RICE UNIVERSITY

Distributed Hydrologic Modeling of Large Storm Events in the Houston-Galveston Region

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Master of Science

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HOUSTON, TEXAS
MAY 2013

ABSTRACT

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By Roni Deitz

In conjunction with the SSPEED Center, large rainfall events in the upper Gulf of Mexico are being studied in an effort to help design a surge gate to protect the Houston Ship Channel during hurricane events. When hurricanes hit Galveston Bay, there is a funneling effect and, depending on the track of the hurricane, the storm surge can vary by as much as 5 to 10 feet. For instance, Hurricane Ike produced a surge of about 13 feet in the bay; however, other tracks and higher winds could bring a worst case scenario of 20 to 25 feet of storm surge. Since the Houston Ship Channel is only protected from flooding up to 14-15 feet, and is currently the world's second largest petrochemical complex, it is critical to understand the linkage between rainfall and storm surge to better protect the region.

In this effort, rainfall events in the Houston-Galveston area are being examined. Given the large size of the watersheds flowing from the north and west, statistical methodologies, such as the Probable Maximum Precipitation (PMP) and Precipitation Depth Duration Frequency (PDDF), were employed to better design and predict the shape, pattern, size, and intensity of large rainfall events. Using Hydrometeorological Report (HMR) 52, as well as local hydrologic reports, the 24 hour PMP storm event was created for the upper Gulf of Mexico. In addition, large historic storms, such as Hurricane Ike, and simulated rainfalls from Hurricanes Katrina and Rita, were modeled over the Houston-Galveston region in a hydrologic/hydraulic model with the use of radar and rain gauge data.

Vflo^{TM}, a distributed hydrologic model was used to model the aforementioned storms. The region was first calibrated to USGS stream gauge data from Greens Bayou Brays Bayou and Peach Creek, and the modeled results accurately depict key features of observed hydrographs, including time to peak, discharge, and the double peak discharge phenomenon caused by double rain bursts. Once calibrated, Vflo^{TM}, is used to quantify the effect that storm size, intensity, and location has on timing and peak flows in the upper drainage area.

Results indicate that there is a double peak phenomenon with flows from the west draining earlier than flows from the north. With storm surge typically lasting 36-48 hours, this indicates the flows from the west and north are interacting with storm surge, with flows from the west arriving before flows from the north downstream. Gate operations were optimized in the model to account for the relative timing of upland runoff and hurricane surge, as well as the capability of the gate structure to protect the Ship Channel industry was quantified.

Acknowledgments

A very special thank you to my advisor and mentor, Dr. Philip Bedient. Over the past four and a half years, you have helped me to learn, mature, grow and develop into the engineer and person I am today. Thank you for not only teaching me about hydrology and water resources, but also about how to approach problems inside and outside of the classroom, and for giving me the opportunity to be a part of this program.

Thank you to my committee, Dr. Leonardo Dueñas-Osorio and Dr. Loren Raun for offering to be on my committee and for helping to play a vital role in my education at Rice University. Thank you to Dr. Jason Christian for your collaboration, your dedication to my research and constantly pushing for the best results possible. Thank you to the Severe Storm Prediction, Education, and Evacuation from Disasters (SSPEED) Center and other collaborators in this project. Thank you to Dr. Baxter E. Vieux and Vieux, Inc. for your assistance with radar rainfall data and with my Vflo questions.

Many thanks to the Bedient Research Group at Rice University for your support in my studies and for making this office feel like a family. A special thanks to undergraduate researchers, Gage Wright and Molly Horn, for their assistance.

A special thanks to my family and friends, who are always by my side, supporting and believing in me, even hundreds of miles away.

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Chapter 1: Introduction

1.1 Introduction and motivation of work

The focus area of this analysis is the San Jacinto River Basin, an approximately 4,500 square mile region located in seven counties, as seen in Figure 1a, and encompassing many large watersheds, as seen in Table 1. The San Jacinto River Basin includes multiple watersheds, with some draining into the Houston Ship Channel and the majority of the watersheds drain into the San Jacinto River. The watersheds located in Harris County are seen in Figure 1b.

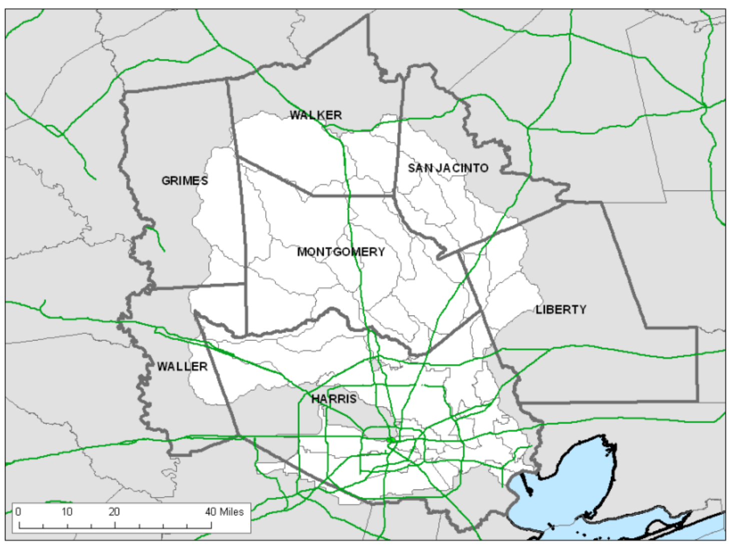


Figure 1a: The San Jacinto River Basin

Table 1: Counties and Watersheds of the San Jacinto River Basin

County	**Watersheds**
Grimes	West Fork San Jacinto
Harris	Brays Bayou, Buffalo Bayou, Carpenters Bayou, Cypress Creek, Greens Bayou, Hunting Bayou, Jackson Bayou, San Jacinto River, Spring Creek, Sims Bayou, Spring Gully and Goose Creek, and Vince Bayou
Liberty	East Fork San Jacinto
Montgomery	West Fork San Jacinto and East Fork San Jacinto
San Jacinto	East Fork San Jacinto
Walker	West Fork San Jacinto and East Fork San Jacinto
Waller	Buffalo-West Fork San Jacinto

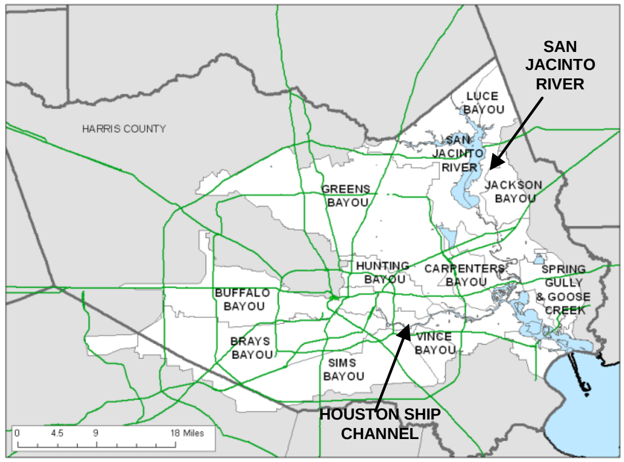


Figure 1b: Watersheds in Harris County

The northern counties of the San Jacinto River basin drain into Lake Houston. The San Jacinto River begins at the southeastern tip of Lake Houston (the San Jacinto Dam) and travels for nineteen miles before converging with the Houston Ship Channel in southeastern Harris County. From there, the two travel approximately nine miles before emptying into Galveston Bay, as illustrated in Figure 2.

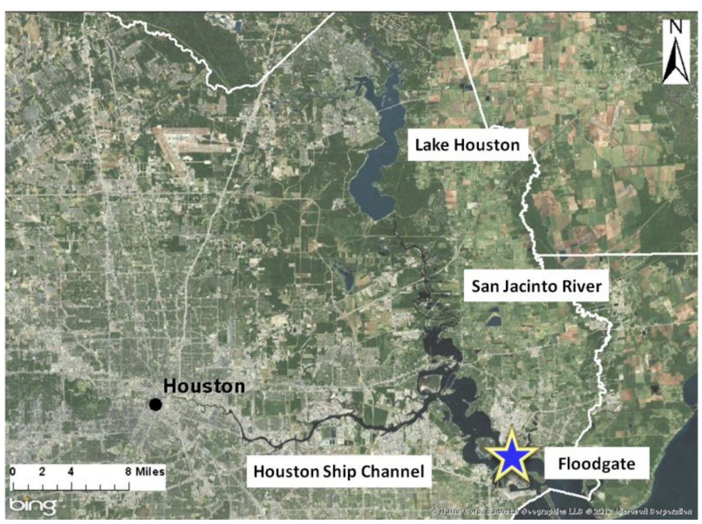


Figure 2: Important water features in Harris County, including Lake Houston, the San Jacinto River, the Houston Ship Channel, and the proposed location of the floodgate.

In the early hours of September 13, 2008, the eye of Hurricane Ike made landfall over the north end of Galveston Island as a Category 2 hurricane with maximum sustained winds of over 110 miles per hour and storm surges greater than 17 feet in Harris County (Bedient, Lessons from Hurricane Ike, 2012). However, even as only a Category 2 hurricane, Hurricane Ike resulted in 112 US deaths and resulted in approximately 30 billion US dollars in damage, making it the third of costliest storm in US History (Turner, 2012). According to Dr. Philip Bedient, Director of the SSPPED Center, “had that same storm struck 30 miles south, it could have easily have caused $100 billion in damage. Had it struck that location as a Category 4 storm, like Carla, the results would have been catastrophic” (Boyd, 2010).

This is not the first large storm event to hit the Houston-Galveston region, as seen in Table 2. However, the significant damage that resulted from Hurricane Ike acted as a warning sign to the region with regards to the damage that could ensue from future hurricane events. In order to better protect the region, the SSPEED Center proposed structural and non-structural improvements, including the construction a floodgate across the mouth of the Houston Ship Channel to protect the ship-channel industry from storm surge, which would look similar to the floodgate in Figure 3 (Turner, 2012).

Table 2: Selected Hurricanes of the Houston-Galveston Region

Hurricane	Year	Location at Landfall	Saffir-Simpson Category at Landfall	Estimate property damage (current US Dollars)
Galveston Hurricane	1900	Galveston, TX (Keim & Muller, 2009)	4	30 million (NOAA, 2012)
Atlantic-Gulf Hurricane	1919	Port Aransas, TX (Keim & Muller, 2009)	4	22 million (NOAA, 2012)
Carla	1961	Port O’Connor and Port Lavaca, TX (Keim & Muller, 2009)	4	2 billion (NOAA, 2012)
Alicia	1983	Galveston, TX (Keim & Muller, 2009)	3	2 billion (NOAA, 2012)
Bret	1999	Padre Island, TX (Keim & Muller, 2009)	3	15 million (NOAA, 2012)
Ike	2008	Galveston Island, TX (Bedient, Lessons from Hurricane Ike, 2012)	2	30 billion (Bedient, Lessons from Hurricane Ike, 2012)

Figure 3: Proposed Floodgate below the Fred Hartman Bridge. The proposed gate would be 0.4 miles in width, with 25 foot levees (already present) on each side (seen in red). This is the view looking in to Galveston Bay and the superimposed flood gates are the Rotterdam flood gates (SSPEED Center, 2011)

In order to better understand these structural improvements and ways to protect the region, the 4,500 square mile region flowing to this outlet has to be modeled and studied. Large area water resources management is complex as there are many difficulties in developing a model that is computationally efficient, has land data and rain gauge available for input, and produces accurate results, as explained by Arnold, et al. (1998). In addition, due to the fact that the San Jacinto River Basin is such a large drainage area, difficulties arise when trying to employ design storms. Reoccurrence interval design storms (i.e. 100 year storm) cannot be employed due to the improbability of such a large and intense storm occurring over such a large region for a long period of time in a uniform manner. For instance, while Tropical Storm Allison dropped a range of 15-40 inches of rain inside the 610 loop during the week of 6/4/2001 to 6/11/2001, regions outside the loop received approximately 10-15 inches. This is similar to the rainfall patterns of the October 1994 storm on the San Jacinto River, where the San Jacinto River watershed received between a 100-500 year recurrence interval of rainfall, with regions inside the 610 loop receiving between a 10 and 50 year recurrence interval of rainfall (Harris County Flood Control District, 2012). As a result of the large variability of the amount of rain present in the study area, a Soil Conservation Service (SCS) type III, 100 year distribution would not be a practical tool for modeling the amount of flow present at the confluence of the San Jacinto River and the Houston Ship Channel (Bell & Vieux, 2006).

Better statistical methods to approximate worst case rainfall scenarios have been developed for larger regions, including the PMP and the PDDF. The definition of PMP is the greatest amount of precipitation for a given storm duration that is theoretically possible for a given study area and geographic location (Texas Geographic Society, 2007; The Ohio Department of Natural Resources, 2001). The PMP is a useful tool for planning and design purposes, including designing dams, reservoirs, and managing local storm water drainage (Texas Geographic Society, 2007). The method to create the PMP is outlined in Hydrometeorological Report (HMR) 51 and 52 for Houston, Texas. The rainfall values were originally outlined in Technical Paper (TP) 40 and HMR 51, but were updated by Liscum for Houston in 2004 after Tropical Storm Allison. Liscum provides the PDDF values in his report “Determination of Precipitation Depth Duration Frequency-values for Harris County, Texas, after Tropical Storm Allison” (2004).

These design storms can be imported as rainfall tiles into a distributed hydrologic model. Hydrologic models are computer based models that simulate how rainfall falling over a watershed travels through time and space to create volumetric flow in the basin. Hydrologic models can be categorized as lumped or distributed parameter, event or continuous, and stochastic or deterministic depending on how parameters are entered and interpreted as well as which equations are used to simulate the hydrograph response (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012). Whether lumped or distributed, both types of hydrologic models incorporate watershed parameters, including soil type, imperviousness, infiltration, and initial saturation, to route the water through the watershed. Since the 1990's, distributed parameter models have become very popular to compute overland flow and channel routing as a result of GIS and the widespread availability of digital elevation data (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012).

VfloTM, a physics- based, distributed hydrologic model by Vieux & Associates, Inc., was used to model the San Jacinto River Basin. Vflo allows for spatial variability of input parameters to be considered within the watershed when calculating runoff (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012). Once the model had been created and rainfall had been simulated, the resulting flow hydrographs at multiple locations throughout the model (i.e. outlet or pour point of Brays Bayou) can then be used as inputs into the Hartmann Bridge Gate Model in HEC-RAS. Gate operations can be adjusted in the model to account for the relative timing of upland runoff and hurricane surge, for instance, adjusting the length of time at which the gate stays closed during the storm event in HEC-RAS. Vflo was chosen to model the region due to the availability of GIS data for a variety of parameters, such as elevation, land use, and soils, which are used as inputs to the Vflo model. Moreover, the region includes a wide distribution of soil types, elevation, and land uses, and employing a distributed parameter model allows for a more accurate representation of the land. In addition, Vflo was chosen due to its ability to process rainfall spatially distributed across the basin.

This study establishes a calibrated, fully distributed hydrologic model of the San Jacinto River Basin. In addition, multiple rainfall event scenarios were explored, including the 24 hour PMP storm event and simulated Hurricane Katrina and Hurricane Rita rainfall events, as if they had made landfall in the Houston-Galveston region. Moreover, Hurricane Ike, as it made landfall in 2008, was modeled. The Vflo model, as well as the different storms, was used to compare the rainfall-runoff response of the basin with different locations and intensities of the design storms by examining resulting hydrographs downstream of the proposed flood gate. Other hydrograph results throughout the model, specifically for individual watersheds are then used to further the design and operation of a surge gate and model the effects that a surge gate would have in protecting the Houston Ship Channel from hurricanes.

1.2 Summary of Objectives

This thesis employs a distributed hydrologic model to analyze large rainfall events of different sizes and intensities in the San Jacinto River Basin in a larger study to design and optimize a surge gate to protect the Ship Channel. The objectives of this thesis include:

- Build and calibrate a distributed model for the San Jacinto River Basin located in Harris, Montgomery, Walker, Waller, Grimes, Liberty and San Jacinto counties in Southeast Texas (see Figure 1a).
- Evaluate historical and design rainfall events for large areas that differ in intensity, space and load the rainfall tiles into the distributed model.

- Evaluate peak flow and timing of the discharge hydrographs downstream of the proposed flood gate.

- Analyze the timing and peak interaction between the discharge and storm surge hydrographs in the San Jacinto River Basin.

- Coordinate hydrologic results from Vflo with Dr. Jason Christian, PhD, PE, at University of Georgia, who is using the Vflo hydrographs as inputs as lateral flow inputs throughout the unsteady HEC-RAS model used to simulate the gate.

- Examine the effect that the flood gate has on reducing water surface elevation upstream of the flood gate during heavy rainfall and hurricane events.

This thesis will now discuss tropical cyclones and provide details about some of the past storms that have devastated the Gulf-Coast region. It is important to understand the size, magnitude, rainfall, storm surge and impacts associated with these historic storms as they are motivation for the study and also the storms being modeled. In addition, the study area will be introduced, including size and key soil and land use parameters. These parameters and some of the key features of the model as variables such as hydraulic conductivity, roughness, and soil depth assist in routing the runoff throughout the model. The thesis will then discuss hydrologic modeling and the reasons for using a distributed hydrologic model, specifically Vflo. Once the framework of Vflo has been established, the model development, sensitivity analysis, and calibration will be presented. It is crucial to understand the parameters driving the model and how sensitive each parameter is in order to produce and communicate accurate results. Next, the process used to develop the historic and design rainfall events will be explained, as a combination of radar and rain gauge rainfall data, as well as the statistical design methodologies that were used. The thesis will then present and discuss the current hydrologic and hydraulic findings. The goal of the hydrologic results is to understand the timing interaction between rainfall and storm surge, as well the expected flows at the proposed flood gate. The goal of the hydraulic results is to examine the ability of the gate structure to minimize water surface elevations upstream of the gate structure and, specifically, in the Houston Ship Channel.

Chapter 2: Rainfall and Hydrologic Modeling

2.1 Tropical Cyclones

Hurricanes and tropical storms are both types of tropical cyclones differing only in their wind speed. A tropical storm has winds of 39 to 73 miles per hour, while a hurricane has winds greater than 74 miles per hour (NOAA, 1999; Bedient, Lessons from Hurricane Ike, 2012).

There are many factors that determine the growth and decay of a tropical cyclone, with the most important factors being sea surface temperatures, vertical wind shear, and atmospheric moisture (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012). Hurricanes typically form where the surface water temperature is warm (26^{o}C) or greater and where surface winds converge (Ahrens, 2000).

On average, a tropical cyclone (tropical storms and hurricanes included) will produce 10-15 inches of rainfall over its traveled path. The forward motion of the storm is the most important aspect related to the amount of rainfall the storm will bring, with slower tropical systems producing greater amounts of rainfall than a faster moving system (Bedient, Lessons from Hurricane Ike, 2012). A rule of thumb used to estimate the amount of rainfall a tropical cyclone will produce is to divide 100 by the speed of the forward motion of a system (Harris County Flood Control District, 2012). The typical speed of the forward motion of a system for Houston, 29.7^{o} N latitude, is 12.5 miles per hour; however, some systems stall, often causing more rain, as was the case with Tropical Storm Allison, which stalled and looped over the region producing 35 inches of rain in five days (Dorst, 2007; NOAA, 1999; Harris County Flood Control District, 2012).

In addition to rainfall, storm surge is an important characteristic of hurricanes. Many factors affect the height of the storm surge as well as the distance inland the storm surge travels, including the size and intensity and forward speed of the storm, the topography of the region where the storm makes landfall, as well as the size of the storm's winds. It should be noted that storm surge and the category of the hurricane are not correlated – that is a Category 2 storm can result in greater storm surge effects than a Category 4 storm, as was the case with Hurricane Ike versus Hurricane Dolly (Harris County Flood Control District, 2012).

As a result of the lack of correlation between the category of a hurricane and the resulting storm surge, other categorization scales are being evaluated, such as IKE, the Integrated Kinetic Energy System. Integrated Kinetic energy would include a framework that would take into consideration more of the physical processes of a hurricane that produce forceful waves and storm surge. It would also consider the effect that the winds have on structures and the extent of the wind field (NOAA, 2006).

2.2 Historic Storms

The Gulf Coast region is one which is prone to tropical storms and hurricanes, with twenty mainland US hurricanes from 2001 to 2010. This is over three times the average number of hurricanes per decade since 1851. These events are deadly and disastrous, with events like Hurricane Katrina resulting in 1,833 deaths and 81 billion dollars (Bedient, Lessons from Hurricane Ike, 2012). The 1994 Storm, Hurricane Katrina, Hurricane Rita, and Hurricane Ike are discussed in further detail in the next sections as a result of their magnitude of rainfall, their large size and/or their storm surge.

2.2.1 1994 Storm

The 1994 flood on the San Jacinto River topped all previous historic events and is the largest storm to hit the region. From October 15-26, 1994, a non-tropical storm brought significant rainfall to the San Jacinto River Basin near Houston, Texas. An effective uniform depth of 17.5 inches of rain, with some areas receiving as much of 30 inches of rain fell over the watershed (University of Houston Geosciences and San Jacinto River Association). An illustration of the rainfall totals over the region is illustrated in Figure 4. According to the US Weather Bureau Technical Paper Number 49, the 4-day 100 year rainfall for the San Jacinto River watershed is 14.8 inches (Hershfield, 1961), making this event larger than a 100 year storm event and a 500 year event in certain tributaries in the watershed.

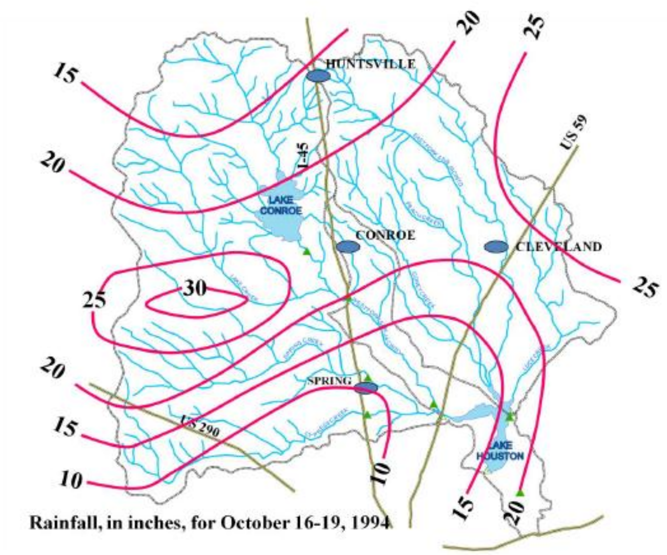


Figure 4: Rainfall totals (inches) for October 16-19, 1994 Source: (Johnson, 2004)

The USGS stream gauge at Sheldon, TX reported flows of 360,000 cfs, nearly 1.6 times that of the 100 year flow at that gauge, and exceed the 100-year flood stage by about 2.6 feet (Johnson, 2004; University of Houston Geosciences and San Jacinto River

Association). Bill Read, director of the National Hurricane Center, stated that “area-wise, it was a much bigger event than Allison, but the Allison rains fell right on the urban area… had the system been displaced some 30 miles southwest, it would have been worse than Tropical Storm Allison.” More than 10,000 people were displaced from their homes, 20 died from flooding, 25 counties were declared federal disaster areas, insured losses exceeded $700 million, and it was the first time that the newly completed portions of I-10, which run below grade inside the 610 Loop, flooded (Berger, 2008).

