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Analysis and Prediction of Rainfall and Storm Surge Interactions in the Clear Creek Watershed using Unsteady-State HEC-RAS Hydraulic Modeling

by

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Abstract

Analysis and Prediction of Rainfall and Storm Surge Interactions in the Clear Creek Watershed using Unsteady-State HEC-RAS Hydraulic Modeling

This study presents an unsteady-state hydraulic model analysis of hurricane storm surge and rainfall-runoff interactions in the Clear Creek Watershed, a basin draining into Galveston Bay and vulnerable to flooding from both intense local rainfalls and storm surge. Storm surge and rainfall-runoff have historically been modeled separately, and thus the linkage and interactions between the two during a hurricane are not completely understood. This study simulates the two processes simultaneously by using storm surge stage hydrographs as boundary conditions in the Hydrologic Engineering Center's – River Analysis System (HEC-RAS) hydraulic model. Storm surge hydrographs for a severe hurricane were generated in the Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters (ADCIRC) model to predict the flooding that could be caused by a worst-case scenario. Using this scenario, zones have been identified to represent areas in the Clear Creek Watershed vulnerable to flooding from storm surge, rainfall, or both.

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Chapter 1: INTRODUCTION

1.1 Research Motivations

The following discussions reflect the motivations behind this research.

1. The Clear Creek Watershed is home to 118,000 people (in Harris County) in residential developments such as Clear Lake, Friendswood, Pearland, Kemah, and the Lyndon B. Johnson Space Center (HCFCD, 2007). Located on Galveston Bay, this area is extremely vulnerable to flooding caused both intense rainfalls and hurricane storm surge. The damage caused by Hurricane Ike, though severe, was not a worst case scenario. Modeling a worst case storm surge scenario could bring insight to where the vulnerable areas are located in addition to the potential damages that may result if preventative action is not taken.
2. Storm surge and rainfall-runoff have historically been modeled as separate processes and assumed to be additive because of inadequate storm surge data availability, a limited understanding of storm surge behavior, and computation limitations. These modeling restrictions are both the cause and effect of our incomplete understanding of hydrologic and hydraulic interactions between storm surge and rainfall-runoff. By understanding these interactions we can better determine which areas will be vulnerable to flooding from storm surge and rainfall, and which areas may be vulnerable to both. Such knowledge would be invaluable for preparedness, evacuation planning, development, and insurance purposes.
3. The development of a flood-alert system that can incorporate real-time storm surge predictions is an area of research that could potentially have wide-reaching

impacts. Real-time damage predictions, increases in evacuation lead times, and better insight into floodwater recession times are just some of the possible benefits. Since the study presented here creates an unsteady-state hydraulic model for the Clear Creek Watershed, an area which is vulnerable to storm surge, it is an important first step to advancing flood-alert technology to include storm surge to be applied to other watersheds.

1.2 Research Objectives

The research objectives for this study are included below.

1. Update the existing hydrologic model (HEC-HMS) for the Clear Creek Watershed and Armand Bayou.
2. Match modeled HEC-HMS flows to those from historic storm events using NEXRAD radar rainfall model input.
3. Run an unsteady-state HEC-RAS model for the Clear Creek Watershed and Armand Bayou for Hurricane Ike and match modeled stages to observed stages during the storm.
4. Run the same unsteady-state HEC-RAS model for a hurricane scenario with more severe storm surge in order to simulate a worst-case flooding scenario from storm surge.
5. Identify which areas along Clear Creek are vulnerable to storm surge, rainfall, and which areas are vulnerable to both.
6. Create floodplain maps depicting inundation depths for Hurricane Ike and the worst-case scenario. Compare each against standard floodplains to better characterize each storm.

1.3 Study Area

The Clear Creek Watershed (Figure 1-1, A) has an area of approximately 197 mi^2 and is located in Harris, Fort Bend, Brazoria, and Galveston Counties. The basin is home to 16 cities including Houston, Brookside Village, Pearland, Friendswood, League City, Pasadena, the Clear Lake Area communities and five drainage/flood control districts (HCFCD, 2007). The main channel, Clear Creek, drains into Galveston Bay, is primarily a wooded stream, and represents the border of Harris County. Containing about 154 miles of open streams, Clear Creek's largest tributary is Armand Bayou (Figure 1-1, B) (HCFCD, 2007). Other tributaries to Clear Creek include Hickory Slough, Turkey Creek, Mary's Creek, Cowart Creek, Chigger Creek, and Taylor Bayou (Figure 1-2).

