. A lower depth could have cause a higher storm surge.

The prediction point Q701 is also a case of doubt. Station located in a channel perpendicular to the Mississippi River. The prediction point is located in the Mississippi river. Distance between point and station is relatively small. A site visit to observations station is needed, to investigate if a structure or dam is located in between.

Quantity of stations and prediction points
The total number of maximum water level observations for hurricane Rita is 8. The total number of eSURF prediction points validated is 8. The total number of eSURF prediction points is 1024.

Structerally over- or underestimated

The scatter plot in visualizes how accurate eSURF predicted the maximum water levels for hurricane Rita. It seems like eSURF heavily underestimated the maximum water levels for this hurricane. Almost all points are located beneath the dotted line. The coefficient of determination R^2 for hurricane Rita is 0.69. eSURF underestimated the maxim water level for this hurricane.

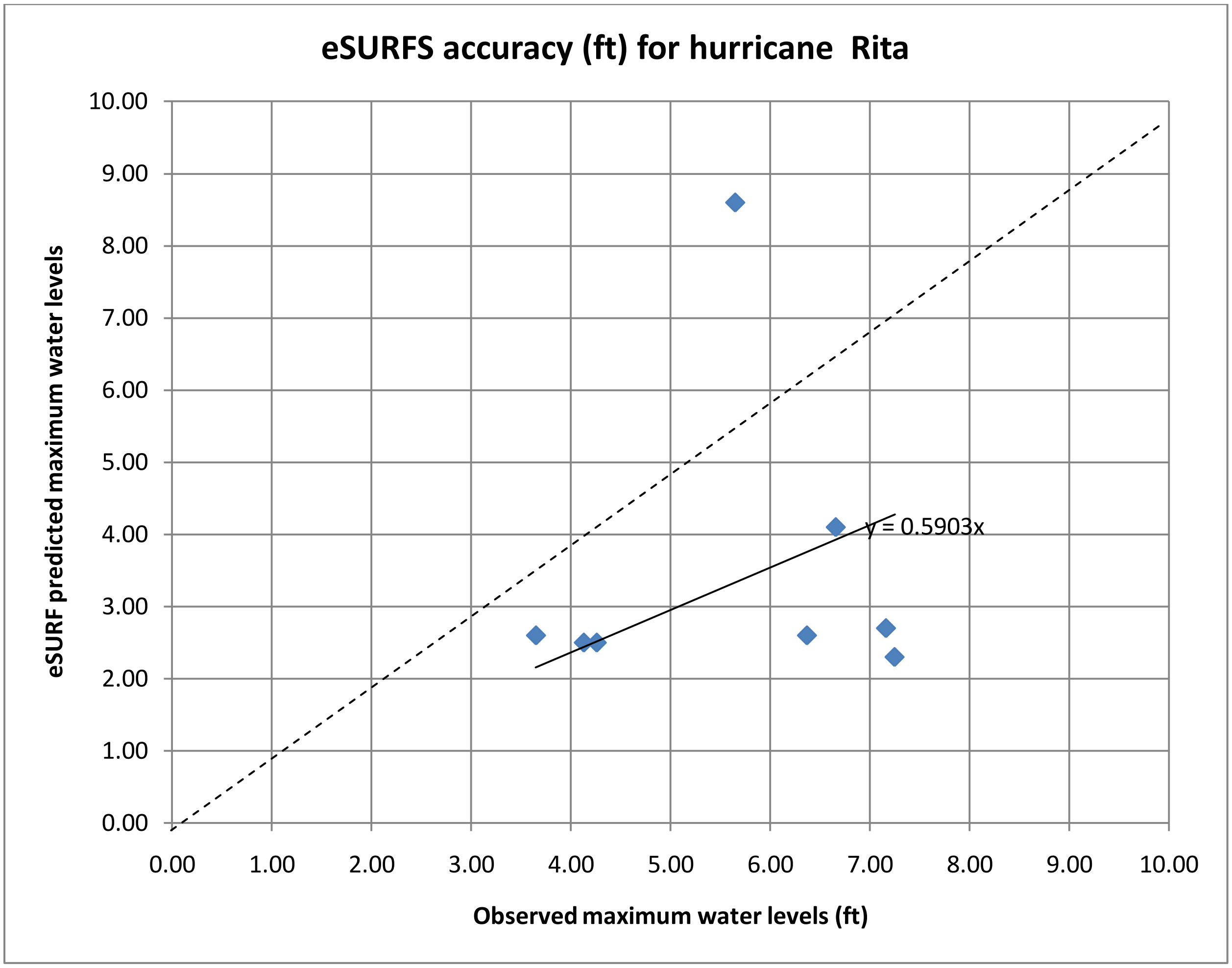


FIGURE 8-18: SCATTERPLOT FOR HURRICANE RITA

Hurricane characteristics

Hurricane Katrina made landfall in south-east Louisiana as a major hurricane (category 3). The date and time of landfall are August 29th; 11:10 hour (UTC). Remarkable is the fact that, Katrina had a similar RMW as Ike. In addition, the maximum 1-minute sustained wind speeds rapidly decreases till landfall. Furthermore, the minimum pressure rises. Table 8-21 visualizes this. The maximum storm surge (above predicted tide) in Louisiana described in the tropical cyclone report of Katrina is 18.7 feet (Knabb, Rhome, & Brown, Tropical Cyclone Report: Hurricane Katrina, 2005). Figure 8-19 visualizes the track of hurricane Katrina.