2.2.2 Hurricane Katrina

Hurricane Katrina, which hit the Louisiana/Mississippi coast in late August of 2005, was the third deadliest, costliest natural disaster and most destructive hurricane in terms of property loss along the American coast in the United States history (Keim & Muller, 2009). After reaching Category 5 intensity in the Gulf of Mexico, Katrina weakened to a Category 3 storm before making landfall on August 29, 2005 in Louisiana. The storm affected an area of nearly 90,000 square miles (Townsend, 2006).

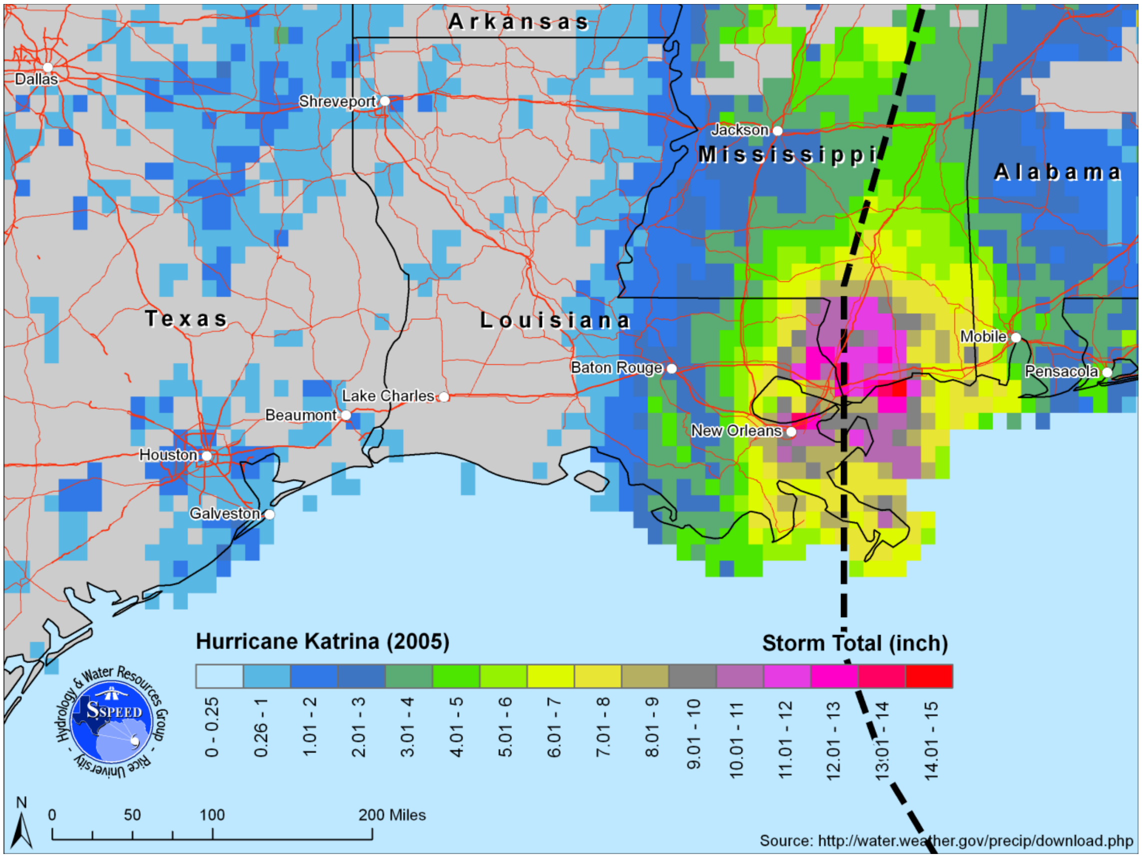


Figure 5: Rainfall totals (inches) for Hurricane Katrina

Hurricane Katrina, whose radar rainfall totals from NOAA are illustrated in Figure 5, has been recognized as a storm with strong winds and significant storm surge. Katrina made several landfalls, with the hurricane's strongest winds ranging from 140-150 mph when it crossed locations such as Grand Isle and then the Louisiana-Mississippi border. With strong winds came storm surge (Drye, 2005). High water mark observations from the Louisiana, Mississippi and Alabama coasts were collected and analyzed by FEMA. These results indicated that storm surge ranged from 24-28 feet along the Mississippi coast for a length of 20 miles, centered on St. Louis Bay, and ranged from10-15 feet from east to west along the Alabama Coast. In the greater New Orleans region of Louisiana, Katrina's storm surge caused over fifty different levee breaches, resulting in over eighty percent of the region to be inundated with storm waters (Graumann, et al., 2006).

As a result of Hurricane Katrina, lives were lost, significant structural damage occurred, and the national economy was affected. According to NOAA, 1833 people were confirmed dead across the Gulf Coast region (Graumann, et al., 2006). In addition, thousands of homes were destroyed, with direct damage to residential and non-residential property estimated at $21 billion dollars and another $6.7 billion in damage to public infrastructure (ASCE Hurricane Katrina External Review Panel, 2007). In total, Hurricane Katrina resulted in $81 billion in damages (Bedient, Lessons from Hurricane Ike, 2012). Moreover, fifteen refineries, nearly all in Louisiana and Mississippi were shut down or damaged. These fifteen refineries have a combined capacity of 3.3 million barrels a day, or 20 percent of the US refining capacity (Isidore, 2005).

2.2.3 Hurricane Rita

Less than a month after the devastation of Hurricane Katrina, Hurricane Rita was the second hurricane that season to reach Category 5 intensity in the Gulf of Mexico before making landfall on September 23, 2005 as a Category 3 Hurricane. While Rita was slow to become a Hurricane, Rita quickly intensified as a result of warm waters in the Gulf of Mexico and an environment of very weak vertical wind shear. Rita strengthened from a tropical storm to a Category 5 hurricane in less than 36 hours (NOAA, 2005). Hurricane Rita, whose radar rainfall totals are illustrated in Figure 6, was one of the strongest storms on record in the Atlantic Basin with peak sustained winds of 175 mph and the third most powerful hurricane on record in terms of central pressure, 897 mb (NOAA, 2005; NASA, 2005).

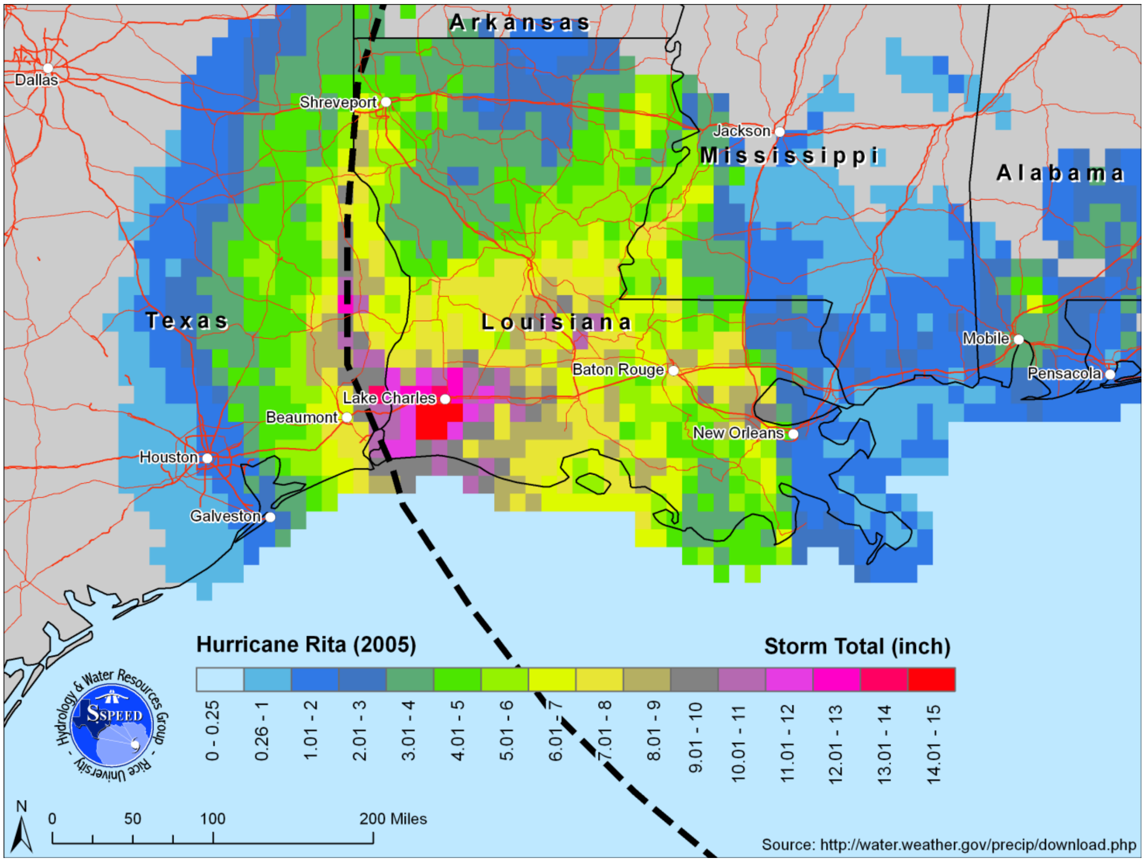


Figure 6: Rainfall totals (inches) for Hurricane Rita

Rita came ashore near the Texas and Louisiana border, about 35 miles north of Beaumont, Texas. As Rita moved inland, the storm's heaviest rains fell in Louisiana. The heavy rains plus a 15 foot storm surge along the Louisiana coastline caused massive flooding. (NASA, 2005).

Less than a month after Hurricane Katrina, the threat of another severe storm making landfall in the northern Gulf Coast caused much commotion in the region, including ordered mandatory evacuations and speculation of what effect another storm would have on the refineries (Blumenthal, 2005). Luckily, Hurricane Rita did not have as severe impacts as anticipated in the Houston-Galveston region, as the storm struck farther east. However, it was an evacuation disaster for the region, with evacuees spending more than 12 hours in traffic jams on Houston highways and over 100 deaths reported from the hurricane, car accidents, and health problems (Horswell & Hegstrom, Exodus weighs heavily in death toll: 107, 2009). In addition, prior to the storm making landfall, meteorologists and economists worried that Rita was such a large and strong storm that it could affect refineries at Port Arthur, Texas and Galveston, Texas if it made landfall at either location. If Rita did hit the Houston-Galveston area, as well as the Port Arthur-Beaumont region, it could take out more than 3 million barrels of capacity a day (Isidore, 2005).

2.2.4 Hurricane Ike

Hurricane Ike was the third costliest hurricane to ever make landfall in the United States, making landfall on September 13, 2008 as a Category 2 storm near Galveston, Texas (Berg, 2009). At its peak intensity, Hurricane Ike was a Category 4 storm with maximum sustained winds of 145 mph and a wind field spanning 450 miles at landfall (Bedient, Lessons from Hurricane Ike, 2012). While Hurricane Ike brought little rainfall, as seen from its radar rainfall in Figure 7, to the Houston-Galveston region in comparison to Hurricanes such as Katrina and Rita, Hurricane Ike was able to cause significant damage as a result of its storm surge. The highest storm surge value for Hurricane Ike recorded by USGS sensors was 17.5 feet located about 10 miles inland in Chambers County, with both Jefferson County, Texas and Cameron Parish, Louisiana recording surge heights of up to 17 feet (Bedient, 2012; Berg, 2009).

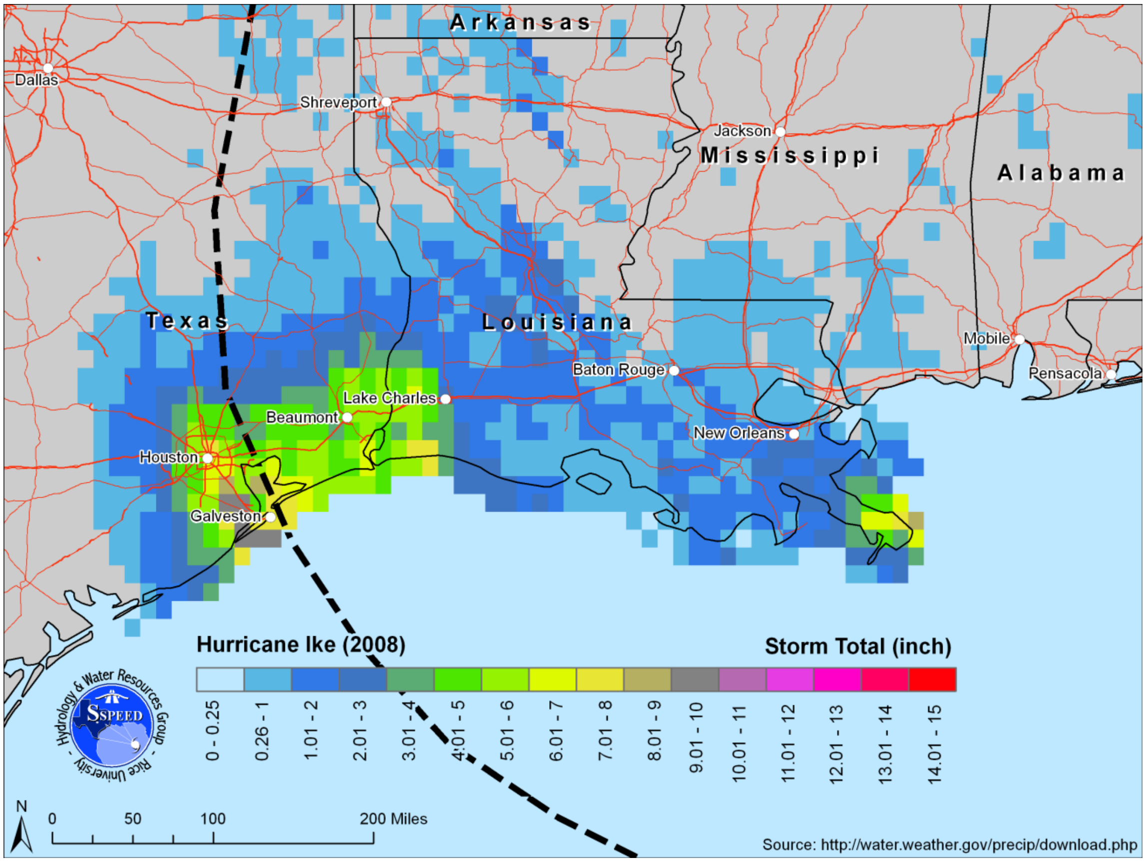


Figure 7: Rainfall totals (inches) for Hurricane Ike

Hurricane Ike resulted in $24.9 billion in damages, including nearly complete destruction on Bolivar Peninsula. Many homes were flooded on Galveston Island and effects were strongly felt in downtown Houston, where the pressure from the storm and high winds blew out the glass from the windows of many skyscrapers. While Hurricane Ike did not cause significant damage to the refineries located in the Houston Ship Channel, according to Philip Bedient, director of the SSPEED Center, if Hurricane Ike had made landfall just 50 miles south along the Texas Coast, the devastation and deaths would have quadrupled due to the fact that the storm would have brought a 20 foot storm surge to the Clear Creek area, which was not evacuated during the storm (Bedient, Lessons from Hurricane Ike, 2012).

The magnitude, intensity, and severity of the aforementioned storms illustrate the need to better understand and study the effect that large storm events have on the region and how to better defend industries and residences from disasters. These events can be better quantified and mitigation strategies can be examined through the use of hydrologic and hydraulic models.

2.3 Hydrologic Modeling

Hydrologic modeling employs computer based models to simulate hydrologic responses under a number of assumptions within the watershed area. Hydrologic models incorporate various equations, such as Kinematic Wave Analogy and Snyder Hydrograph Generation, to simulate how the rainfall falling over a basin would travel through time and space while accounting for water balances and storage. Within the larger framework of hydrologic modeling, models can be categorized as lumped or distributed parameter, event or continuous, and stochastic or deterministic depending on how parameters are entered and interpreted as well as which equations are used to simulate the hydrograph response (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012).

Lumped models, also referred to as empirical models, represent each basin with a single set of parameters. Then, empirical relationships are used to generate and route the runoff through the watershed. However, criticism of lumped models arises from the fact that the parameters of empirical relationships often do not have physical meaning or cannot be measured. For example, lumped models use SCS curve numbers for runoff generation, which are estimated for soil properties and land cover (Vieux, Distributed Hydrologic Modeling Using GIS, 2004).

In comparison, distributed models avoid averaging parameters and input to better represent watershed characteristics. This ability to explicitly represent the variability within each basin is due to the fact that distributed hydrologic models use continuous raster data for each parameter in the creation of the model. Then, the watershed is discretized, or divided into many smaller cells, creating a drainage network, and a set of equations is used to route the runoff throughout the model. Also, this is a physics based model, which uses conservation of mass, momentum, and energy equations to represent hydrologic processes (Vieux & Vieux, Vflo: A Real-Time Distributed Hydrologic Model). Differently from the lumped parameter model, the physics-based approach has parameters that are physically realistic and can thus be measured (Vieux, Distributed Hydrologic Modeling Using GIS, 2004). For instance, slope, is measureable or estimated from the elevation data loaded into the model. Also, the Green and Ampt equation, which relates the infiltration rate to the total depth of water infiltrated in the soil, uses physics based parameters and can be measured or estimated from soil properties. The Green and Ampt equation is:

$$f = K_s(1 - \frac{M_d \varphi}{F})$$

Where f is the infiltration rate,
K_s is the vertical saturated hydraulic conductivity
M_d is the moisture deficit
And   is the wetting front suction head.

There are some advantages and disadvantages to using physics-based, distributed models. An advantage of a distributed model is that the parameters used in the model come from geospatial data. In addition, physics based models can be solved using gridded precipitation input from radar or satellites, in addition to gauge data. However, this requires more data than lumped approaches and also increases the computational resources to solve the model (Shultz, 2007).

Vflo was chosen to model the region for multiple reasons. First, the soil and land use data was easily obtained from public, online sources, which is needed for input parameters to Vflo. In addition, due to the fact that the terrain varies widely in the 4,500 square mile region, Vflo, a distributed model, was able to better capture the spatial variability of the terrain through the input of continuous raster data. Moreover, the use of a physics-based model ensured that the parameters retained their physical meaning, which was of great assistance in the calibration process (see section 3.3). Next, Vflo permits for the use of radar rainfall, which captures the spatial and temporal variability of the rainfall. Instead, had a lumped parameter model had been chosen, the spatial variability of the input parameters, as well as the spatial and temporal variability of the rainfall would not have been as accurately captured. In addition, with such great variability in terrain, the computational time and computational space needed to create an adequate model would have been much more intensive.

2.4 General Description of Vflo Model

Vflo is a physics-based distributed hydrologic model that numerically solves the kinematic wave equations for runoff routing, and the Green-Ampt infiltration equations and saturation excess for runoff generation (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012). GIS is used to preprocess elevation, soil, and land use data to be inputted into the Vflo model. The inputs for Vflo are in the form of continuous raster data, and then the model is discretized and a network is formulated based on Finite Element Method (Vieux & Vieux, Vflo: A Real-Time Distributed Hydrologic Model). Once the model is parameterized, the model is also designed to use distributed rainfall either derived from radar, rain gauge, or independently created rainfall files to spatially and temporally represent rainfall data. Next, the runoff is generated using saturation and infiltration rates, with runoff then being routed from overland grids that connect channels within the drainage network. An illustration of the Vflo grid and flow characteristics for each cell is shown in Figure 8.

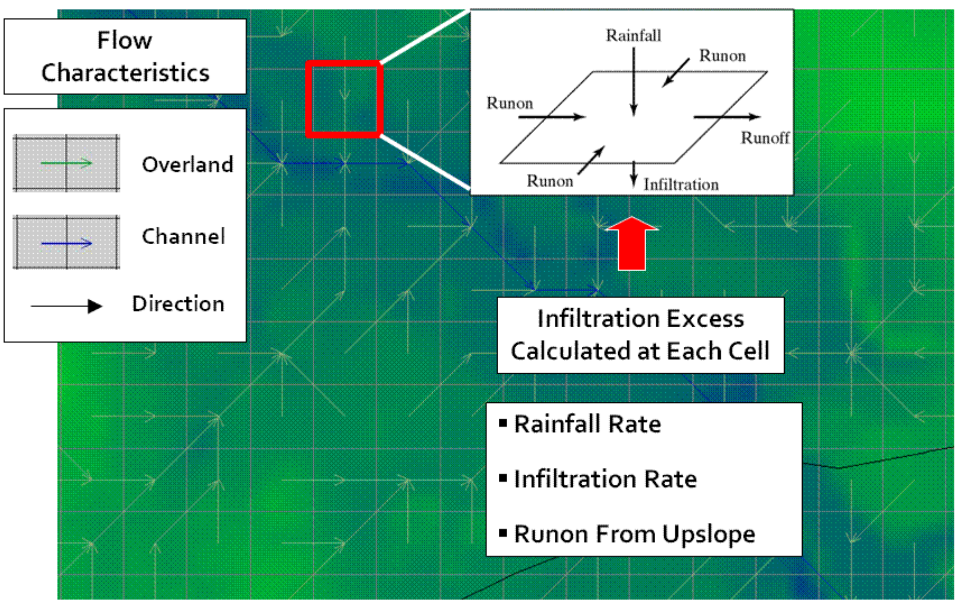


Figure 8: Vflo grid and flow characteristics for each cell Image source: (Doubleday, 2012)

The different forms of the momentum equation, as seen in Table 3, are solved numerically for the drainage network based on the conservation equations. Both overland and channel flow can be represented using this equation with the proper modifications. The numerical solution of the kinematic wave (steady uniform) yields useful approximations without having to solve the full Saint Venant Equations (unsteady nonuniform), which are often difficult to solve for a watershed with a large array of conditions. Certain assumptions are made in order to use steady uniform, such as small change of water depth (*d*y/*d*x) as well as the longitudinal velocity gradient term (v/g)(*d*v/*d*x) and the time rate of change of the velocity term (1/*g*)(*d*v/*d*t) will typically be less than 0.001 in a typical shallow stream (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012).