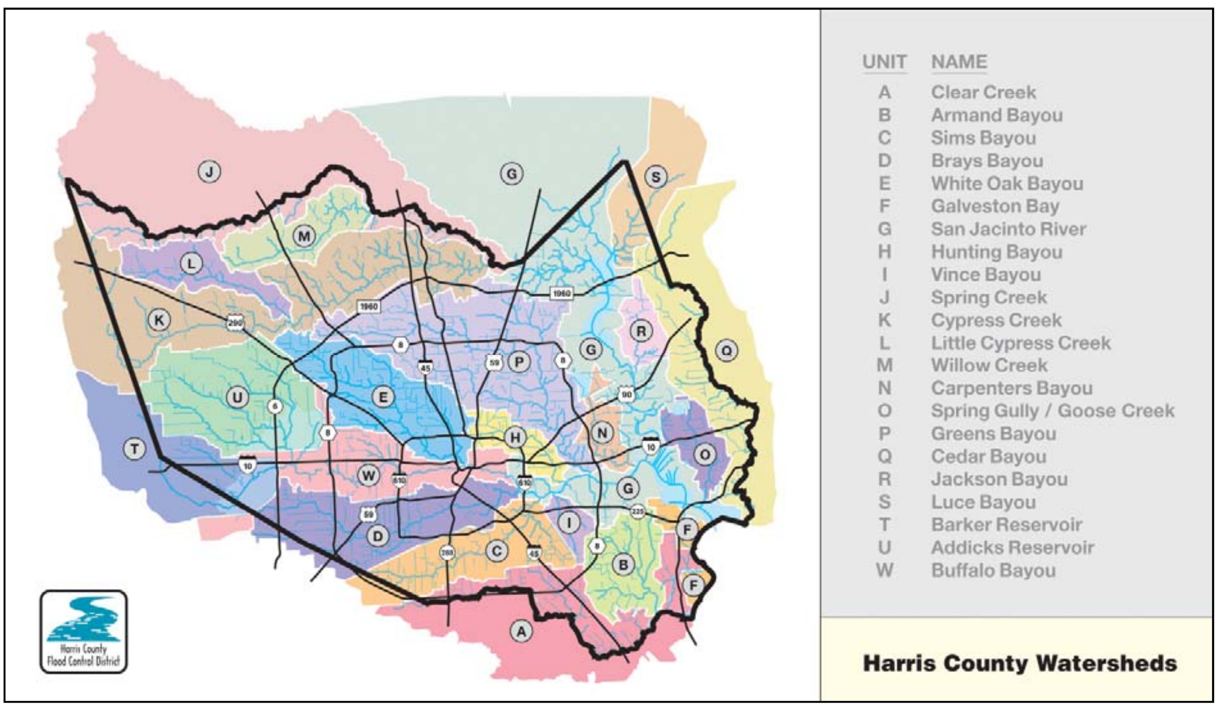


Figure 1-1: Harris County Watersheds (HCFCD, 2012)

The Clear Creek Watershed has been under investigation for frequent flooding problems since Congress authorized the Clear Creek Flood Control project in 1968. The legislation called for a comprehensive restudy of structural works, floodplain regulation, and floodplain management in order to "avoid uneconomic, hazardous, or unnecessary development of the area subject to flooding," (USACE, 2011).