TABLE 8-21: HURRICANE CHARACTERISTICS OF KATRINA (HURRICANE RESEARCH DIVISION)

Katrina	-12:00 hour	-06:00 hour	Landfall
Category	5	4	3
Maximum 1-minute sustained wind speeds (mph)	160	145	125
Minimum pressure (mbar)	905	913	923
Speed (mph)	11	11	11
Radius to maximum winds (Nmi)	-	-	35

FIGURE 8-19: TRACK OF HURRICANE KATRINA

Maximum, minimum and mean error

Hurricane Katrina does not have an exceptional mean error (%). Hence, hurricane Gustav (45.4%) and Rita (48.7%) had high mean error (%) compared to Ike and Ida. Furthermore, hurricane Katrina has the highest maximum error (feet). The maximum, minimum and mean errors have been visualized in Table 8-22.

TABLE 8-22: ACCURACY OF ESURF FOR HURRICANE KATRINA

	Error (ft)	Error (%)
Maximum	6.48	88.3
Minimum	0.20	2.5
Mean	2.00	44.8

Histogram of errors (ft)

For all stations having maximum water levels and prediction points available, a histogram has been made. This histogram in Figure 8-20 provides a clear overview on the amount of error for the prediction points in feet.

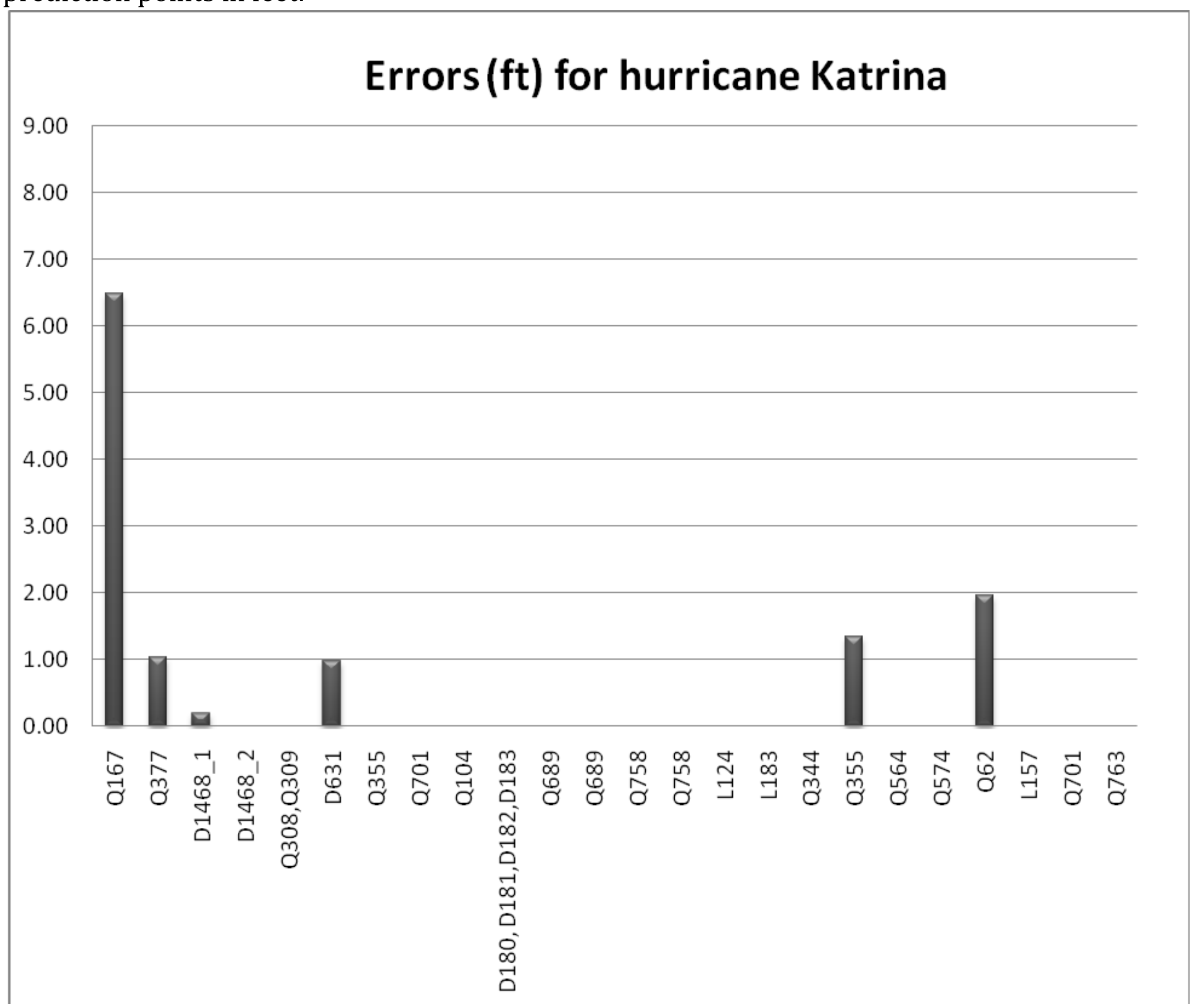


FIGURE 8-20: HURRICANE KATRINA ERROR IN FEET BY PREDICTION POINT.

Errors exceeding 2.0 feet
Figure 8-20 shows 1 error peak with value exceeding 2.0 feet. This point is displayed in Table 8-23.