Table 3: Different Forms of the Momentum Equation (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012)

Table 4–1 Forms of the Momentum Equation

Type of Flow	Momentum Equation
Kinematic wave (steady uniform)	$S_f = S_0$
Diffusion (noninertia) model	$S_f = S_0 - \partial y/\partial x$
Steady nonuniform	$S_f = S_0 - \partial y/\partial x - (v/g)\,\partial v/\partial x$
Unsteady nonuniform	$S_f = S_0 - \partial y/\partial x - (v/g)\partial v/\partial x - (1/g)\partial v/\partial t$

Vflo allows specific watershed characteristics to be incorporated into the model as well. For instance, channel cross sections can be imported from the digital elevation model or manually imputed from surveyed cross sections. In addition, rating curves can be imported to accurately depict the relationship between stage and discharge, and information about dams and reservoirs can be included in the model, if included in the watershed.

Vflo allows four different types of precipitation inputs for its model, which can be further categorized into two different types of precipitation inputs for its model, point and grid values. All four types of precipitation inputs were used in modeling the San Jacinto River Basin.

The first option is rain gauge data. Rain gauge data, which comes in the form of point data, can be spatially distributed over the model using different weighting options, including exponential and inverse distance weighting methods within the Vflo model (Vieux & Vieux, Vflo: A Real-Time Distributed Hydrologic Model). In regions such as

Harris County, where there is an extensive rain gauge network maintained and calibrated, and with data archived by Harris County Office of Emergency Management (HCOEM), gathering data from many rain gauges and using inverse distance weighting over the region can provide a budget friendly, good estimate of the true storm event (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012). Thus, for simulating Hurricane Ike in Harris County, rain gauge data was used. It is important to note that human errors do still arise and gauges often malfunction or lose functionality in large storm events. Thus, interpolated rain gauge data was checked against radar rainfall data in Greens Bayou to ensure accuracy.

Next, Vflo allows for the use of radar rainfall. Radar rainfall or combined radar and gauge rainfall data, which is a gridded input, is becoming increasingly popular as a result of increasing technology for hydrologic purposes. Radar rainfall data is useful for applications where models are simulating streamflow events and being employed to make flood predictions. Rainfall derived from radar is a useful tool as it far exceeds the spatial density of most rain gauge networks and also is capable of measuring patterns of rainfall not only in space, but over time as well (Bedient, Huber, & Vieux, Hydrology and Floodplain Analysis, 2012). This ensures that models are more closely calibrated to historic data and that simulated events more accurately predict the actual rainfall-runoff response in the watershed. Thus, radar rainfall, which is spatial information, can be a useful supplement to rain gauge data, which is always point measurements, in simulating events (Bardossy, 2007). Radar rainfall data was employed in regions outside of Harris County where rain gauges were sparse.

In addition, Vflo allows for user-created gridded rainfall data inputs. As will be discussed in more detail in Chapter 5, the 24-hour PMP storm and rainfall simulations from Hurricane Katrina and Hurricane Rita for the Houston-Galveston region were created and modeled in Vflo. These design storms were modeled over the region as the result of Vflo's ability to allow the user to import multiple rainfall grids to simulate a storm event.

The final type of gridded rainfall data that Vflo can process is Design Storm Data. Vflo allows the user to select the SCS Design Storm Type based on the region the model is located in (i.e. Type I, IA, II, III, depending on where the study area is located in the United States), the SCS rainfall depth based on the design storm (i.e. 13.5 inches for 100-year storm for Houston, Texas), and duration (i.e. 24-hour storm). Vflo will then generate an SCS storm hyetograph for a uniform rainfall event over the modeled region. While this is impractical for large scale models, it is very useful for small models. Thus, when calibrating the model, for small watersheds without stream gauges to calibrate to, design storms were calibrated to results from 2007 Tropical Storm Allison Recovery Project (TSARP) results. This will be explained in greater detail in Chapter 4.

2.5 Spatial and Temporal Distribution of Rainfall

The Probable Maximum Precipitation is the greatest amount of precipitation, for a given storm duration, that is theoretically possible for a particular study area and geographic location (The Ohio Department of Natural Resources, 2001). The PMP is being employed in this study due to the fact that an upper bound for extreme rainfall events over large areas is desired.

The PMP methodology employs both metrological and historical records to determine the probable maximum rainfall value for a region. For instance, one method used to determine the PMP is “moisture maximization”, where the maximum possible atmospheric moisture for a region is applied to rainfall data from a historic storm. This process increases the rainfall depths, thus bringing them closer to their maximum value (The Ohio Department of Natural Resources, 2001).

HMR 51 goes into further detail about the procedures and methods used for developing the estimates for the PMP and presents all-season estimates, the greatest for any time of the year, for basins ranging in size from 10 to 20,000 square miles and for durations of six to 72 hours, east of the 105^{th} meridian (NOAA, 1978). HMR 51 contains information of 53 large storms that were used in the development of TP 40, HMR 51, and HMR 52 (Riley & Moore).

HMR 52 explains the spatial and temporal methodology of the estimates derived in HMR 51, including shape and orientation of isohyetal patterns for a given PMP value. For example, an elliptical isohyetal pattern with a ratio of major to minor axes of 2.5 to 1 is recommended and a procedure is outlined for obtaining the values for the different isohyets and different storm orientations based on location (NOAA, 1982). More information on the spatial and temporal creation of the PMP will be discussed later on in Chapter 5.

While HMR 51 presents all-season estimates for the PMP, Riley argues that none of the events in the original HMR-51 databases were fully instrumented and recorded and most lost records at least some point during a storm event (Riley & Moore). Thus, it is beneficial to examine more recent PMP studies because of better gauge data, and even look at Houston specific studies for the most appropriate values for the region. PMP studies have been conducted for Houston, Texas, including *Depth-Duration Frequency of Precipitation for Texas* by Asquith in 1998 and *Determination of Precipitation Depth Duration Frequency-values for Harris County, Texas, after Tropical Storm Allison* by Fred Liscum, et. al. for ASCE in 2004. Liscum updated previous PMP studies after Tropical Storm Allison occurred in 2001. Liscum argues that the gauges used in previous studies of this region were poorly distributed and did not accurately depict storm events. Thus, as compared to the 1998 Asquith study, Liscum increased the number of rain gauges used for the area, increased the length of the record analyzed, and included Tropical Storm Allison event into his study. Liscum argues that the values from his analysis are “consistently equal or higher for all durations and all recurrence intervals greater than 50-years than values determined in previous studies for the area” and that the “recorded rainfall amounts recorded for every duration greater than 1-hour (i.e., 3-, 6-, 12-, 24-hours) were greater that the computed depth duration values for the 500-year recurrence interval” (Liscum, Johnson, Woodward, & Spenn, 2004). Thus, due to its more updated gauge distribution and data, the rainfall values for the PMP for Houston, Texas were obtained from the Liscum article. More about the methodology used to create the PMP, including size, orientation, and temporal arrangement of rainfall, is located in Appendix 9.1. These rainfall events were created as grids to be used in Vflo, which will be discussed in Chapter 5.

3. Study Area and Model Development

The study area for this thesis is the San Jacinto River Basin. The region is 4,500 square miles, making it a very large watershed to model. Thus, as will be explained in the following sections, certain adjustments were made in order to accurately model the entire region. For instance, three models were created and linked together to describe the study area using boundary conditions within Vflo.

3.1 The San Jacinto River Basin

The San Jacinto River watershed is a large watershed located in Southeast Texas. The channels within the watershed help to drain seven counties, Harris, Montgomery, Waller, Walker, Grimes, Liberty, and San Jacinto counties. In Harris county, the San Jacinto River watershed covers about 487 square miles, including the San Jacinto River, Lake Houston and the Houston Ship Channel (Harris County Flood Control District, 2010). The San Jacinto River is composed of the East Fork (69 miles) and the West Fork (99 miles) of the San Jacinto River, which were dammed to create Lake Houston in the 1940's and 1950's (Harris County Flood Control District, 2010; Webb & Gore, 2010). The San Jacinto River then flows from the San Jacinto Dam located at the southern rim of Lake Houston in northeast Harris county and flows southeast for roughly nineteen miles before its confluence with the Houston Ship Channel, and then flows another nine miles before it reaches its mouth, Galveston Bay (Harris County Flood Control District, 2010).

Lake Houston is a 19 square mile reservoir situated on the West Fork of the San Jacinto River. The drainage basin above Lake Houston is approximately 2,828 square miles (The Texas Water Development Board, 2003; Johnson, 2004). At the southern tip of the reservoir, just below the confluence of the East and West Fork, is the San Jacinto Dam. These features are illustrated in Figure 9. The dam consists of reinforced concrete slab and buttress spillway section that is 3,160 feet in length, with the spillway crest elevation of 44.5 feet msl. According to 1965 surveying reports, Lake Houston records a storage capacity of 146,769 acre-feet (as compared to the 53 million acre-feet per capita per day for Houston in 2003 (Dallas Indicators)) and a surface area of 12,240 acres at the spillway crest elevation of 44.5 feet msl (The Texas Water Development Board, 2003).

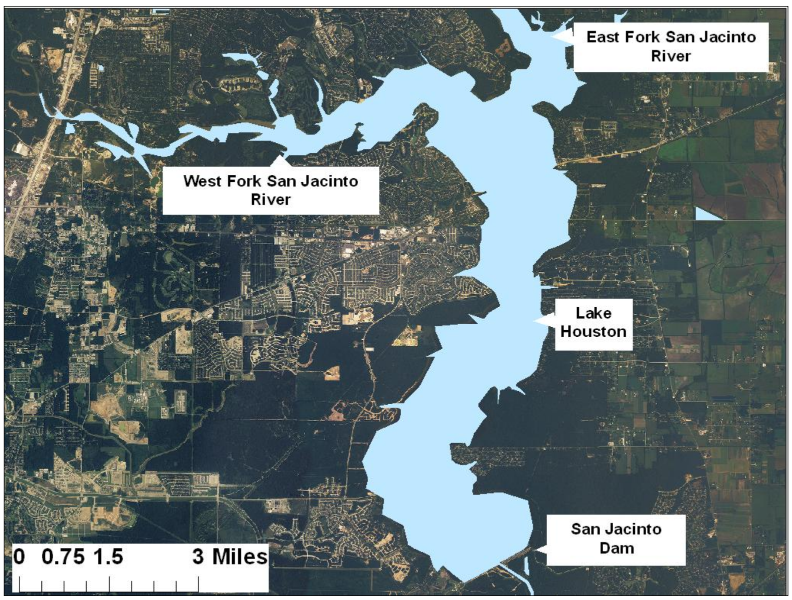


Figure 9: Lake Houston and important water features

The City of Houston constructed the manmade lake and dam in 1953 for multiple purposes and deliberate impoundment of water began in April of 1954 (Breeding; Horswell, Houston's Thirst Takes Toll on Sinking Lake Conroe, 2011). State Board of Water Engineers permits from the early 1940’s authorized the City of Houston to originally impound 152,000 acre-feet of water and the use of 112,000 acre-feet of water annually for municipal, industrial, recreational, mining, and irrigation purposes. In the late 1940’s, the State Board of Water Engineers authorized an increase in the impoundment capacity to 160,000 acre-feet and increased the allocation to 168,000 acre-feet of water per annum and allowed irrigation of 1,500 acres of land (The Texas Water Development Board, 2003).

The Houston Ship Channel as seen in Figure 10, part of Buffalo Bayou and located in Southeast Houston, is one of the busiest waterways in the United States and is the largest petrochemical complex in the United States. Even dating back to the 19th century, Buffalo Bayou was one of the most traveled routes for goods, visitors, and immigrants as it proved to be the only "dependably navigable" waterway in Texas (Sibley). Today, the Houston Ship Channel helped generate more than $178.5 billion US dollars in statewide economic impact, and supplies over a million jobs throughout Texas associated to ship-channel related businesses (Port of Houston Authority, 2012).

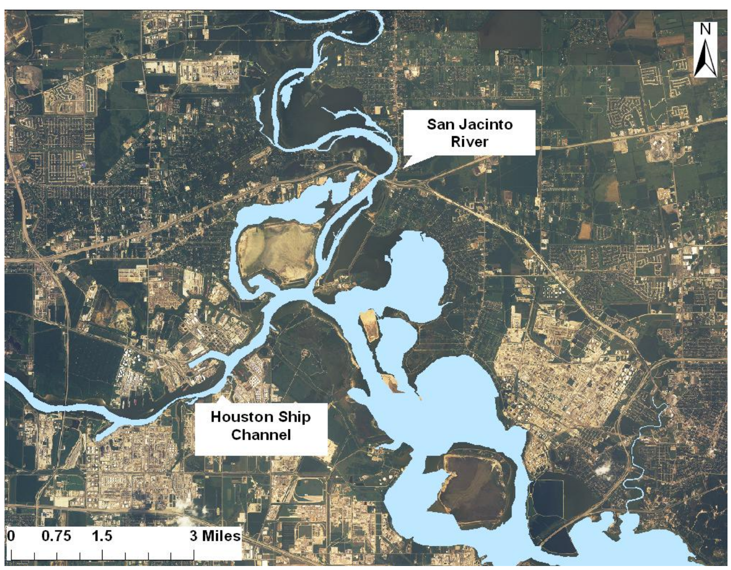


Figure 10: The San Jacinto River and the Houston Ship Channel

3.2 Data Analysis of Study Area

The San Jacinto River Basin has a drainage area of about 4,500 square miles, a very large region to model since Vflo caps each model at 50,000 cells in order to minimize computational time and space. If only one model had been used, the cells would have had to have been so large that the detail of the region would have been jeopardized. Thus, in order to ensure accurate and reliable results, three models were created: An “Upper San Jacinto River” model, a “Houston Ship Channel West Inflow” model, and a “Lower San Jacinto River” model, as seen in Figure 11.

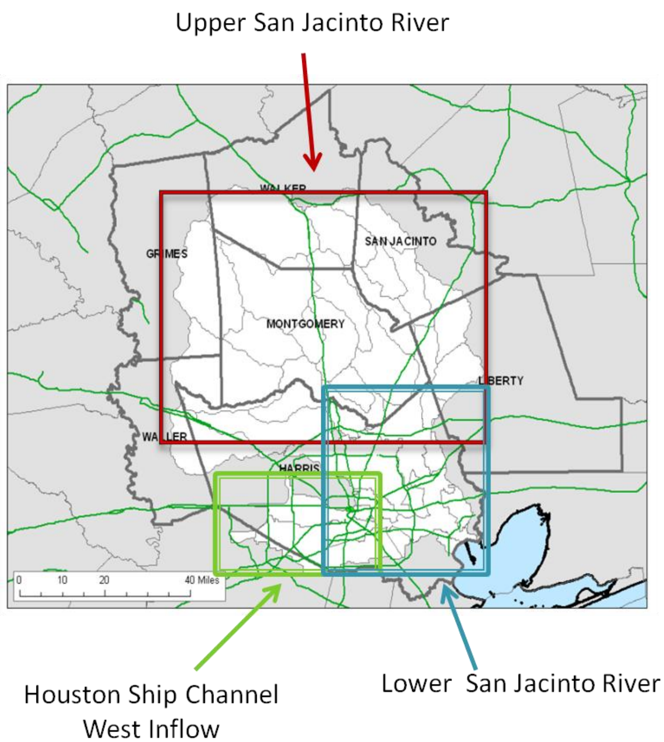


Figure 11: Map of regions represented in each Vflo model.

In the “Upper San Jacinto River” model there are thirteen watersheds that eventually flow into Lake Houston, including Luce Bayou, East Fork San Jacinto River, Lake Conroe, Cypress Creek and West Fork San Jacinto River watersheds. (San Jacinto River Authority, 2012). In the “Houston Ship Channel West Inflow” model, Sims, Brays, and Buffalo Bayou Watersheds were modeled. Finally, in the “Lower San Jacinto River” Model, the San Jacinto River below Lake Houston, Jackson Bayou, Spring Gully and Goose Creek, Carpenters Bayou, Greens Bayou, Hunting Bayou, Vince Bayou, and the

Houston Ship Channel were modeled. The outputs from the former two models were used as inputs into the latter model to ensure accurate timing and peak flows.

The San Jacinto River Basin is interesting to study due to the wide array of soil, land use, and elevation characteristics within the basin. A summary of the drainage area, major streams and characteristics for some of the major watersheds is presented in Table 4. The major bodies of water are the bayous and rivers present in each watershed. In addition, the average slope, average roughness, and average hydraulic conductivity are the average value of the parameter for the watershed. In the Vflo model, each cell has its own, unique value; thus, this average value is a composite of actual values in each cell and not a uniform value used throughout the region.

Table 4: Summary of drainage area for major watersheds in all three models, as calculated in Vflo

Watershed	Major Bodies of Water	Size (sq mi)	Average Slope (%)	Average Roughness	Average Hydraulic Conductivity (in/hr)
Greens Bayou	Greens Bayou Halls Bayou Garners Bayou Reinhardt Bayou	212	0.10	0.03	0.27
Brays Bayou	Brays Bayou Keegans Bayou Willow Waterhole Bayou	127	0.37	0.02	0.08
Buffalo Bayou	Buffalo Bayou	103	0.50	0.05	0.31
Upper San Jacinto	The San Jacinto River Caney Creek Peach Creek East Fork San Jacinto River Luce Bayou Cypress Creek Spring Creek Lake Creek Lake Conroe White Oak Creek West Fort San Jacinto River	2500	0.70	0.11	0.98

Much attention must be given to the characteristics of each watershed and region as small deviations from the actual conditions can have large impacts on the height and timing of the surge gate. For instance using a roughness value that is too low could result in flows with too large of a maximum discharge and peaking earlier than expected.

3.3 Input Data Categories in GIS

Hydrology of the San Jacinto River Basin in Harris Country was modeled using the fully distributed, hydrologic model, Vflo. Vieux recommends first gathering the data sets to be used as input parameter maps before building a Vflo basin; these include, elevation data, soil data, land use data, basin extent, and the stream network, and must be preprocessed in GIS and then imported into the Vflo Model. Once the parameters are obtained, Vflo then uses these parameters to calculate infiltration and runoff and route the water through the watersheds.

Elevation data is used by Vflo to determine the slope and flow direction for each cell, and can be used to extract channel-cross sections from as well. The elevation data used in this thesis is a digital elevation model (DEM) from Houston-Galveston Area Council (HGAC) and originally had a 15 ft resolution. The DEM was then resampled in GIS to a 60 meter resolution and clipped to the watershed boundary to minimize processing time.

Soils data were obtained from the National Resource Conservation Service (NRCS) Soil Data Mart. The soils data was preprocessed in Microsoft Access, Microsoft Excel, and GIS in order to derive the Green and Ampt infiltration parameters needed for Vflo. Once the appropriate soil type was known from documents from National Resources Conservation Service (NRCS), these parameters were correlated with the values presented in Rawls, Brakensiek, and Miller (1983). For example, Soil Data Mart will provide the type of soil, and then Rawls, Brakensiek, and Miller (1983) will provide the appropriate range of values for different soil parameters, such as hydraulic conductivity. The data was then imported back into GIS, where individual raster maps for parameters such as soil type, hydraulic conductivity, effective porosity and total porosity were created. In addition, a raster for the soil depth was created, accepting the top layer of soil for each soil type to be the soil depth. This assumption is accepted for the study area due to the fact that intensity of the rainfall is so great that most will become runoff. In addition, minimal infiltration is expected for the study area as a result of the soil type.

Land use data and imperviousness data was obtained by USGS. The land use data was 30 meter resolution and was resampled to match the 60 meter resolution of the elevation data. The decision was made for resampling up due to the fact that a greater amount of computational time and space would have been needed to process 30 meter resolution data, and since the study area is so large, the 30 meter resolution level of detail was not needed for accuracy. Next, the land use data was originally classified by type, but could then be correlated to an appropriate roughness value, as provided by Vieux and Associates. The imperviousness data had to be reclassified to a fraction between 0 and 1 before it could be imported into Vflo as a parameter. Figure 12 illustrates what the preprocessed GIS grids look like before they are imported to Vflo.

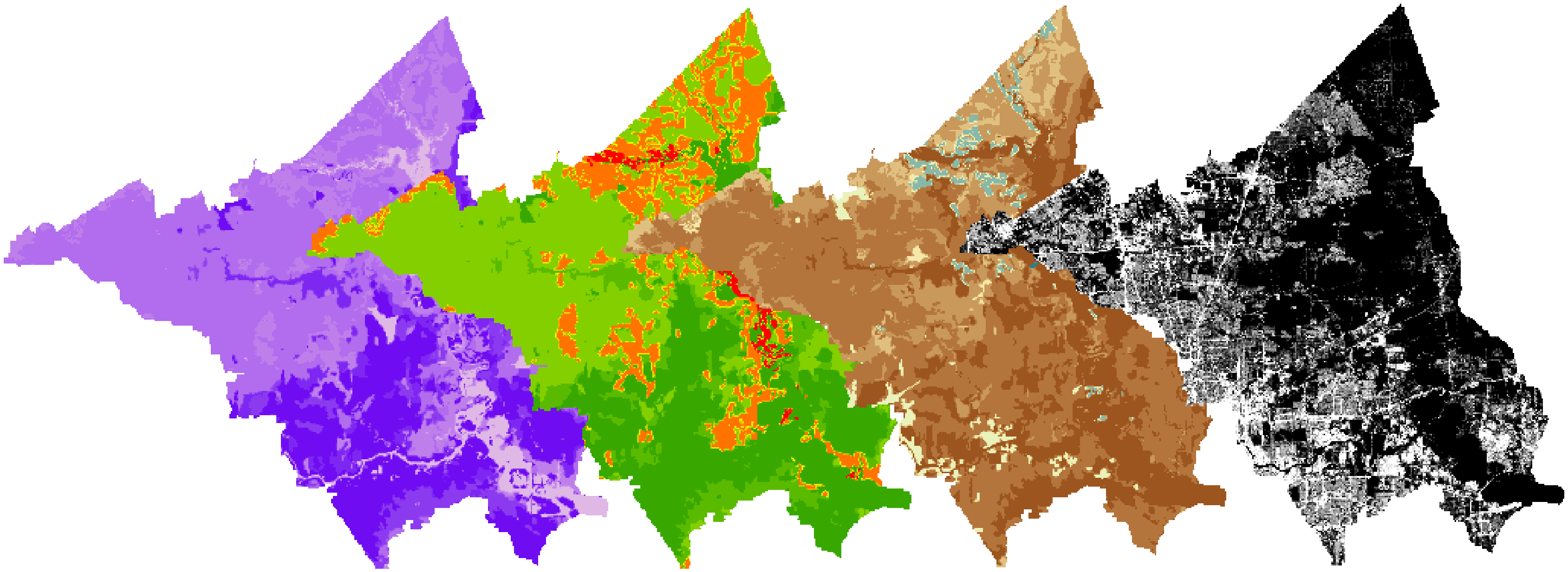


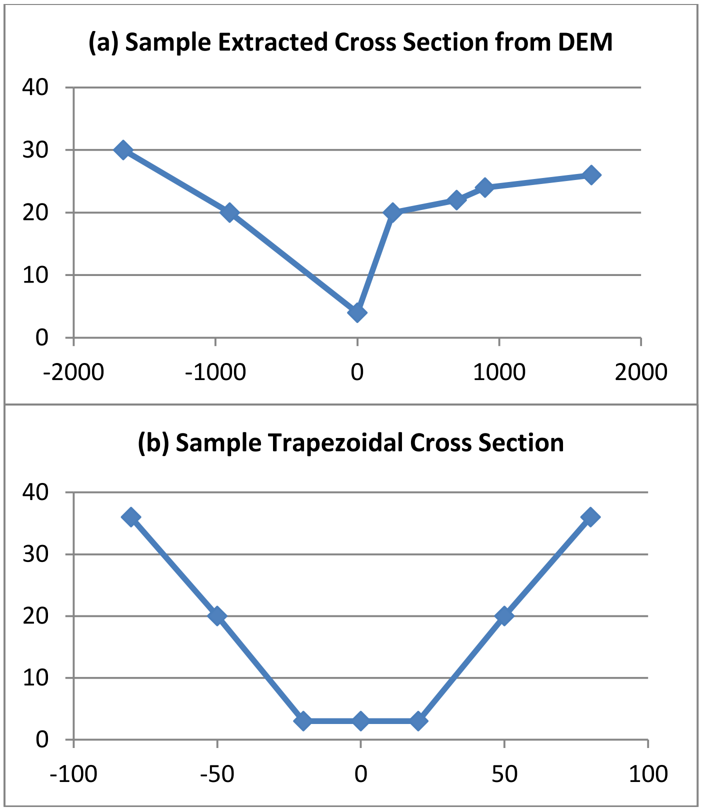
Figure 12: Illustrations of the preprocessed GIS grids for Vflo Model. From Left to Right: Wetting Front Suction, Hydraulic Conductivity, Soil Depth, Imperviousness

3.4 Model Development

Once the parameters had all been preprocessed in GIS, the AutoBOP feature in Vflo can be used to generate a new model. The first input is the DEM raster and any shapefiles used to establish boundaries or channels. Next, the user specifies the cell size. Any model containing more than 50,000 cells requires much more time and processing space to compute; thus, three models were created and linked together to model the entire region. A cell size of 1000 feet (304.8m) by 1000 feet (304.8m) was chosen for the "Lower San Jacinto River" model and the "Houston Ship Channel West Inflow" model, and a cell size of 2000 feet (609.6m) by 2000 feet (609.6) was chosen for the "Upper San Jacinto River" model to meet this upper limit. Both the "Houston Ship Channel West Inflow" model and the "Upper San Jacinto River" model flow into the "Lower San Jacinto River" model in the form of boundary conditions. For example, the outflow hydrograph for Hurricane Ike at Brays Bayou ("Houston Ship Channel West Inflow" model) was then used as an observed boundary condition at the location where Brays Bayou connects with the Houston Ship Channel in the "Lower San Jacinto River" model for the Hurricane Ike event.

Next, the channel threshold must be defined by the user as to what percentage of cells within the watershed should be channel cells. While the model defaults to ten percent, a channel threshold between seventeen and nineteen percent was chosen for the three models as it best matched the shapefile of the channels provided by TSARP 2006 as well as a map of the rivers and streams in Texas. Channel cells were also enforced based upon this shapefile; however, due to the complex channel network provided, manual correction occurred in a couple of regions to ensure proper subwatersheds. This was achieved by manually going in to each cell in Vflo and changing either its flow direction or cell type (overland versus channel). Next, an outlet cell, or the point to which all the water in a watershed drains, was chosen. In instances where multiple watersheds were modeled in one hydrologic model, multiple outlet cells were selected as it assists the model in creating the correct drainage network. Finally, the preprocessed parameters were imported into the AutoBOP.

Due to the difficulties Vflo software has with sharp changes in channel cross sections, as illustrated in Figures 13a and 13b, channel cross sections were not extracted everywhere from the DEM, but rather assumed to be trapezoidal with some cross sections added in throughout the models. In order to ensure accurate representations of the channels, the bottom width of the trapezoids was approximated from LiDAR data and Google Earth data. Once trapezoidal cross sections were placed into the model, DEM cross sections were added. Vflo allows the user to extract cross sections from everywhere in the DEM or from select locations; thus, select locations where sharp changes were not an issue were brought into the model. This inability to have exact cross section data throughout the model is one of the shortcomings of the software. For a smaller region, it is possible to manually enter the dimensions and measurements of cross sections; however, for a region of such large area, it would have been impractical to enter in these specifications on a cell-by-cell basis. Instead, best approximations were used; however, this could have an effect on results in the model.



Figures 13a and 13b: (a) Sample Extracted Cross Section from DEM with sharp changes and (b) Sample Trapezoidal Cross Section

After the Vflo grid had been created and all preprocessed parameters were incorporated, it was important to test the model for sensitivity of the calibration parameters and to calibrate modeled results to observed data.

Chapter 4: Sensitivity Analysis and Model Calibration

4.1 Sensitivity Analysis

Before the model was calibrated, the calibration parameters were tested to see how sensitive the model was to each watershed parameter. The goal was to see if one parameter drove the model more than another, or if it was a combination. In addition, the model was tested to see how it reacted to slight and large changes in calibration factors. The two parameters that were tested were roughness and hydraulic conductivity, as they were the two parameters used to represent the land use and channel properties in the watershed. While the parameters were changed, the calibration factors were still scaled to a reasonable extent, attempting to still retain the true meaning of each variable. This will be discussed further in section 4.2. Moreover, while one parameter was being tested, all other parameters and factors were held constant at the values used in the calibrated model.

The sensitivity analysis was done on the subwatershed flowing into USGS gauge 8076000 for Hurricane Ike (see Figure 16a for gauge location). This gauge location was chosen due to the fact that it is a relatively small, 68.7 square mile, watershed, and changes in the calibration factors should be easily noticeable. In addition, Hurricane Ike was the storm chosen to run the sensitivity analysis on due to the fact that a complete set of data is available for the USGS gauge 8076000.

The sensitivity analysis demonstrated that channel and overland roughness are most responsible for changes in peak timing and peak volume, while hydraulic conductivity had little effect on the peak timing or flows.

4.1.1 Roughness

When roughness was left uncalibrated, the model peaked too soon and had too large of a maximum discharge value, illustrated in Figure 14. However, once the channel and overland roughness were increased, the timing and maximum discharge on both peaks began to take shape of the observed streamflow data. When the final roughness calibration factor was reached (2.90), the rising and falling limbs had a strong match, with peak flows on both peaks differing by less than 5%.

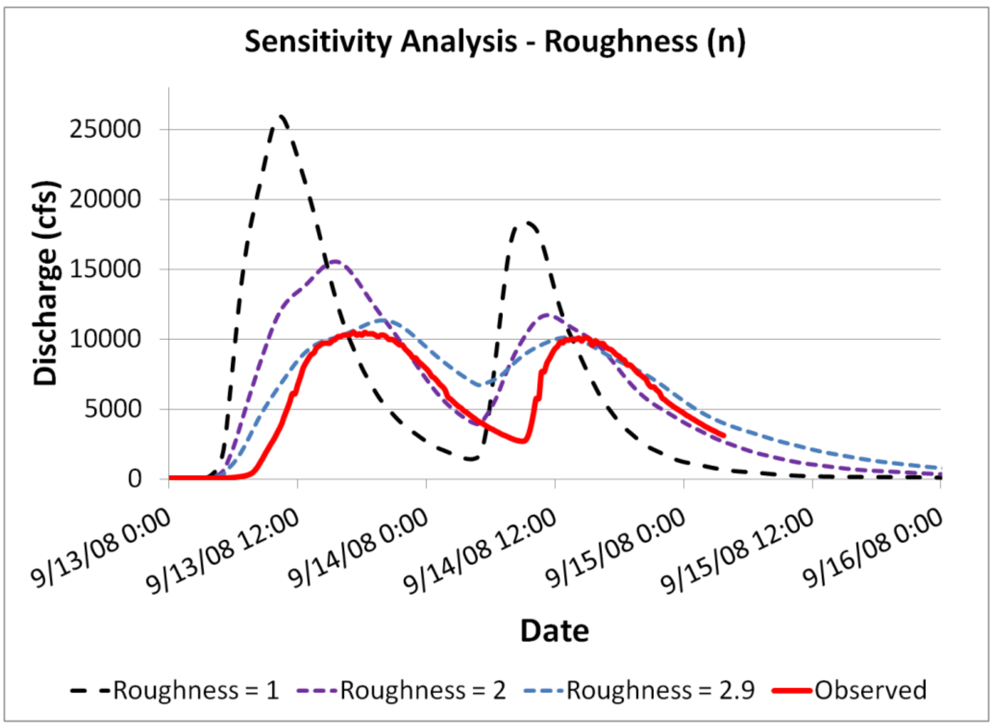


Figure 14: Sensitivity Analysis for Roughness

4.1.2 Hydraulic Conductivity

When hydraulic conductivity was left uncalibrated, the modeled first peak reached its maximum volume roughly three hours after the observed peak and the modeled second peak reached its maximum volume roughly two hours before the observed peak. This is illustrated in Figure 15. When the hydraulic conductivity was scaled up by a factor of 4, the time to peak on both peaks stayed roughly the same, yet the maximum discharge on first peak decreased. While this new calibration did not represent the true volume of the rainfall, it had little effect on the results as compared to roughness (n). Also, it became apparent that hydraulic conductivity had no noticeable effect on timing. Ultimately, a calibration factor of 2 was decided upon for hydraulic conductivity for the subwatershed.

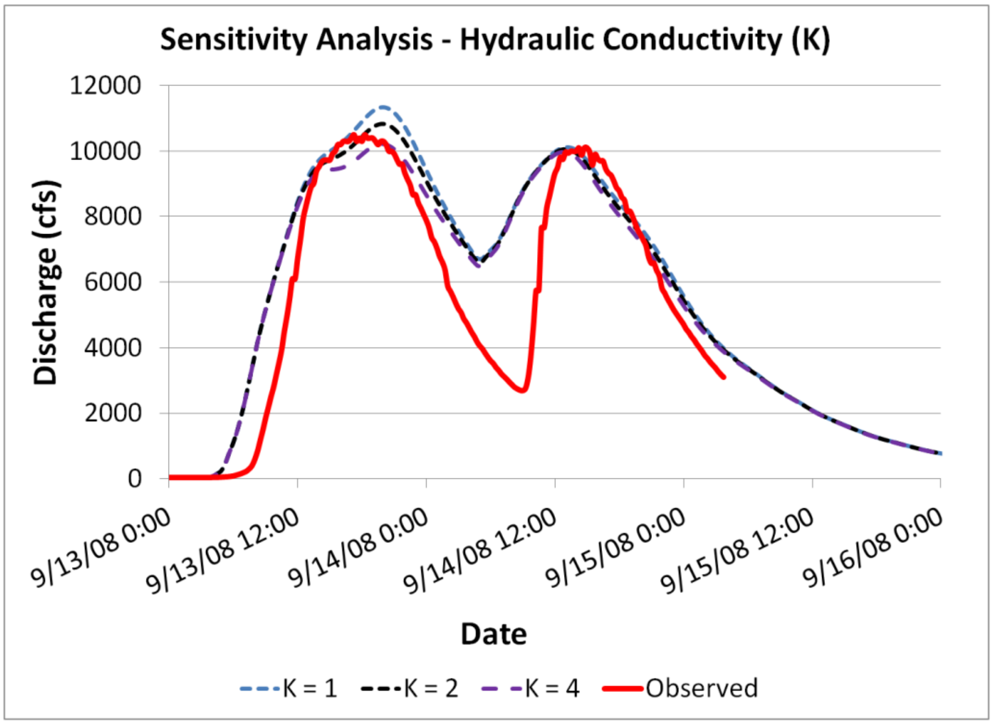


Figure 15: Sensitivity Analysis for Hydraulic Conductivity

Thus, it became apparent that overland and channel roughness was truly the parameter which drove the model. Once that was accurately represented in the model, the modeled data matched the observed data, with the preprocessed raster data correctly representing the soil characteristics of the region. More details can be found in Table 5.

Table 5: Comparison of sensitivity analysis for roughness and hydraulic conductivity

	Percent error for rainfall volume	Difference in timing from observed for first peak (hours)	Difference in timing from observed for second peak (hours)
Roughness uncalibrated (K=1)	50%	-8	-4
Roughness calibrated (K=2.9)	10%	+2	-1
Hydraulic Conductivity uncalibrated (K=1)	14%	+3	-2
Hydraulic Conductivity calibrated (K=2)	10%	+3	-2

4.2 Model Calibration and Calibration Results

In order to ensure that the results produced by the model are reasonably accurate, it is recommended to calibrate the model to approximately three events – a “small” storm, a “medium” storm, and a “large” storm where possible. The three storms chosen were the April 2009 storm, Hurricane Ike, and Tropical Storm Allison. When possible, the rainfall employed was mainly rain gauge data as the Harris County Flood Control District has 133 gauges across the region (Harris County Flood Control District, 2012). In regions outside of Harris County, where rain gauges are not as abundant, radar rainfall data, processed by Vieux and Associates, was used.

Calibration of a Vflo model is done in the software and has many degrees of freedom. Calibration factor scales include parameters like hydraulic conductivity, roughness, soil depth, and initial saturation, and can be increased or decreased to match modeled hydrographs to observed streamflow hydrographs. In addition, the calibration factors can be scaled for a single cell, a group of cells in a subwatershed, channel cells, or overland cells. However, it is important to recognize the meaning of each of the calibration factors and to scale accordingly. For instance, while an increase in the initial saturation should result in a decrease in the peak flow values, this should only be done if it was particularly dry in the months preceding this storm event. Thus, the process involves using engineering judgment based on the purpose of each parameter in order to achieve a close match between observed and modeled. The user must be careful to not over fit the model to one particular storm event, but rather closely represent the expected peaks and timing of volumetric flow for all storm events. A more detailed methodology is explained in 4.2.1.1.

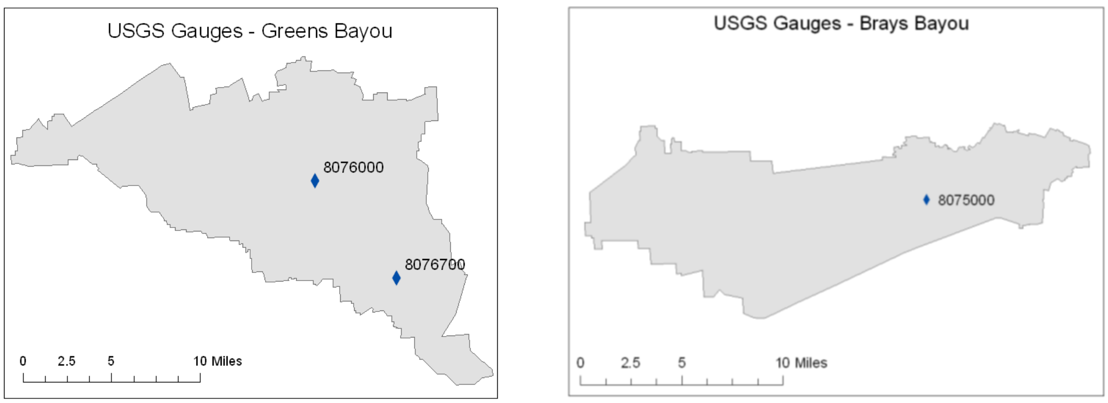
4.2.1 "Lower San Jacinto River" and "Houston Ship Channel West Inflow" Models

4.2.1.1 Methodology

As stated prior, the rainfall data for these events was rain gauge data collected from ten to twenty gauges around the study area, and then Vflo uses inverse distance weighting to create a rainfall grid for the storm. The rain gauge data was compared to radar rainfall data processed by Vieux and Associates for Greens Bayou for Hurricane Ike, which proved to produce very similar discharge hydrographs. Thus, due to the ease of gathering rain gauge data versus radar rainfall data, rain gauge data was used for the calibration analysis.

Observed streamflow data was obtained from the USGS National Water information system for gauges 8076000 and 8076700 in Greens Bayou. Two gauges were chosen in Greens Bayou due to the fact that the upper gauge represents a less developed region as compared to the gauge farther South. Therefore, both developed and undeveloped regions were explored in the methodology used to fully calibrate Greens Bayou, and similar methodologies were employed in the other watersheds.

Gauges in Greens Bayou (Figure 16a) and Brays Bayou (USGS gauge 8075000) (Figure 16b) were chosen as the locations for the calibration due to the abundance of information on storm events in the watershed as well as the presence of multiple USGS stream gauges. Observed hydrographs from these gauges were then used to calibrate the model to observed streamflow data.



Figures 16a and 16b: USGS gauges for observed streamflow in (a) Greens Bayou and (b) Brays Bayou

In watersheds in the two models where there were no USGS gauges, a 24 hour, 100 year, SCS III storm was uniformly applied over the watershed and the Vflo results were adjusted to match the timing and peak flows of the TSARP 2007 HEC-HMS 3.3 models for these watersheds. While uniform storms are not a practical design measure for a large river basin, they are useful when designing on the watershed level (1-300 square miles), especially when no other gauge data is available. Also, Ray (2009) discusses the similarity of results between HEC-HMS and Vflo model results, and thus calibrating to this data would allow for a good approximation where no other historic data was available.

For Greens Bayou and Brays Bayou, the three storms chosen to calibrate the model with were the April 2009 storm, Hurricane Ike, and Tropical Storm Allison. The April 2009 storm delivered rains ranging from 4-9 inches of rain over the region in a 2 day period. Differently, Hurricane Ike delivered 7.5-13.5 inches of rain over the region in a 12 hour period with a bit more rain falling later in the afternoon, categorizing the storm as a 50 to 100 year storm event. Finally, Tropical Storm Allison brought rains of as much as 28 inches in Greens Bayou over the region in a 24 hour period, categorizing the storm as a 100-500 year storm event (Harris County Flood Control District, 2012). These storms resulted in much flooding and elevated stream flow throughout the study area, thus proving to be good storms for hydrologic analysis and calibration.

Multiple parameters were adjusted in order to achieve a close match between observed and modeled data. The first storm calibrated was Hurricane Ike. Initial saturation was the first parameter adjusted as it was particularly dry in the months preceding the event. Thus 10 % infiltration is reasonable to expect in Harris County due to the intensity of the storm events and the soil types of the region. Next, channel roughness was adjusted, which had significant effects on timing and peak flow. As stated prior, uniform trapezoidal cross sections were employed throughout the model where DEM cross sections were not useable, and thus, channel roughness was used to represent the varying properties in the channels. Lastly, hydraulic conductivity was adjusted to bring the first peak of the modeled results closer to that of the observed results. Once Hurricane Ike had been successfully calibrated for an upstream and downstream USGS gauge in Greens Bayou and a USGS gauge in Brays Bayou, Tropical Storm Allison was examined. First, the initial saturation was increased as it had rained in the days prior to the Tropical Storm Allison event being modeled. The gauge in Brays Bayou was not completely functional during Tropical Storm Allison, thus a calibration process only took place in Greens Bayou for this storm event. However, only slight adjustments were made to the channel roughness and hydraulic conductivity, which were then cross checked against the Hurricane Ike rainfall. Once a close match was achieved for both storms, the April 2009 event was tested, and with few adjustments, the model was calibrated for all three storm events.

Once calibration factors had been adjusted for Greens Bayou and Brays Bayou, these calibration factors were then tested on other watersheds in their respective model to make sure that there was still accuracy between the observed and predicted results from the TSARP models or other USGS gauges where applicable.

4.2.1.2 Results

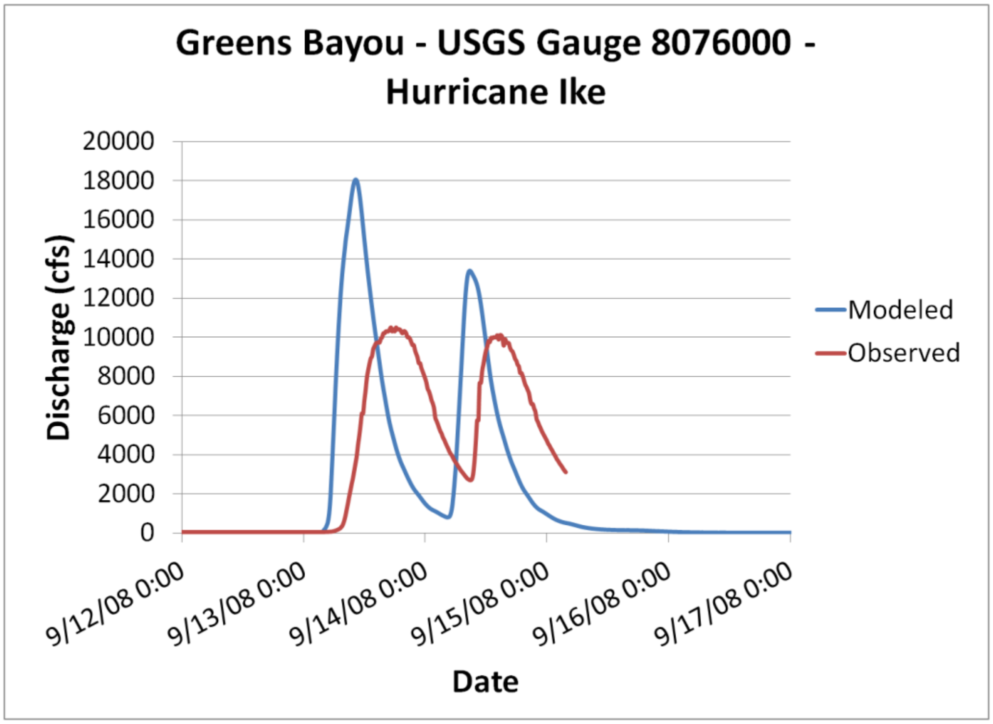
Calibration of the three historical storms to the designed model in Greens Bayou and Brays Bayou was successful, with total rainfall volume, observed streamflow peaks, and timing matching at multiple locations in Greens Bayou and farther downstream in the "Lower San Jacinto River" model as well as in the "Houston Ship Channel West Inflows Model".