TABLE 8-23: ERRORS IN ESURF PREDICTIONS EXCEEDING 2.0 FEET FOR HURRICANE KATRINA.

nr	Station ID	Observed maximum water level (ft)	eSURF point	eSURF prediction (ft)	Error (ft)	Error (%)	Case of doubt?
1	8760922	10.88	Q167	4.40	6.48	59.6	no

There are no artificial or natural barriers between eSURF prediction point Q167 and NOAA station 876092. Therefore it seems that the influence of terrain type characteristics could possible not be the cause of the high amount of error.

Quantity of stations and prediction points
The total number of maximum water level observations for hurricane Rita is 6. The total number of eSURF prediction points validated is 6. The total number of eSURF prediction points is 1024.

Structerally over- or underestimated
The scatter plot in visualizes how accurate eSURF predicted the maximum water levels for hurricane Kartina. The dotted line describes the best possible fit to the reality, if observations are correct. It seems like eSURF has quite accurately predicted the maximum water levels. One exception is the prediction for Q167. The coefficient of determination R^2 for hurricane Katrina is 0.84. Figure 8.23 visualizes the scatter plot.

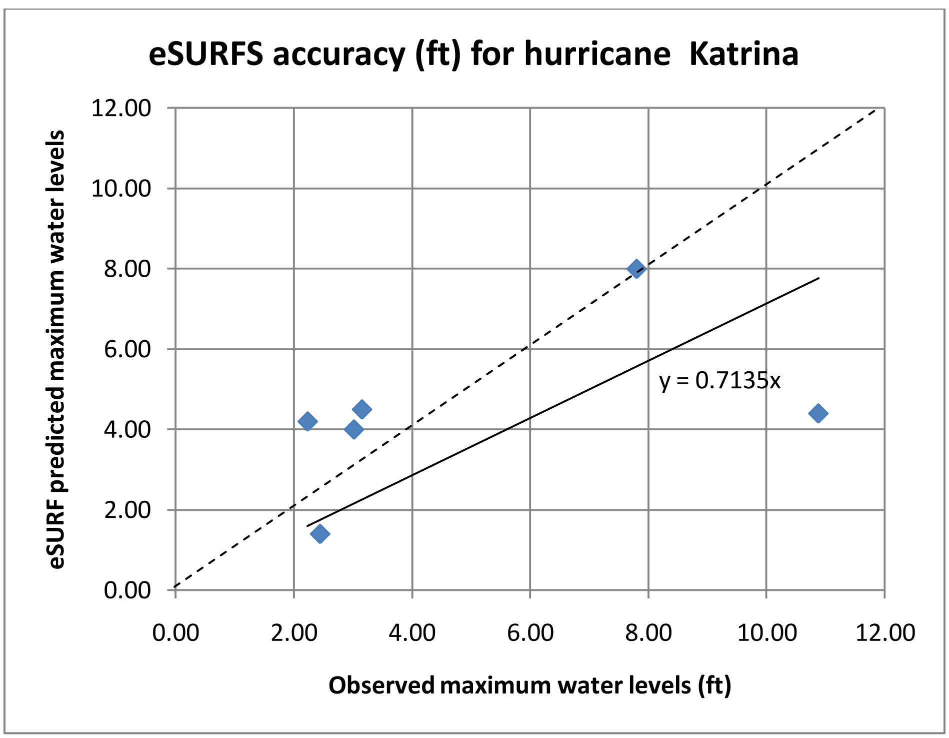


FIGURE 8-21: SCATTER PLOT FOR HURRICANE KATRINA