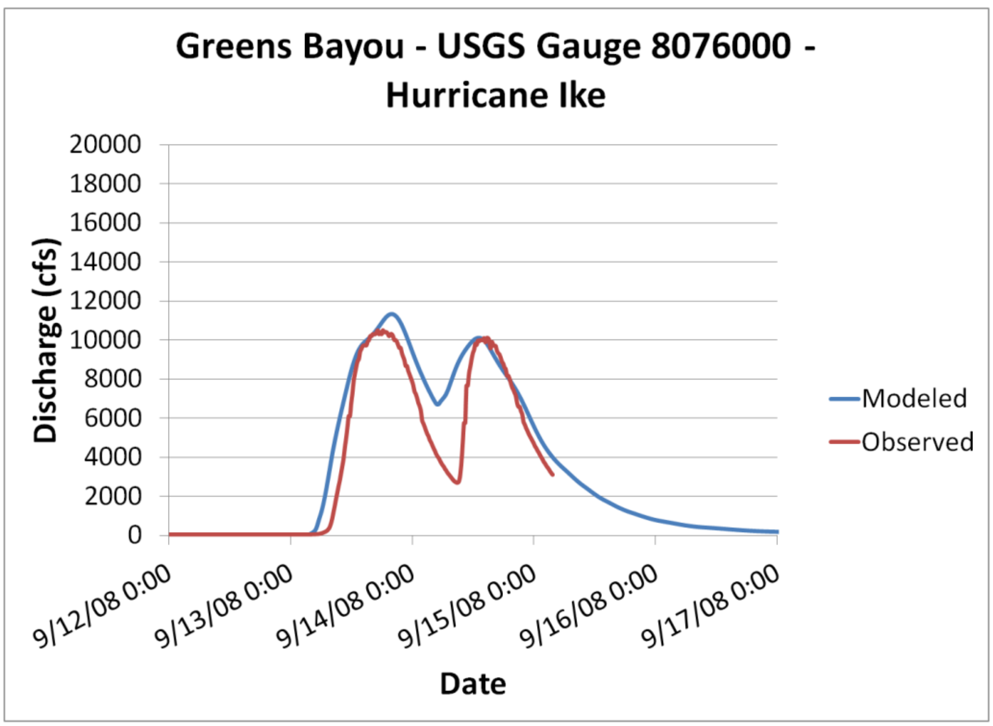
The hydrologic model, Vflo, was evaluated and compared against measured streamflow data at USGS gauge 8076000 further North in Greens Bayou and with a smaller drainage area, as well as at USGS gauge 8076700 further South in Greens Bayou and having a large drainage area, including the region represented by gauge 8076000.

Vflo was also evaluated and compared for a large portion of Brays Bayou at USGS gauge 8075000.

4.2.1.2.1 Hurricane Ike

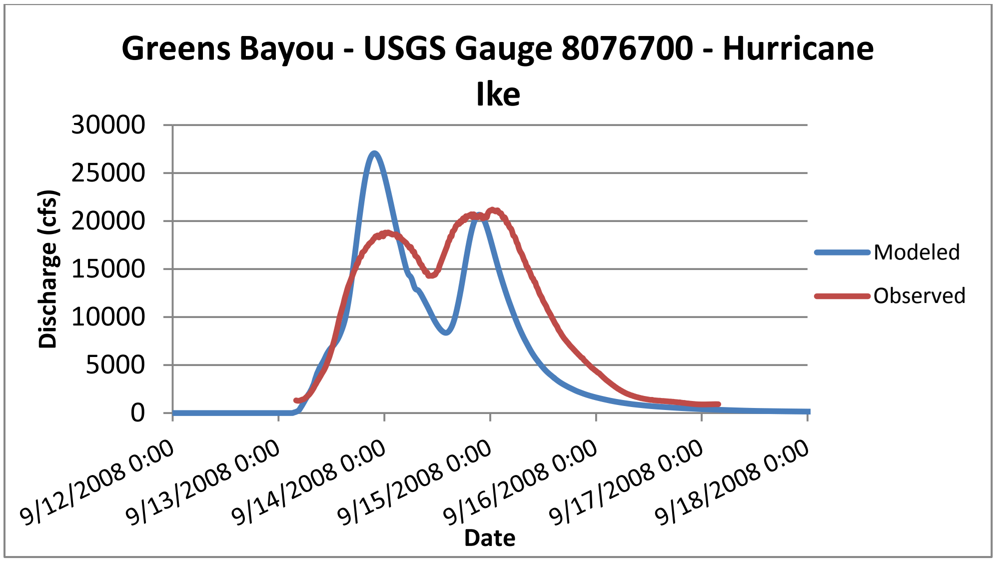
The streamflow results for Hurricane Ike compared to the modeled results simulated by Vflo. Hurricane Ike took place in September 2008, after two weeks of almost no precipitation in the Houston-Galveston region (HCFWS). The calibration efforts produced an average channel roughness of 0.03 and an average overland roughness value of 0.031 in Greens Bayou and an average channel roughness of 0.037 and an average overland roughness value of 0.035 in the Buffalo, Sims, and Brays Bayou region, which are appropriate given the ways in which the land is used (a combination of high residential, low residential, commercial, and forested) in the watersheds, as well as the channel characteristics. Hurricane Ike produced double peak results at both gauges in Greens Bayou as well as Brays Bayou, which are notably difficult to match. However, at USGS gauge 807600, the timing of the first peak was delayed by only three hours, and was off by less than an hour for the second peak. In addition, the observed peak was 4.6% greater than the observed peak. Figure 17a shows a comparison of the modeled and observed results before calibration whereas Figure 17b shows a comparison of the modeled and observed results after calibration.

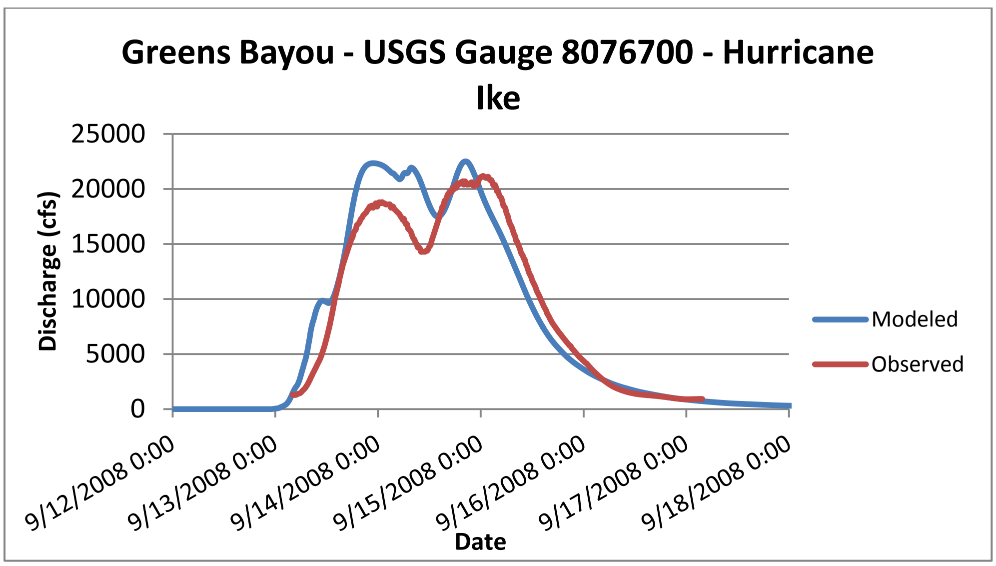




Figures 17a and 17b: Modeled results before (a) and after (b) calibration to USGS observed data at gauge 8076000 for Hurricane Ike

Downstream at USGS gauge 8076700, the timing of the first peak was early by about three hours and the second peak was delayed by about three hours. In addition, total rainfall volume was over predicted by approximately 13%. Figure 18a shows a comparison of the modeled and observed results before calibration whereas Figure 18b shows a comparison of the modeled and observed results after calibration. The calibration results for Greens Bayou for Hurricane Ike is summarized in Table 6.





Figures 18a and 18b: Modeled results before (a) and after (b) calibration to USGS observed data at gauge 8076700 for Hurricane Ike

Table 6: Comparison of uncalibrated and calibrated results for Hurricane Ike in Greens Bayou

	Percent error for rainfall volume	Difference in timing from observed for first peak (hours)	Difference in timing from observed for second peak (hours)
USGS Gauge 8076000 uncalibrated	50%	-8	-4
USGS Gauge 8076000 calibrated	10%	+3	-1
USGS Gauge 8076700 uncalibrated	22%	-3	-2
USGS Gauge 8076700 calibrated	13%	-3	-3

In Brays Bayou at USGS gauge 8075000, the timing of the first peak was early by about two hours and the second peak represents the total volume of the second peak, yet is off in timing and shape. This is illustrated in Figure 19. With regards to peak discharge, the model produced a result of roughly 28,000 cfs, whereas the observed value is slightly less, by about 10-12 percent.

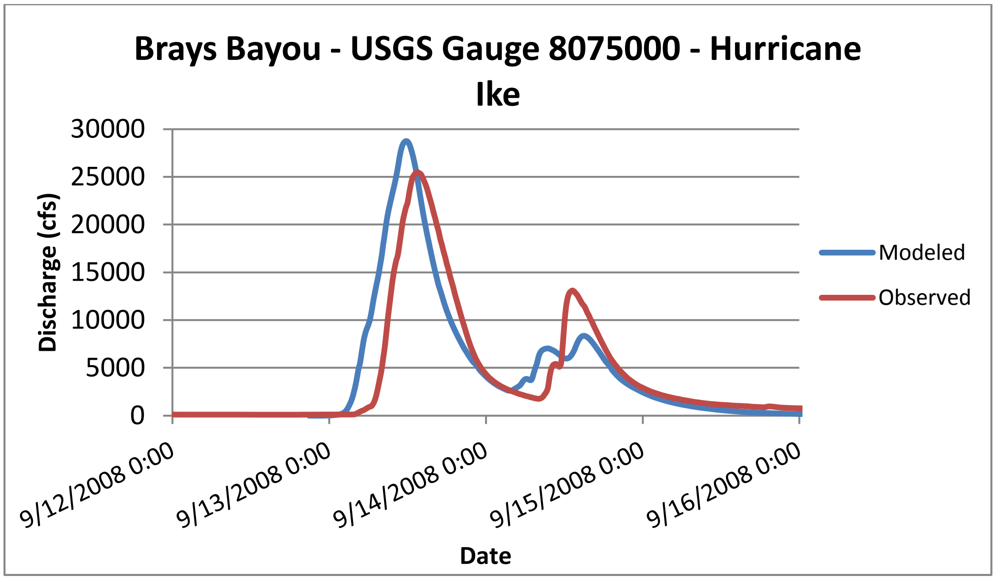


Figure 19: Modeled results calibrated to USGS observed data at gauge 8075000 for Hurricane Ike

4.2.1.2.2 Tropical Storm Allison

The streamflow results for Tropical Storm Allison are also well represented by the Vflo model. The same channel and overland roughness values from the Hurricane Ike calibration were used in this calibration effort as well. While the Greens Bayou upstream USGS gauge, 8076000, was able to record streamflow, the downstream USGS gauge, 8076700, lost power and results are not reliable. This loss of power occurred at the USGS Gauges in Brays Bayou as well. However, at USGS gauge 807600, the timing of the rising limb matches closely and the maximum peak of the modeled hydrograph was approximately 4 hours off from that of the observed data, as illustrated in Figure 20.

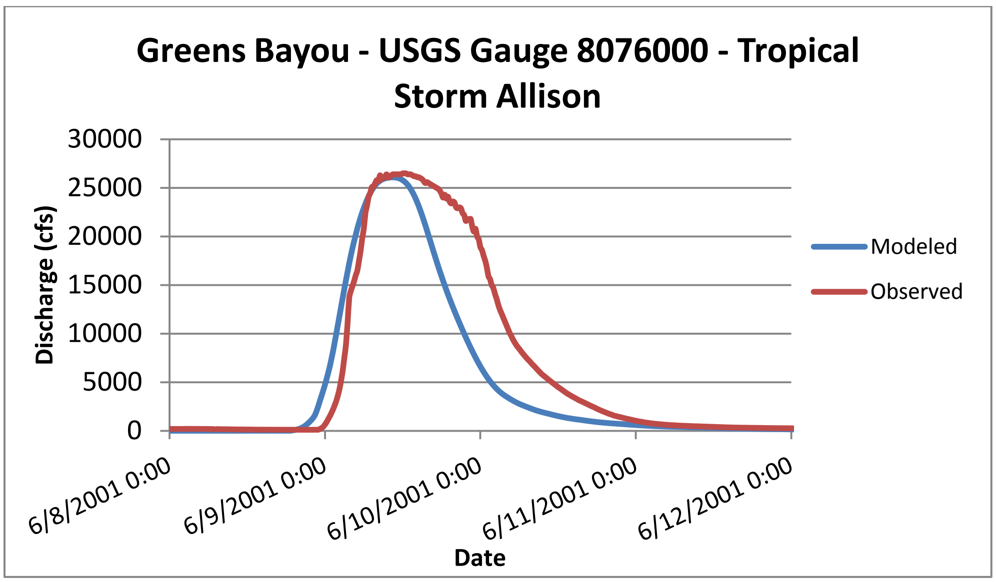


Figure 20: Modeled results calibrated to USGS observed data at gauge 8076000 for Tropical Storm Allison

4.2.1.2.3 April 2009 Storm

The April 2009 storm was the last storm to which the Vflo model was calibrated. The same channel and overland roughness values from the Hurricane Ike and Tropical Storm Allison were used to calibrate the model to this storm as well. The fact that the same roughness values from Hurricane Ike and Tropical Storm Allison are used in the April 2009 event is an assumption that is justified in this model due to the fact that the

Upper San Jacinto River Basin is mainly a forested basin (Sam Houston National Forest is in this region), Brays Bayou has been at a fully developed state for over a decade now, and most of the new growth has taken place in the western part of Harris County, which is not included in this study.

Opposite from that of Tropical Storm Allison, Greens Bayou USGS gauge, 8076000, lost power and data is not available for this event at that location. However, at Greens Bayou USGS gauge 8076700, the timing of the rising limb is slightly early for the maximum peak, and the falling limb is slightly delayed, as seen in Figure 21. While it is hard to get a true rainfall volume comparison due to the limited data at this gauge for the complete event as well, the maximum peak matched nearly exact in timing and had slightly less than 12% difference in maximum peak values.

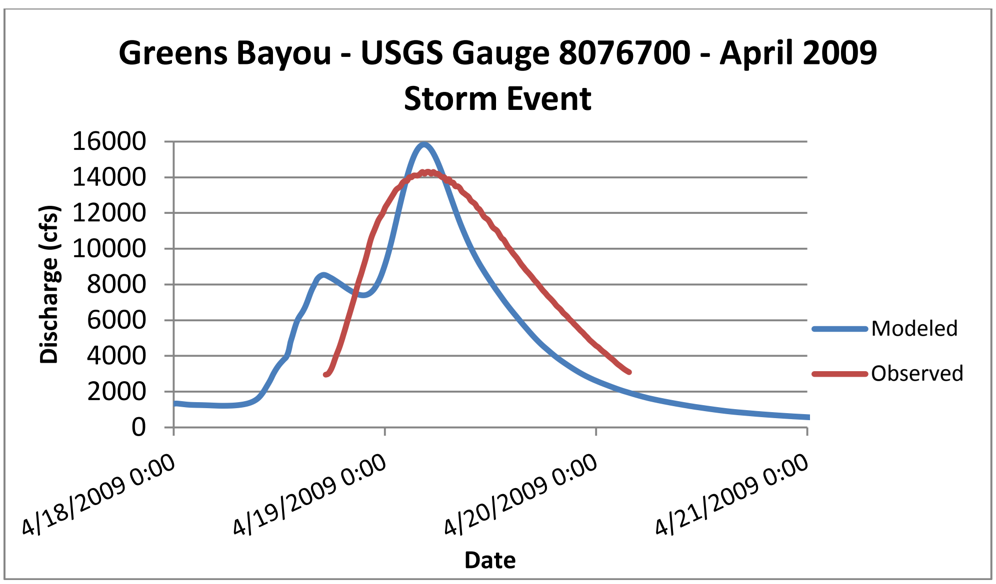


Figure 21: Modeled results calibrated to USGS observed data at gauge 8076700 for April 2009 Storm Event

In Brays Bayou, the latter part of the rising limb of the peak matches (Figure 22), as does the falling limb. In addition, the peak discharge from the modeled matches closely with that from the observed data. While the model does not accurately depict the first, smaller peak, Vflo does a fairly accurate job depicting the volume of rainfall as a result of it, and these double peak events are very difficult to match perfectly.

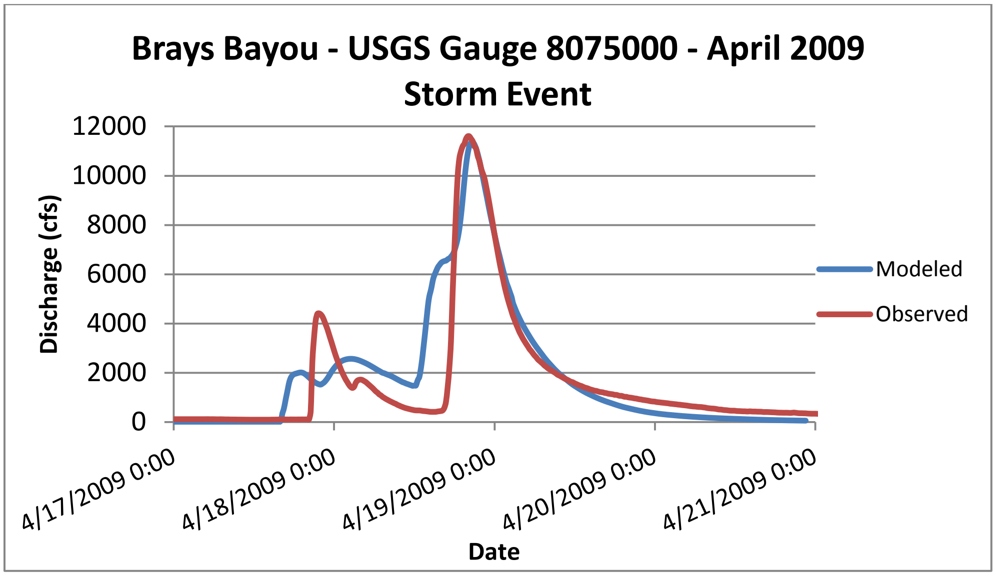


Figure 22: Modeled results calibrated to USGS observed data at gauge 8075000 for April 2009 Storm Event

4.2.2 "Upper San Jacinto River" Model

4.2.2.1 Methodology

The "Upper San Jacinto River" model, where the majority of the region is not located in Harris County, could not be calibrated using rain gauge data as a result of sparse rain gauges. Thus, radar rainfall data for Hurricane Ike, processed by Vieux and Associates, was used to calibrate to USGS streamflow data for Hurricane Ike to the modeled results. Only one storm was chosen due to the fact that it is costly to process multiple storm events, Tropical Storm Allison delivered its most intense rain inside the 610 loop, and all of the watersheds in the Upper San Jacinto flow into Lake Houston, where stage could be calibrated to in the HEC-RAS model as well.

Observed streamflow data was obtained from the USGS National Water information system for six gauges throughout the region, including gauge 8068000 located at West Fork San Jacinto River near Conroe TX, gauge 8070000 located at East Fork San Jacinto River near Cleveland, TX, gauge 8071000 located at Peach Creek at Splendora, TX and gauge 8068800 located at Cypress Creek at Grant Road near Cypress, TX. As seen in Figure 23, these gauges were chosen in order to have gauges throughout the entire region and also due to their availability of streamflow data. Similarly, the hydrographs from these gauges were then used to calibrate the model to observed streamflow data.

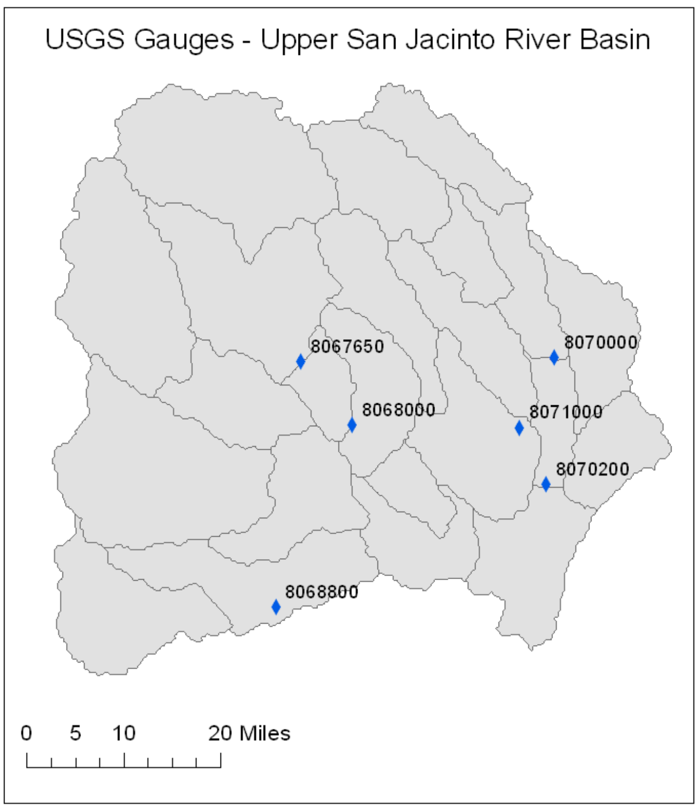


Figure 23: USGS Gauges in the Upper San Jacinto River Basin

4.2.2.2 Results (Hurricane Ike)

The Vflo modeled results for Hurricane Ike matched nicely compared to the observed results recorded by USGS. Similar to the method used in the prior calibrations, initial saturation, roughness, and hydraulic conductivity were adjusted to represent the soil and channel characteristics of the region. The calibration efforts produced an average channel roughness of 0.098 and an average overland roughness value of 0.108. These values represent the dredge channels comprised of clay and silty clay loam with vegetation covering the bottom and side slopes (Chow, 1959). Hurricane Ike proved to calibrate well throughout the model. For instance, as seen in Figure 24, at USGS gauge 8071000, the rising limb of the modeled and the observed data matches well, with the maximum peak occurring within two hours of one another. In addition, the maximum peak discharges are very close. While the falling limb of the modeled hydrograph does not accurately represent the timing or slope of the discharge, the volume of rainfall which fell over the region is equal to the observed hydrograph, which is one of the most important factors in the calibration process.

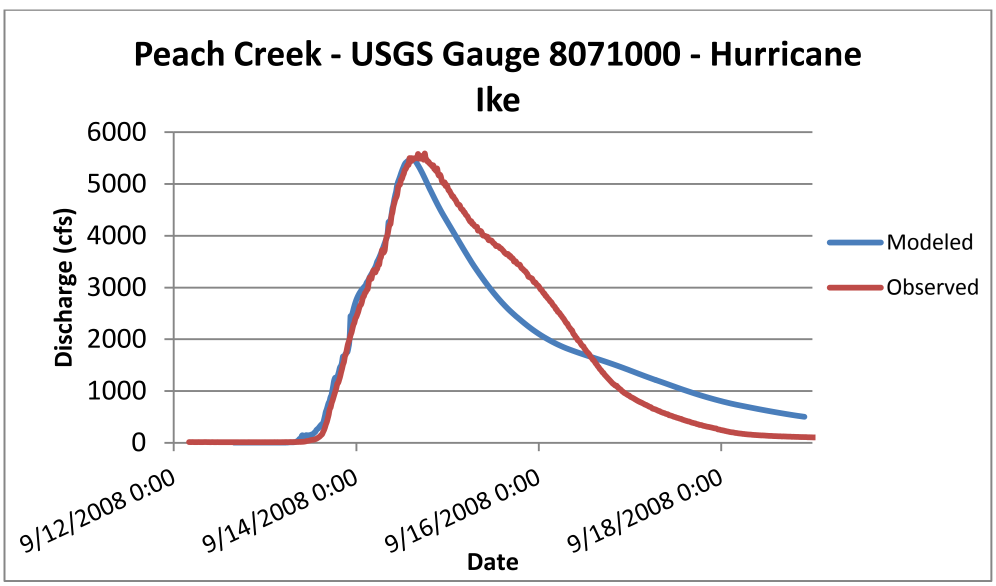


Figure 24: Modeled results calibrated to USGS observed data at gauge 8071000 for Hurricane Ike

Table 7: Final calibration results for select watersheds in all three models

	Percent error for rainfall volume	Difference in timing from observed for first peak (hours)	Difference in timing from observed for second peak (hours)
Brays Bayou (8075000) for Hurricane Ike	12%	-2	-2
Brays Bayou (8075000) for April 2009	15%	+6	-1
Greens Bayou (8076000) for Tropical Storm Allison	32%	-1	N/A
Greens Bayou (8076700) for April 2009	14%	-4	N/A
Peach Creek (8071000) for Hurricane Ike	4%	-1	N/A

The calibration results have been summarized in Table 7. Once the models were calibrated, design rainfall events could be analyzed. The process used to create the rainfall grids will be explained in the next chapter.

Chapter 5: Rainfall Development

The design and placement rainfall for the PMP storm and simulated hurricanes, Katrina and Rita is explained in the following sections. Hurricanes Katrina and Rita were selected as there are only a few storms with well documented data in the past 10 years in the Gulf Coast region. In addition, these storms were extremely large and resulted in significant damage making them desirable to simulate for the Houston-Galveston region.

5.1 Rainfall Design

Due to the large size of the study area, the PMP storm was used to simulate a 100 –year storm of 24 hour duration. The storms were designed consulting HMR 51 while using the procedure outlined in HMR 52 and the precipitation depths were provided by Liscum, 2004. A similar methodology was used to simulate historical storms. For a 24 hour, 5000 square mile PMP storm, the rainfall values for the first three isohyets are illustrated in Table 8a. The first three isohyets for the simulated Hurricane Katrina and Hurricane Rita results are in Table 8b and 8c. More detail on the rainfall design can be found in Appendix 9.1 and 9.2.

Tables 8a, 8b, 8c: Simulation Rainfall Data for the PMP Storm Event (a), Hurricane Katrina (b), and Hurricane Rita (c).

5000 square mile PMP storm:				
Isohyet	**0-6 hours (in)**	**6-12 hours (in)**	**12-18 hours (in)**	**18-24 hours (in)**
A	3.05	13.15	0.82	0.80
B	2.95	12.37	0.82	0.80
C	2.88	11.58	0.81	0.80

Hurricane Katrina Simulation Data				
Isohyet	**0-6 hours (in)**	**6-12 hours (in)**	**12-18 hours (in)**	**18-24 hours (in)**
A	0.06	8.87	0.89	0.72
B	0.06	8.83	0.89	0.72
C	0.06	8.58	0.86	0.69

Hurricane Rita Simulation Data				
Isohyet	**0-6 hours (in)**	**6-12 hours (in)**	**12-18 hours (in)**	**18-24 hours (in)**
A	0.08	10.85	1.09	0.88
B	0.08	10.85	1.09	0.88
C	0.07	10.52	1.06	0.85

5.2 Rainfall Placement

Once the numerical values for the PMP and historic storms had been created, the location as to where the storm would be centered had to be determined. Since the goal of this study was to see the interaction between rainfall-runoff and storm surge, the heaviest rains were placed closer rather than farther from Galveston Bay since longer travel times to Galveston Bay would create less of an interaction between the two factors. Thus, the three locations chosen to center the rainfall over were Lake Houston, The Houston Ship Channel, and the Confluence – where the Houston Ship Channel and the San Jacinto River meet. Specifically, Lake Houston was chosen as a storm center location due to the fact that the 1994 rainfall event had tremendous impacts on the Lake, and the Ship Channel and Confluence were chosen as a result of observed and modeled tracks of Hurricane Ike. The storm center locations are illustrated in Figure 25.

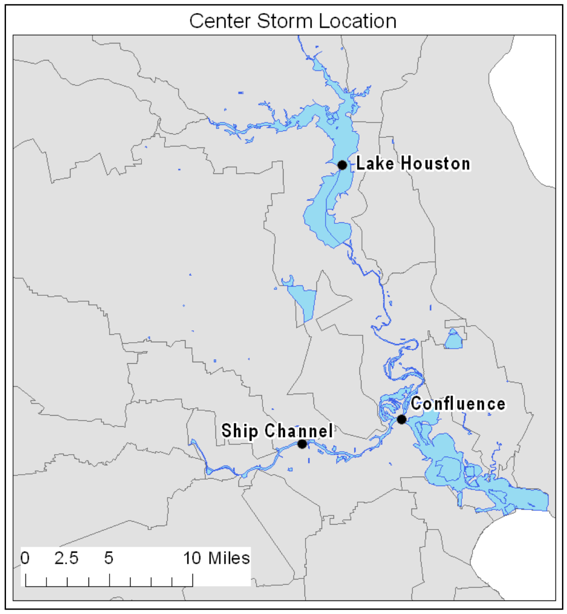


Figure 25: Map of three different locations for placement of storm centers for design storms

The PMP storm event (Figure 26), the rainfall from Hurricane Rita and the rainfall from Hurricane Katrina design storms were centered over each location for a total of three runs per each storm event. The timing and maximum discharged were analyzed for each storm event to see where the "worst storm" would occur. The "worst storm" in this context is defined as the location of the storm center that would create the largest maximum discharge and have the shortest time to peak, thus having the most interaction with storm surge.

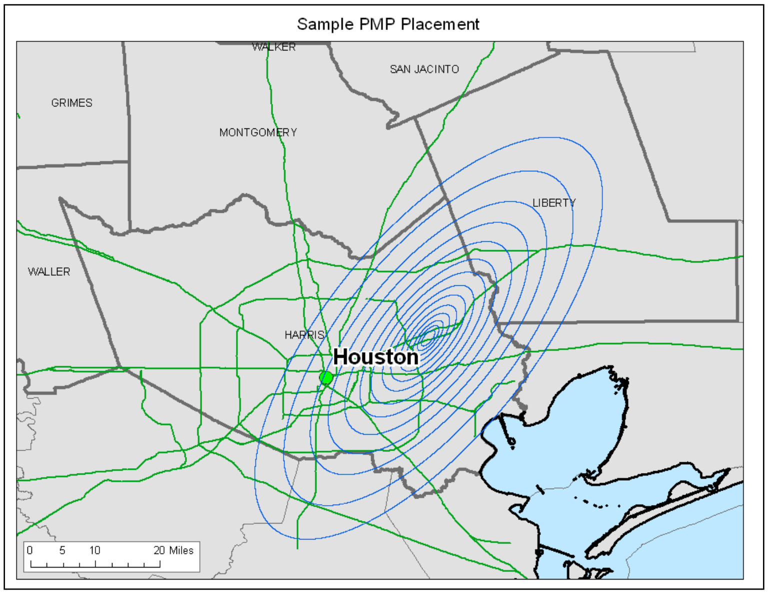


Figure 26: Sample spatial distribution of the PMP Storm Event placed in Harris County

Hydrologic results based on storm event and storm center location will be presented and discussed in the following chapter.

Chapter 6: Vflo Model Results

Once the historic and design storms were modeled in each of the three individual models, outputs from the “Upper San Jacinto River” and “Houston Ship Channel West Inflow” were used as boundary condition inputs in the “Lower San Jacinto River” model. The following sections present the results from the simulation of Hurricane Ike, as well as it compares the design storm results, including simulations of Hurricane Katrina, Hurricane Rita, and the PMP storm. Discharge and timing below the Fred Hartman Bridge were analyzed to see the potential interaction with storm surge. These results can then be used to optimize gate operations.

6.1 Historic Storm Results

Hurricane Ike was modeled as it originally occurred in the Houston Galveston region. Results below the Fred Hartman Bridge were analyzed. As can be seen in Figure 27, there are three peaks, with the last one being significantly larger than the first two peaks, 82,000 cfs, 74,000 cfs, and 116,000 cfs. This is attributed to the fact that flows from the West have a shorter travel distance and thus peaked earlier than flows from the North. Even though flows from the West peak earlier, flows from both directions will interact with storm surge.

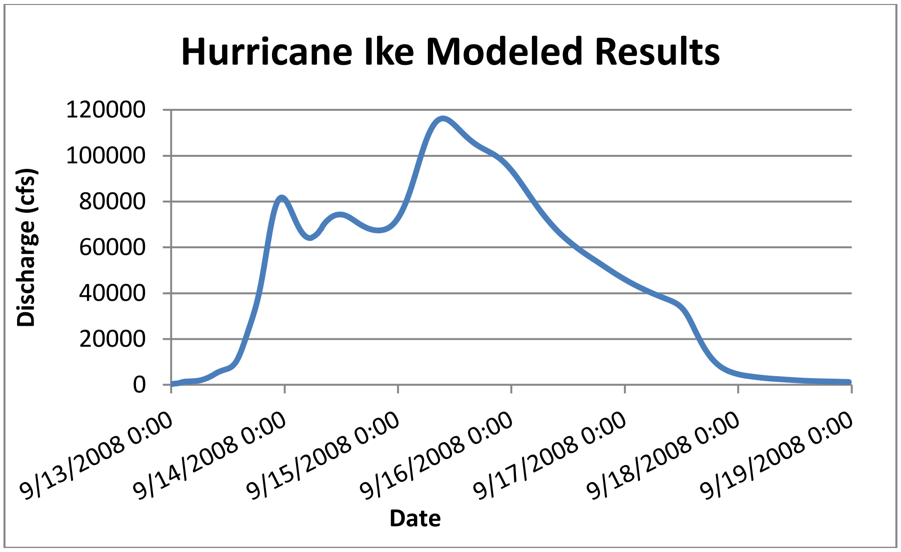


Figure 27: Hurricane Ike Results below the Fred Hartman Bridge, modeled in Vflo

6.2 Design Storm Results

6.2.1 PMP Storm Event

The 24 hour, 5000 square mile PMP was tested at three different center locations, the Houston Ship Channel, the Confluence, and Lake Houston. Results can be seen in Figure 28. When the results from all three locations were compared, it was apparent that a storm centered on the Ship Channel would produce the “worst case” storm.

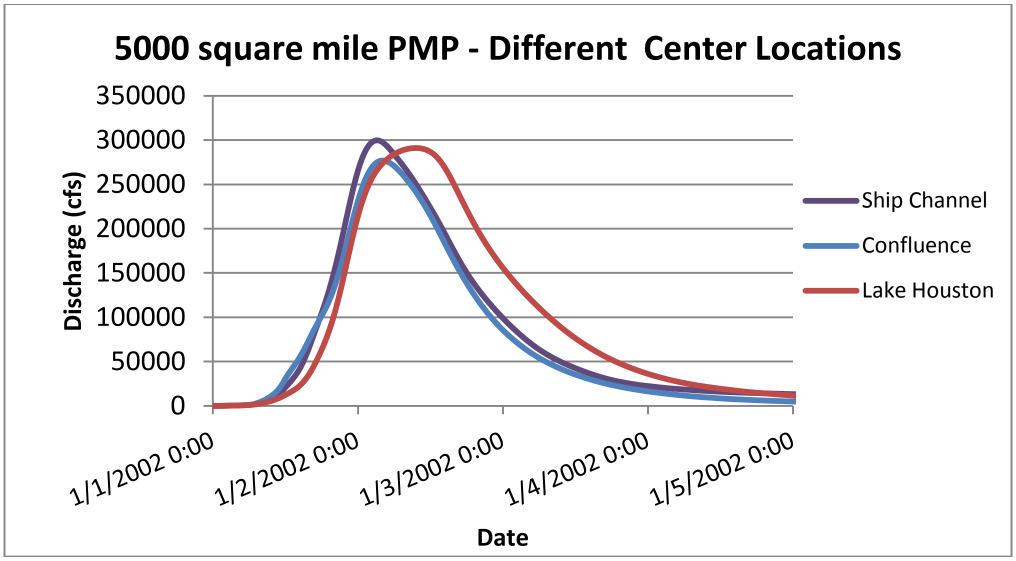


Figure 28: 5000 square mile PMP storm event results below the Fred Hartman Bridge for different storm center locations

A storm centered on the Houston Ship Channel peaked at approximately 3 am on the second day, making the time to peak about 18 hours. Its maximum discharge was almost 300,000 cubic feet per second. A storm centered on the Confluence had a similar time of peaking, just an hour after that of the Houston Ship Channel location. However, due to the orientation and placement of the storm, the Confluence location had a peak of roughly 277,000 cubic feet per second. Finally, a storm centered on Lake Houston peaked last. This location peaked more than 6 hours after the other two locations, with a time to peak of 24.5 hours. This is to be expected given the travel time that a larger portion of the rainfall volume had to travel to reach the outlet, as compared to that of the other two storm locations.

6.2.2 Simulated Storm Events

Hurricane Katrina and Hurricane Rita were also simulated over the Houston-Galveston region. Compared to the flow values of the PMP, Hurricane Katrina's maximum peak discharge was approximately 2.5 times less than that of the PMP and Hurricane Rita's maximum peak discharge was approximately 1.65 times less than that of the PMP. This is to be expected since less rain fell in the hurricane events than as designed by the PMP.

As a result of the spatial and temporal distribution of the rainfall, a storm centered at the Houston Ship Channel peaked first, but a storm centered over Lake Houston produced a greater amount of rainfall volume than the other storm locations. As can be seen by Figure 29, Hurricane Katrina's rainfall centered over the Houston Ship Channel peaked at about 4am, with a time to peak of roughly 17.5 hours. This location produced a maximum discharge of slightly over 113,000 cubic feet per second. In comparison, a Katrina rainfall event centered at the Houston Ship Channel produced flows closer to 118,000 cubic feet per second and peaked 4 hours after the storm centered at the Ship Channel. Since storm surge is usually present for 36-48 hours, a Hurricane Katrina event centered over Lake Houston would produce the “worst storm” due to the fact, even though it peaks about 32 hours after the storm event begins, storm surge would still be present and it would bring the greatest rainfall volume to the region.

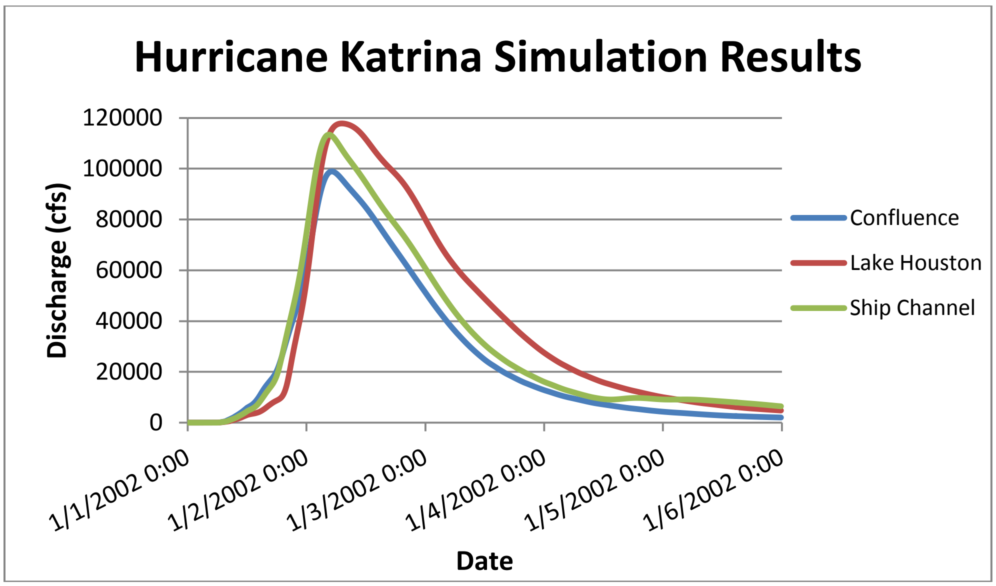


Figure 29: Hurricane Katrina Simulation results below the Fred Hartman Bridge for different storm center locations

Next, Hurricane Rita was simulated. Results, as seen in Figure 30, indicate that a storm centered on either the Houston Ship Channel or the Confluence would peak first, at approximately 4 am the second day, with a time to peak of 17 hours and 45 minutes. The storm events have peak flows of 162,000 cfs and 153,000 cfs, respectively. The Hurricane Rita storm event centered on Lake Houston lagged by 8 hours, with a maximum discharge value of 181,000 cfs. Similar to the analysis for Hurricane Katrina, since storm surge is usually present for 36-48 hours, a Hurricane Rita event centered over

Lake Houston would produce the “worst storm” due to the fact, even though it peaks 36 hours after the storm event begins, storm surge (see Figure 31 for storm surge stage versus time) would still be present and it would bring the greatest rainfall volume to the region, with peak flows about 20,000 cfs greater than that of the other two storm center locations.

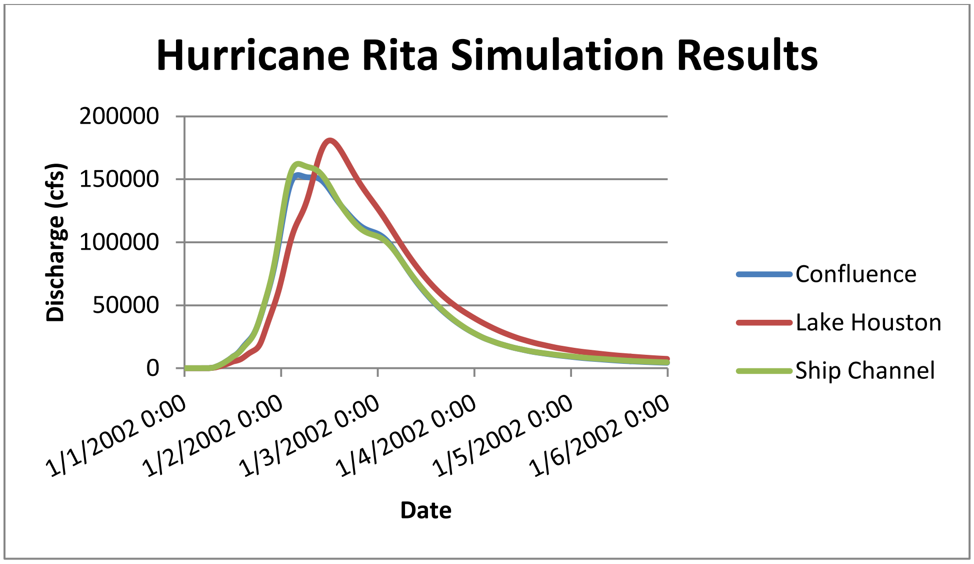


Figure 30: Hurricane Rita Simulation results below the Fred Hartman Bridge for different storm center locations

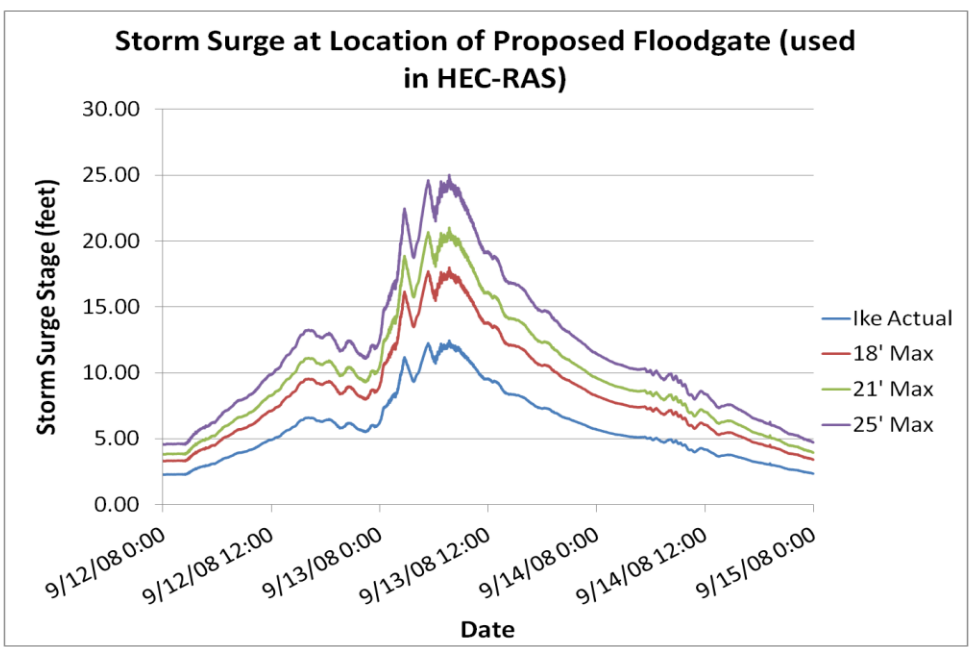


Figure 31: Four different scenarios for storm surge. Storm surge is applied to the HEC-RAS model as a downstream boundary condition at the location of the proposed floodgate. Storm surge is present for 36-48 hours.

A Table summarizing the "worst case" design storms is given below in Table 9.

Table 9: Summary of "worst case" storm center location, discharge and time to peak for design storms

Storm Event	Storm Center Location	Time to Peak (hours)	Maximum Discharge (cfs)
24 hour, 5000 sq mi PMP	Ship Channel	18	300,000
Hurricane Katrina simulation	Lake Houston	21.5	118,000
Hurricane Rita simulation	Lake Houston	25.75	181,000

Chapter 7: Gate Model Results

One of the objectives of this thesis was to coordinate results with Dr. Jason Christian, PhD, PE at the University of Georgia to optimize gate operations for a proposed floodgate below the Fred Hartman Bridge. Christian designed the unsteady HEC-RAS model of the flood gate as part of his doctoral thesis, "Assessing Coastal Vulnerability: Advanced Modeling Methods and Dynamic Hydraulic Characteristics of Gulf Coastal Systems". The flood gate would be used to protect the Houston Ship Channel during hurricane events. As designed by Christian, the gate specifications are 80 foot tall gates with a 27 foot levee (top elevation) and a 25 foot gate (top elevation) (Christian, 2012). More detail on how the dimensions and the design of the gate were established can be found in Christian (2012). The output hydrographs from multiple locations in the Vflo model, for example the outlet of Brays Bayou, Greens Bayou, and Sims Bayou, were inputs into this unsteady HEC-RAS model. The results from Hurricane Ike and the PMP will be discussed in the following sections to illustrate results from one hurricane event and one heavy rainfall event. Complete results are located in Appendix 9.3.

7.1 Hurricane Ike Results

Hurricane Ike was modeled to optimize gate operations since it was the cause for flood mitigation strategies to be examined. Within the HEC-RAS model, stage calibrations occurred in order to ensure accurate results. Figure 32 shows stage calibration of flows from the West (the Houston Ship Channel (HSC)), while Figure 33 shows stage calibrations of flows from the North (Lake Houston and its drainage area).

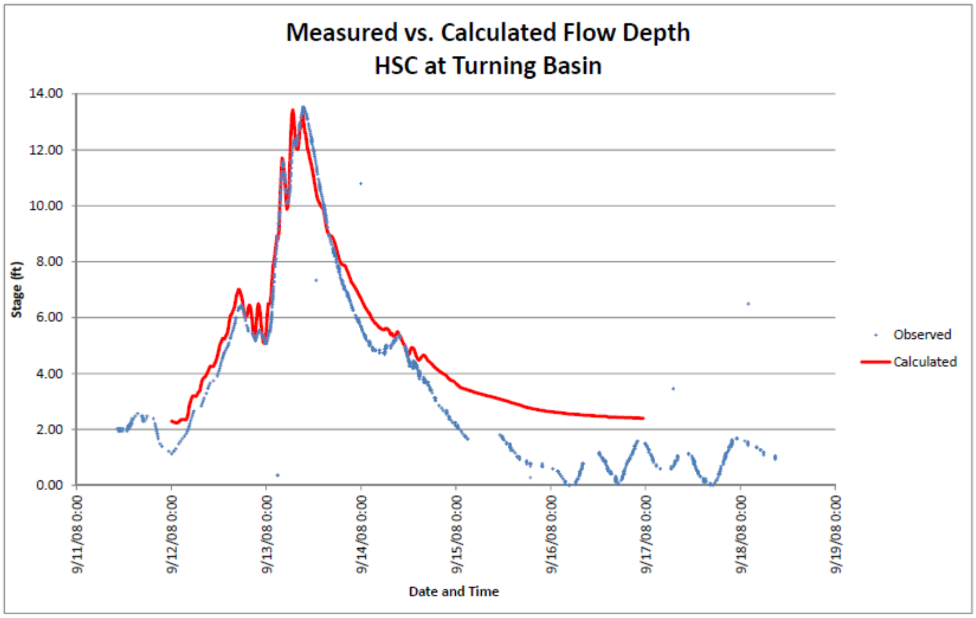


Figure 32: Modeled results in HEC-RAS calibrated to observed stage data for the Houston Ship Channel at Turning Basin

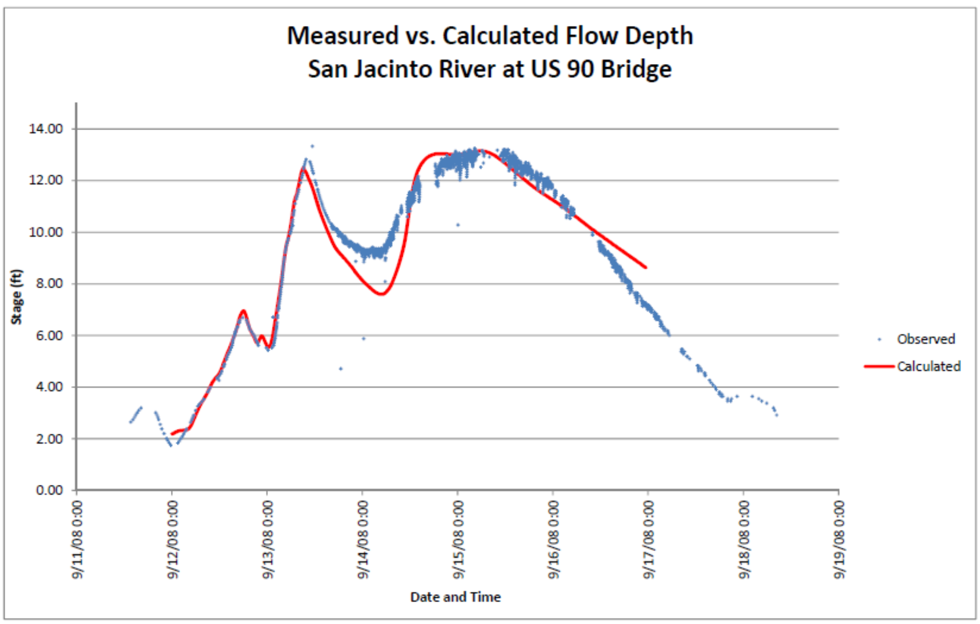


Figure 33: Modeled results in HEC-RAS calibrated to observed stage data for the San Jacinto River at US 90 Bridge

Graphs from both stage calibrations show strong calibration results with regards to accurately depicting timing and peak flows.

The gate model was run for four Hurricane Ike surge scenarios, an observed surge and an 18, 21, and 25 foot scaled surge. As can be seen in Table 10, the gate is able to significantly reduce the water surface elevation and protect the Houston Ship Channel during hurricane events. Comparing the "With Gate (ft)" Maximum Water Surface Elevation (WSEL) to the "No Gate (ft)" option, it is apparent that, even with a 25 foot scaled surge event, the gate would be able to lessen the maximum WSEL by 10 to 12 feet throughout the upstream drainage area. In addition, since many of the facilities in the Houston Ship Channel are only protected until 14-15 feet above mean surface level, the gate is successful in protecting the Houston Ship Channel even in the worst case Ike scenario modeled. Moreover, the duration of the gate closure was noted, and times ranged from 26.75-48 hours (1-2 days), depending on the surge.

Table 10: Gate model results for Hurricane Ike Rainfall with different scaled storm surge values (observed, 18, 21, and 25'). Maximum WSEL is compared with and without the gate at multiple observation locations throughout the study area. Maximum ΔWSEL across the gate, or the maximum change in stage from the left to right side of the gate is provided, as well as the length of time for which the gate is closed.

Scenario: Ike Rainfall with Observed Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	12.32	9.01	6.39	26.75
San Jacinto - HSC confluence	12.38	9.15		
HSC @ Beltway 8 bridge	12.44	9.26		
San Jacinto @ SH90 bridge	13.15	13.15		

Scenario: Ike Rainfall with 18' Scaled Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	17.75	10.64	11.01	37.25
San Jacinto - HSC confluence	17.80	10.76		
HSC @ Beltway 8 bridge	17.80	10.85		
San Jacinto @ SH90 bridge	18.03	13.18		

Scenario: Ike Rainfall with 21' Scaled Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	20.61	11.24	14.02	41.25
San Jacinto - HSC confluence	20.62	11.35		
HSC @ Beltway 8 bridge	20.76	11.43		
San Jacinto @ SH90 bridge	20.99	13.26		

Scenario: Ike Rainfall with 25' Scaled Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	24.48	12.00	17.96	46.00
San Jacinto - HSC confluence	24.08	12.10		
HSC @ Beltway 8 bridge	24.42	12.18		
San Jacinto @ SH90 bridge	24.41	13.44		

Model results from runs made Sept 24, 2012 by Jason Christian

7.2 PMP Storm Event Results

When the PMP storm event was simulated in the gate model, it was apparent that the flows were too great and that a gate would not be useful. When the PMP storm event was modeled in HEC-RAS, the resulting maximum WSEL after closing the gates is over 28 feet (just upstream of the gate), which overtops the gate, compared to the maximum surge elevation of 21 feet if there were no gate structure at all. While these results may not be useful to optimize a gate for timing or note water surface elevation reduction, the findings are still vital because it illustrates that the gate is not to be used in heavy rainfall events.

The PMP storm event represents a maximum rainfall amount that could fall over a geographic location for a given period of time; however, hurricanes are not storm events that tend to bring PMP amounts of rain. According to Lindner, the average amount of rain that a hurricane brings to a region is 100 divided by the forward motion of the hurricane, which is 12.5 miles per hour (on average) for Houston (Bedient, Lessons from

Hurricane Ike, 2012). A storm moving at this speed would bring about 8 inches of rain to the region, less than a third of the rain characteristic of a PMP storm event. However, PMP rainfall amounts are not improbable to the Houston-Galveston region; they just are not accompanied by strong storm surge. For instance, Tropical Storm Allison and the 1994 Storm Event over the San Jacinto River both brought 500-year rainfall totals to the region as major rainfall events; however, Tropical Storm Allison was accompanied with only 2 to 3 feet of storm surge (Stewart, 2002). Thus, instead of calling the PMP storm event trivial, it is imperative to note that for a large rainfall event, the flood gate would not be an advised tool. Instead, it is a structural alternative to protect the region during large surge or hurricane events.

Chapter 8: Conclusions and Future Work

8.1 Conclusions

The purpose of this study was to use the fully distributed hydrologic model, Vflo, to examine large rainfall and hurricane events in the Houston-Galveston region. After a hydrologic analysis had been conducted, the results from Vflo would then be used to help optimize an unsteady HEC-RAS gate model to protect the Houston Ship Channel during hurricane events.

Three calibrated, fully distributed hydrologic models were designed in order to fully represent the 4,500 square mile study area, the San Jacinto River Basin. These three models allowed for the evaluation of historical and design rainfall events in the region to better understand the rainfall-runoff response of the large drainage area. Peak flows, discharge volume, and time to peak were compared for different storm events, and the timing and peak interaction between the discharge and storm surge hydrographs in the basin were analyzed as well. Results show that for heavy rainfall events, such as the PMP storm, flows of about 300,000 cfs are to be expected below the Fred Hartman Bridge in Houston, Texas, with a time to peak of 18 hours. This compares with hurricane rainfall events, such as Hurricane Ike, Katrina, and Rita, which, depending on the spatial and temporal distribution of the rainfall, created peak flows of 116,000, 118,000, and 181,000 cfs, respectively, and time to peaks between 20 and 25 hours. Since storm surge is present for usually the first 36-48 hours of a hurricane event, all of these historic and designed storms would have peak flow values interacting with storm surge.

Once a hydrologic analysis had been conducted, resulting hydrographs from multiple watershed outlet cells were used as lateral inflow hydrograph inputs for the unsteady HEC-RAS gate model to help optimize gate operations such as duration of gate closure. When large rainfall events, such as the PMP storm event, were modeled, it was apparent that flows would be too great and that the gate would not be useful. However, these types of heavy rainfall events are not characteristic of a hurricane, which usually brings about a third of the rainfall from the PMP storm event to the region and are not accompanied by high levels of storm surge. Thus, it was concluded that the gate should not be used in heavy rainfall events, such as Tropical Storm Allison or 1994 Storm on the San Jacinto River. In comparison, when hurricane events, such as Hurricane Ike, Katrina, and Rita, were modeled, it was apparent that the surge gate was successful in reducing the water surface elevations. For instance, for a Hurricane Ike storm event with a scaled 25 foot surge, a water surface elevation reduction of about 12 feet is to be expected. With the gate, the maximum water surface elevation at confluence of the Houston Ship Channel and the San Jacinto River was 12.10 feet, meaning the facilities in the Houston Ship Channel that are only protected to 14-15 feet would not flood.

The work presented within this study has the potential to be impactful for the Houston Ship Channel and the San Jacinto River basin. With a better understanding of rainfall-runoff response in large drainage areas, and the investigation of flood remediation strategies, industries and residential areas can be better protected from hurricane events. Moreover, damage to the region, and in this case, the national economy, could be mitigated.

8.2 Future Work

As a result of the work performed in this study, there is now a better understanding between the linkage of rainfall and storm surge during hurricane events in the Houston-Galveston region. A greater comprehension of the interaction between these two variables is critical in order to better protect the region. However, the lessons learned and conclusions resulting from this work, are not only applicable to the Gulf Coast region; they are significant for any costal region, including New Orleans or the Eastern Seaboard, where rainfall and storm surge come together to create worse disasters than either of the two could possibly create on their own.

Locally, the work conducted in this study could be applicable to regions outside of the current focus area, including Clear Creek and Galveston Bay (as seen in Figure 34). Clear Creek, located in southern Harris County, is a region prone to flooding. Flooding occurs frequently along the main channel, as well as its tributaries. According to the Harris County Flood Control District, flooding in the watershed has the potential to extend upstream to I-45. In addition, Galveston Bay, located on the southeastern edge of Harris County, is vulnerable to flooding. Water surface elevations in the watershed are mainly elevated by storm surge as the region is tidally influenced.

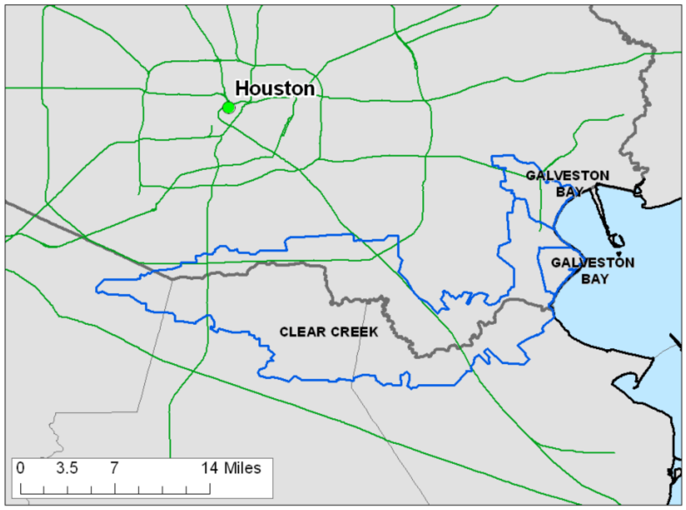


Figure 34: Clear Creek and Galveston Bay

Thus, similar studies to understand rainfall-runoff response in the drainage area, as well as the investigation of flood remediation strategies, such as a surge gate, could be beneficial to the region upstream.

Chapter 9: Appendix

9.1 Probable Maximum Precipitation (PMP) Storm Event

9.1.1 PMP Methodology

The goal of HMR 52 was to provide an outline of how to approximate the temporal and spatial distribution of Probable Maximum Precipitation estimates, including a discussion of the shape, orientation, and size, as well as a discussion of the timing of the rainfall periods based on the duration of the precipitation event. HMR 52 considers characteristics from 53 major rainfalls and six sub regions in the United States East of the 105 Meridian in order to make assumptions for the creation of the PMP storm event.

HMR 52 recommends a shape and pattern for the PMP design storm. When HMR 52 considered the shape of the major rainfalls included in the study, three conclusions were drawn from the analysis. First, 60 percent of the sample of major storms studied had similar shape ratios; thus, it became apparent that the representative shape for all such storms was that of an ellipse with a certain major to minor axis ratio. The second conclusion was that no strong regional variation of shape ratios was apparent. Finally, no strong relation was found between the shape area and total area size. After studying the major rainfalls included in the study, HMR 52 recommended an “idealized (elliptical) isohyetal pattern with a ratio of major to minor axis of 2.5 to 1 for distribution of all 6-hour increments of precipitation” (NOAA, 1982).

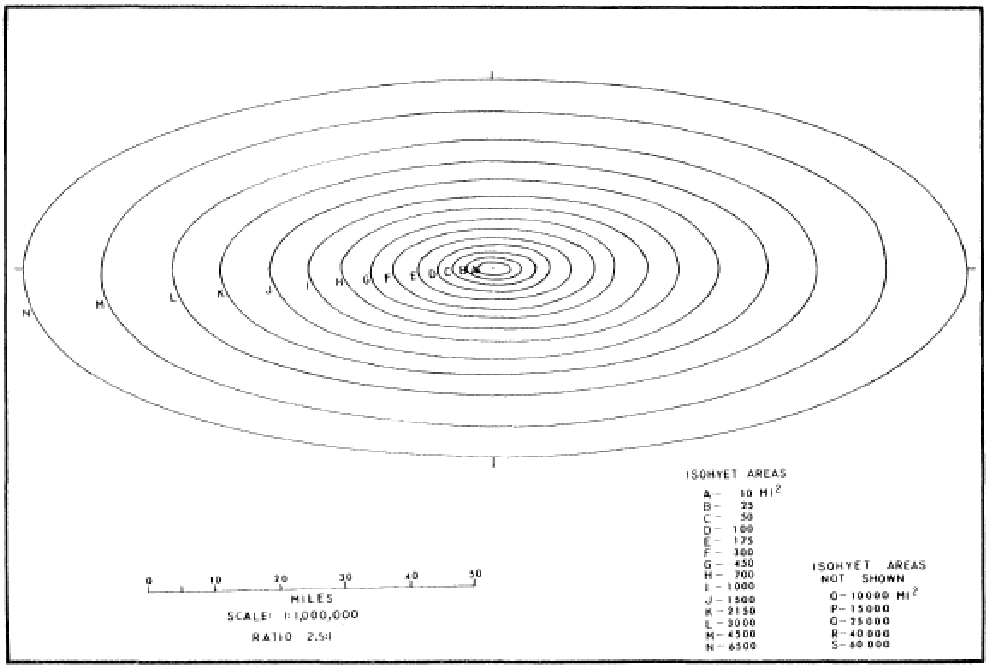


Figure 35: HMR 52 Document Figure 5 – Shape and pattern of elliptical isohyets (NOAA, 1982)

HMR 52 recommends an average orientation of the storm, or direction the storm is travelling, based on the region of the United States where the storm occurs. In order for HMR 52 to calculate the average orientation, certain meteorological conditions were considered and specific assumptions were accepted. Meteorological considerations are influential in determining the isohyetal orientation because different combinations of storm movement, frontal surfaces, moisture influences, and mean tropospheric winds are influential in the storm movement and orientation. Thus, tropical[1], modified tropical[2] , general[3], and local[4] rainfall categories, which are expected to have variation in these categories, were included in the analysis. Eighteen of the thirty-one rains considered in the analysis were from tropical or modified tropical storms, and eleven of the thirteen

[1] Includes all extreme rains that occur as the result of passage of a tropical cyclone within 200 miles of the site of heavy rain
[2] Includes all extreme rains that appear to be derived from moisture associated with a tropical cyclone at some distance or whose moisture has fed into a frontal system that has moved to the vicinity of the rainsite. Also, tropical cyclone rains that become extratropical.
[3] Includes all rains for which no tropical storm was likely involved
[4] Includes all rains for relatively short-duration small-area storms

rainfalls that have storm track information agree within 50 degrees between the storm track and rainfall orientations. Moreover, an assumption made is that the orientation of isohyets for the 6-hour incremental patterns of rainfall is the same as that for the total storm, and from the few incremental isohyetal patterns included in the study, the orientations of the 6-hour ioshyetal increments varied by no more than forty degrees from the total-storm orientation. HMR 52 used the same six sub regions used to study shape ratios to determine the regionally averaged angular orientations and for 50 large storms in the Gulf Coast sub region, an average orientation of 235 degrees was selected, with a range of 140 to 300 degrees. For a more detailed explanation of the methodology used to determine the average orientation, see HMR 52 see section 4 “Isoheytal Orientation”.

Table 11: HMR 52 Document Figure 10 – Average Isohyetal Orientation for each subregion (NOAA, 1982)

Subregion	Average Orientation (deg.)	Range in orientation (deg.)
Atlantic Coast	204	140 to 305
Appalachians (East)	204	155 to 240
Appalachians (West)	278	240 to 305
Gulf Coast	235	140 to 300
Central Plains	256	195 to 300
North Plains	257	185 to 310
Rocky Mt. Slopes	214	170 to 290

While HMR 51 creates the all-season PMP based on the size of the basin, HMR 52 recommends basing the size of the PMP pattern on maximizing the volume of precipitation within the drainage. Maximum volume is a function of pattern centering, basin irregularity of shape, and of the area size of PMP distributed over the drainage. To obtain the area that maximizes precipitation within the drainage, HMR 52 proposes selecting different PMP sizes based on the idealized isohyetal pattern provided, some smaller and some larger, and evaluating the volume corresponding to each pattern. Once the volume corresponding to each pattern has been determined, HMR 52 recommends plotting the results as area size (selected) versus volume (computed) and approximating the area size at which the volume reaches a maximum to use as the design PMP storm.

HMR 52 discusses the temporal distribution of the storm. To obtain the temporal information, HMR 52 divides the storms into categories based on available data, duration and storm type, and then analyzes the “rain burst”[5] characteristics for the major rainfalls included in the study. The findings were then used to recommend a sequence for the PMP increments. To get PMP for all durations within a 72-hour storm requires that the 6-hour increments be arranged with a single peak. HMR 52 also suggests that the 6-hour increments are arranges such that they decrease progressively to either side of the greatest 6-hour increment, implying that the lowest 6-hour increment will be at either the beginning or ending of the rainfall sequence. In addition, HMR 52 suggests the placement of the increments for larger storms based on the notion that the study of major storms suggests that maximum rainfall rarely occurs at the beginning of longer duration sequences.

Liscum’s article records the 1-, 3-, 6-, 12-, and 24- hour precipitation depths for recurrence intervals of 2, 5, 10, 25, 50, 100, 250, and 500 year recurrence intervals. Since a 100-year storm is trying to be reconstructed, the values determined by Liscum were:

Table 12: Precipitation Depths (centimeters) for given durations (hours) and recurrence intervals (years) (Liscum, Johnson, Woodward, & Spenn, 2004)

Exceedance Probability	Recurrence Interval, Years	Precipitation Depths, centimeters determined for Period from 1970-2001 Durations				
		1-Hour	3-Hour	6-Hour	12-Hour	24-Hour
0.01	100	10.98	18.62	24.93	31.28	35.29

[5] Defined as one or more consecutive 6-hour rain increment(s) for which each individual increment has 10 percent or more of the 72-hour rainfall

9.1.2 PMP Results

The 100 year, 24 hour PMP was designed using the PDDF values provided by Liscum and the methodology outlined in HMR 52. Once the 100 – year rainfall levels for 1-, 6-, 12-, and 24- hours were obtained from the Liscum article, the change that occurred between each time period was measured. For instance, the change that occurred in the PDDR rainfall in the first 6 hours was 9.8 inches. Then, for each 6-hour period, for each isohyet, the percent of each increase between the first, second, and third 6- hour PMP increment was calculated.

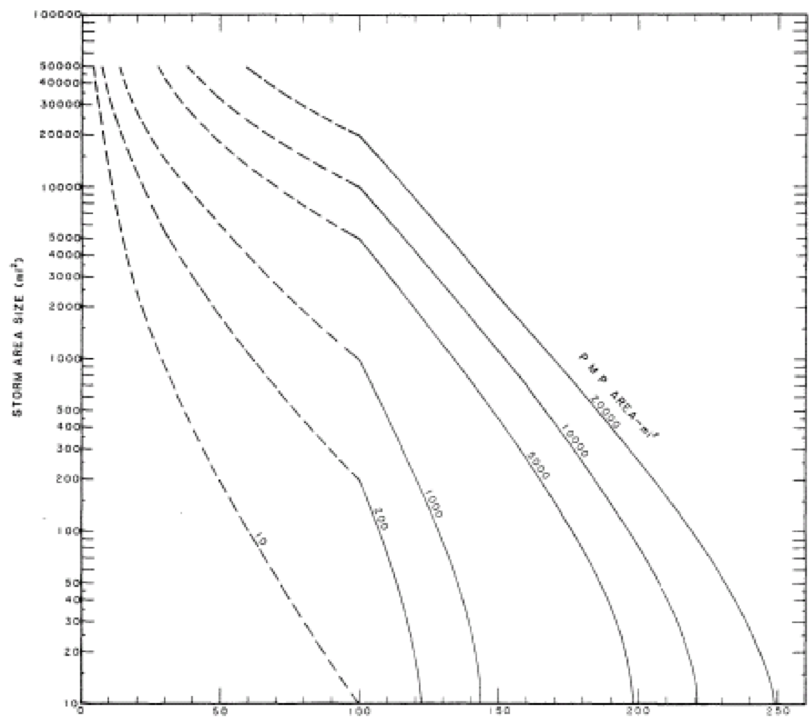


Figure 36: HMR 52 Document Figure 17 – 12 hour within/without-storm curves for standard area sizes (NOAA, 1982)

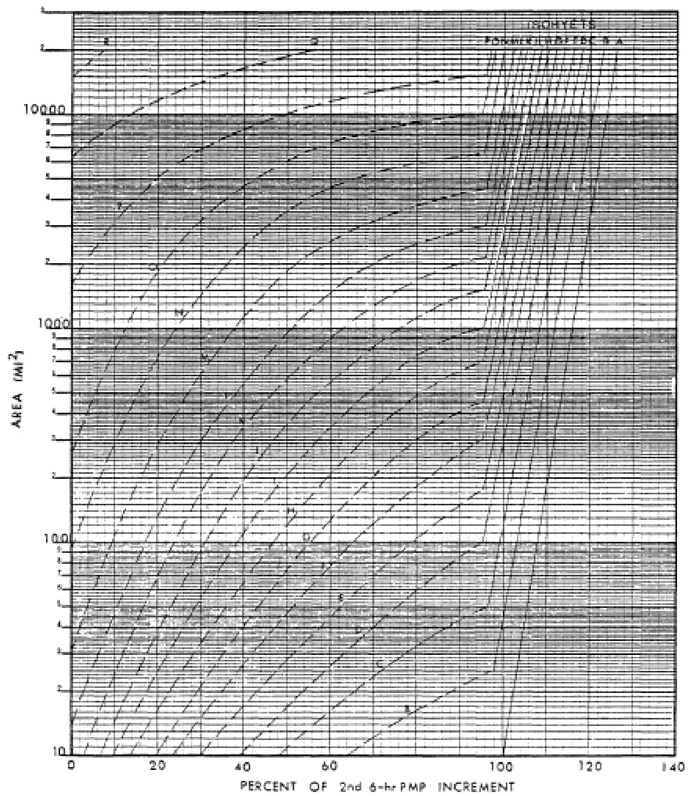


Figure 37: HMR 52 Document Figure 18- Nomogram for the 2nd 6-hr PMP increment and for standard isohyet area sizes between 10 and 40,000 mi^2 (NOAA, 1982)

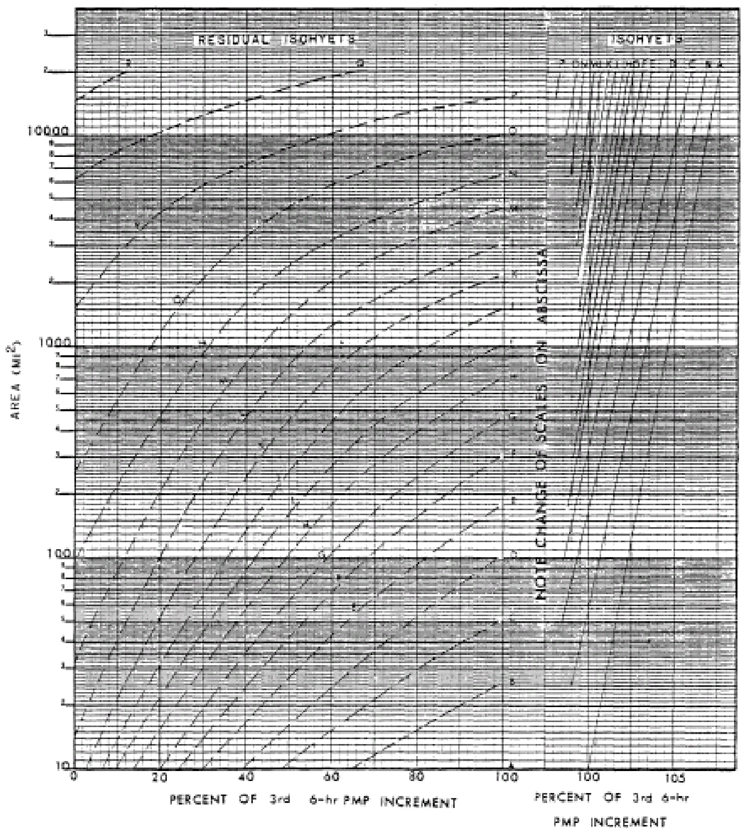


Figure 38: HMR 52 Document Figure 19- Nomogram for the 3rd 6-hr PMP increment and for standard isohyet area sizes between 10 and 40,000 mi^2 (NOAA, 1982)

For each isohyet in each period, the percent of the PMP increment was multiplied by the change in the rainfall amount provided in Liscum to get the PMP level for each isohyet in each 6- hour period.

Due to the fact that the Liscum article did not record an 18-hour rainfall level, the 3rd 6-hour PMP increment, a graph of PMP level against time was created. The estimated PMP level at 18 hours was then interpolated from the created graph. The change between the 12 hour period and the 18 hour period was then calculated and multiplied by the percent determined from the nomogram to obtain the PMP for the 3rd 6- hour increment. Also, levels of residual precipitation were measured for isohyets M and N in the 4th 6-hour PMP increment.

Once the PMP values were obtained, they were temporally organized according to HMR 52.

This process was done for standard isohyet area sizes, including the 500 mi2, 1000 mi2, 5000 mi2, and 10,000mi 2. Once the isohyet values were obtained and organized, the storms were centrally located over the “Lower San Jacinto River” watershed and the rainfall volume versus area of the PMP was maximized. With this process, it became apparent that the 5000 mi2 design storm size for the PMP maximized the rainfall volume per the size of the storm and was used in the design process. The isohyet values for the 24 hour 5000 square mile storm are provided in Table 13, with a hyetograph shown in Figure 39. The center of mass of the rainfall is 8.87 for isohyet A, or roughly 8 hours and 52 minutes.

Table 13: 24 hour, 5000 square mile PMP storm event isohyets values for rainfall (inches)

24 hour 5000 square mile PMP storm:				
Isohyet	**0-6 hours (in)**	**6-12 hours (in)**	**12-18 hours (in)**	**18-24 hours (in)**
A	3.05	13.15	0.82	0.80
B	2.95	12.37	0.82	0.80
C	2.88	11.58	0.81	0.80
D	2.80	10.80	0.80	0.80
E	2.75	10.01	0.79	0.80
F	2.70	9.23	0.78	0.80
G	2.65	8.54	0.78	0.80
H	2.60	7.56	0.78	0.80
I	2.55	5.10	0.78	0.80
J	2.53	4.02	0.78	0.80
K	2.48	3.04	0.78	0.80
L	2.45	2.36	0.77	0.80
M	2.40	1.47	0.77	0.80
N	1.65	0.79	0.64	0.66

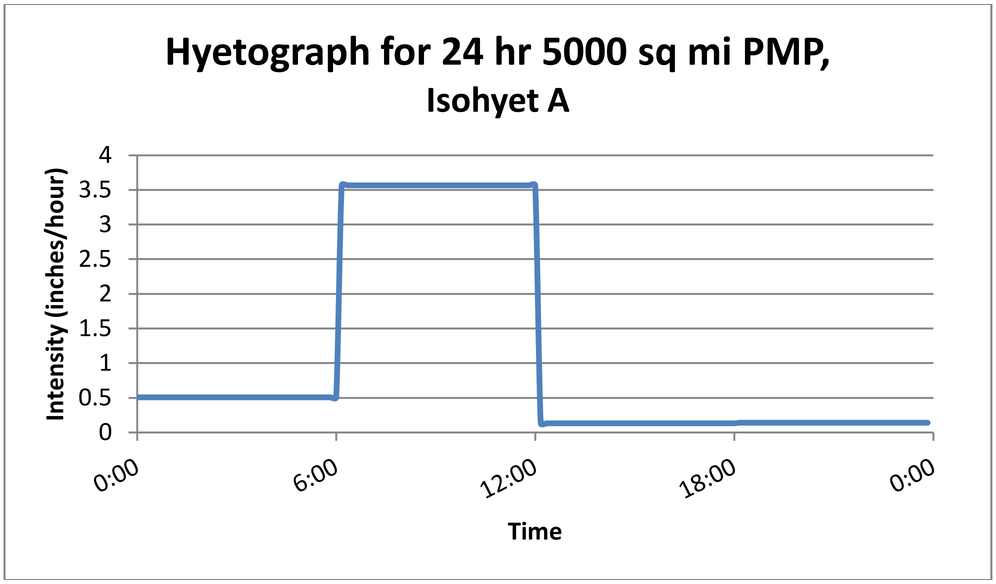


Figure 39: Hyetograph for Isohyet A of the 24 hour, 5000 square mile PMP storm event

9.2 Simulated Storm Events

9.2.1 Simulated Storm Methodology

A similar methodology as outlined in HMR 52 was employed to recreate Hurricane Katrina and Hurricane Rita. Differently from the PMP, the 24-hour precipitation depths for the storms were provided by the NCDC and the 6-, 12-, and 18-hour accumulations were simulated from HMR 51 and Liscum to represent a typical rainfall distribution.

For designing the simulated historic storms, 24 hour radar and rain gage data was obtained from USGS Water Resources of the United States. The data was then converted to shapefiles and imported into GIS. Once mapped, the accumulated rainfall in addition to the distance from the center of the storm was tabulated. The cumulative rainfall versus distance was plotted, and it became apparent that the graph started to level off after roughly 80% of the rainfall. Thus, the 80th percentile of the rain was simulated, as seen in Figure 40.

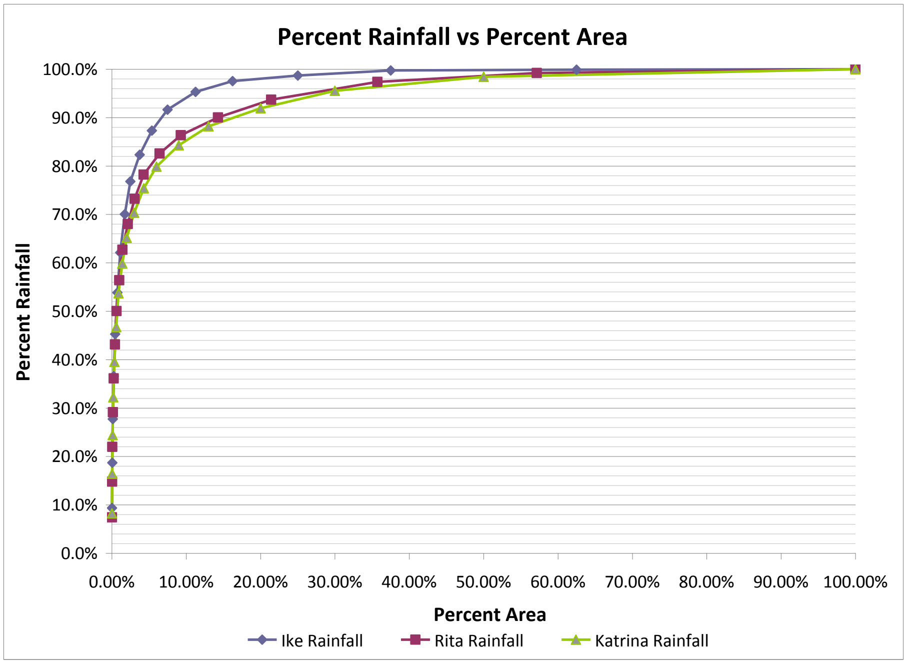


Figure 40: Cumulative rainfall versus distance (area covered) for Hurricane Ike, Hurricane Rita, and Hurricane Katrina

The storm size and orientation was also recorded. This data was then used to recreate the historical storms in an ellipsoid pattern with the given orientation of the actual rainfall pattern over the 24 hour period.

9.2.2 Simulated Storm Results

The Table below illustrates the rainfall accumulation over the four 6-hour periods for Hurricane Katrina and Hurricane Rita (Tables 14a and 14b) that was simulated from the 24 hour rainfall totals.

Table 14a: 24 hour, Hurricane Katrina simulation rainfall isohyets values (inches)

Hurricane Katrina Simulation Data				
Isohyet	**0-6 hours (in)**	**6-12 hours (in)**	**12-18 hours (in)**	**18-24 hours (in)**
A	0.06	8.87	0.89	0.72
B	0.06	8.83	0.89	0.72
C	0.06	8.58	0.86	0.69
D	0.06	8.41	0.85	0.68

E	0.06	7.87	0.79	0.64
F	0.06	7.74	0.78	0.63
G	0.05	7.53	0.76	0.61
H	0.05	6.60	0.66	0.53
I	0.04	5.72	0.57	0.46
J	0.04	5.55	0.56	0.45
K	0.04	5.47	0.55	0.44
L	0.03	4.80	0.48	0.39
M	0.03	4.75	0.48	0.38
N	0.03	4.21	0.42	0.34

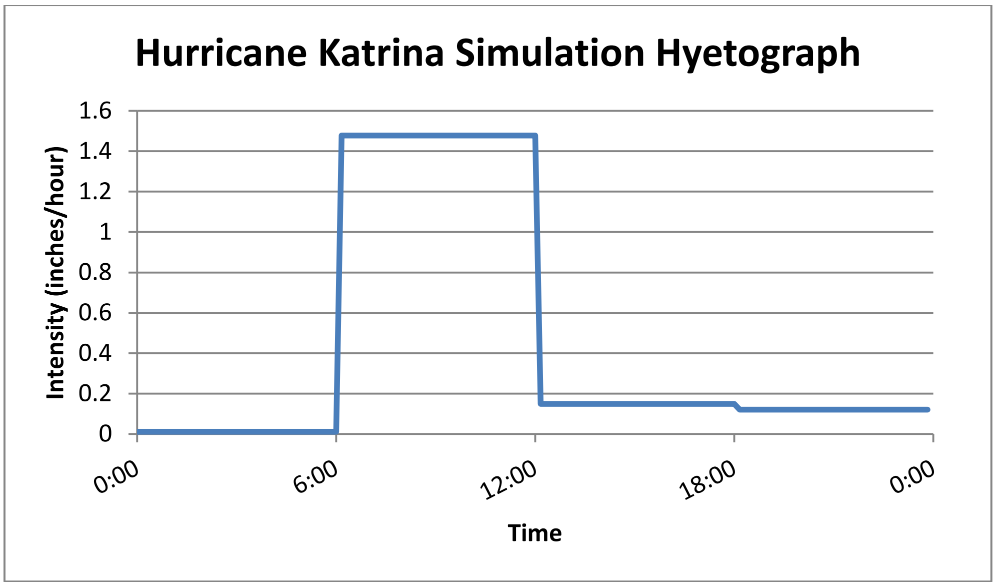


Figure 40a: Hyetograph for Isohyet A of Hurricane Katrina Simulation Rainfall Data

Table 14b: 24 hour, Hurricane Rita simulation rainfall isohyets values (inches)

Hurricane Rita Simulation Data				
Isohyet	**0-6 hours (in)**	**6-12 hours (in)**	**12-18 hours (in)**	**18-24 hours (in)**
A	0.08	10.85	1.09	0.88
B	0.08	10.85	1.09	0.88
C	0.07	10.52	1.06	0.85
D	0.07	10.52	1.06	0.85
E	0.07	10.26	1.03	0.83
F	0.07	10.26	1.03	0.83
G	0.07	10.10	1.01	0.82
H	0.07	9.34	0.94	0.76
I	0.07	9.26	0.93	0.75

J	0.06	7.79	0.78	0.63
K	0.05	7.66	0.77	0.62
L	0.05	7.29	0.73	0.59
M	0.05	6.39	0.64	0.52
N	0.04	5.55	0.56	0.45

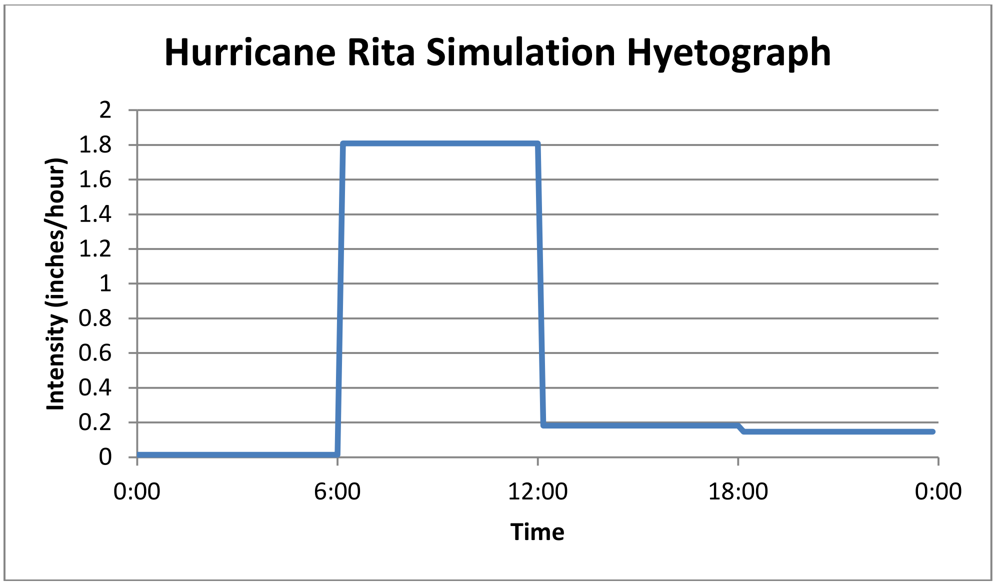


Figure 40b: Hyetograph for Isohyet A of Hurricane Rita Simulation Rainfall Data

9.3 Additional Gate Results

Hurricane Katrina Rainfall:

Table 15: Gate model results for Hurricane Katrina Simulation Rainfall with different scaled storm surge values (observed Ike, 18, 21, and 25')

Scenario: Katrina Rainfall with Observed Ike Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	12.25	8.41	6.89	25.25
San Jacinto - HSC confluence	12.21	8.68		
HSC @ Beltway 8 bridge	12.34	8.90		
San Jacinto @ SH90 bridge	12.46	11.58		

Scenario: Katrina Rainfall with 18' Scaled Ike Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	17.63	10.54	12.37	34.75
San Jacinto - HSC confluence	17.59	10.75		
HSC @ Beltway 8 bridge	17.68	10.91		
San Jacinto @ SH90 bridge	17.88	12.21		

Scenario: Katrina Rainfall with 21' Scaled Ike Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	20.46	11.28	15.37	38.00
San Jacinto - HSC confluence	20.38	11.47		
HSC @ Beltway 8 bridge	20.61	11.60		
San Jacinto @ SH90 bridge	20.76	12.71		

Scenario: Katrina Rainfall with 25' Scaled Ike Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	24.42	11.95	19.33	41.75
San Jacinto - HSC confluence	23.82	11.95		
HSC @ Beltway 8 bridge	24.09	11.97		
San Jacinto @ SH90 bridge	24.20	12.35		

Model results from runs made Oct 5, 2012 by Jason Christian

Hurricane Rita Rainfall:

Table 16: Gate model results for Hurricane Rita Simulation Rainfall with different scaled storm surge values (observed Ike, 18, 21, and 25')

Scenario: Rita Rainfall with Observed Ike Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	12.26	8.57	6.77	24.25
San Jacinto - HSC confluence	12.24	8.91		
HSC @ Beltway 8 bridge	12.40	9.25		
San Jacinto @ SH90 bridge	14.50	14.45		

Scenario: Rita Rainfall with 18' Scaled Ike Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	17.64	11.01	12.34	33.50
San Jacinto - HSC confluence	17.60	11.37		
HSC @ Beltway 8 bridge	17.74	11.66		
San Jacinto @ SH90 bridge	17.85	14.91		

Scenario: Rita Rainfall with 21' Scaled Ike Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	20.47	12.21	15.35	37.00
San Jacinto - HSC confluence	20.40	12.56		
HSC @ Beltway 8 bridge	20.65	12.80		
San Jacinto @ SH90 bridge	20.77	15.26		

Scenario: Rita Rainfall with 25' Scaled Ike Stage Boundary Condition

Observation Location	Maximum WSEL No Gate (ft)	Maximum WSEL With Gate (ft)	Maximum Δ WSEL Across Gate (ft)	Duration Gate Closure (hrs)
Hartman Bridge	24.56	13.41	19.32	40.00
San Jacinto - HSC confluence	23.84	13.70		
HSC @ Beltway 8 bridge	24.15	13.91		
San Jacinto @ SH90 bridge	24.21	15.75		

Model results from runs made Oct 1, 2012 by Jason Christian

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