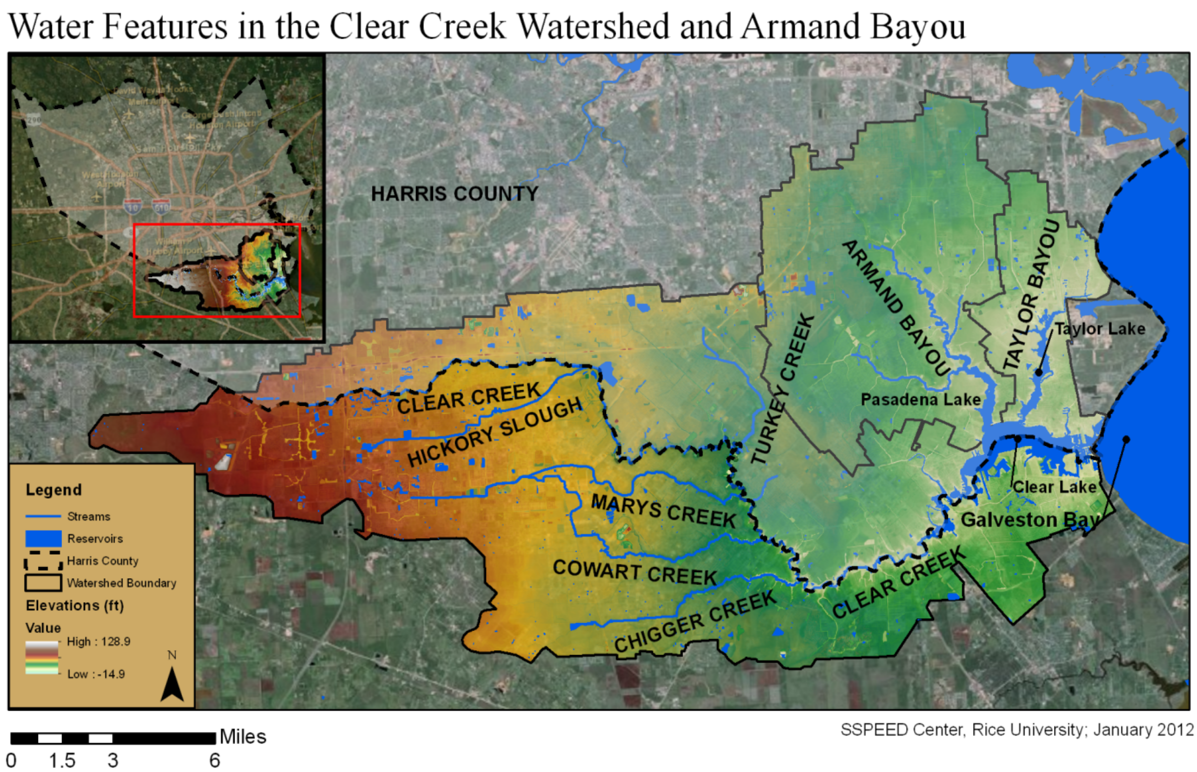


Figure 1-2: Water features in the Clear Creek Watershed and Armand Bayou

In 1982 a preconstruction authorization planning report resulted from this study, recommending that the channel be enlarged and that bends in the river be straightened to contain the 10% annual chance flooding event. In the 1990s construction began on this project. A second outlet with a gated structure was added at the outlet of Clear Lake to ensure that the channel modifications did not cause additional flooding in and around Clear Lake (USACE, 2011). The second outlet, completed in 1997, was built only as an additional release for upstream waters (CCP, 2005). In other words, the gate does not protect the watershed from high tides or storm surge in Galveston Bay.

Though the Clear Creek Watershed's susceptibility to flooding has been known for years and steps have been taken to improve drainage in the basin, Hurricane Ike (2008) reminded us of its vulnerability to storm surge. The damage and destruction brought by Hurricane Ike prompted Rice University's Severe Storm Prediction, Education, and Evacuation from Disasters (SSPEED) Center to further investigate the kind of damage that may be possible given a worst-case storm scenario, how rainfall and storm surge may interact in this basin, and what authorities should be prepared for. The research presented in the following pages provides answers to these questions for a worst case scenario.

Chapter 2: Background and Literature Review

The Gulf Coast of the United States is subject to extremely intense rainfall and storm surge. The states of Texas, Louisiana, and Mississippi are especially vulnerable to severe storm surge due to the shallow slopes of the bathymetry just offshore. Similarly, the shallow land slopes in the coastal areas, when combined with intense rainfall, can create devastating flooding conditions. Since the Gulf Coast is vulnerable to both storm surge and rainfall, the potential impact of hurricanes is of particular concern. This literature review will discuss the threats associated with hurricanes, the particular vulnerability of the Clear Creek Watershed, modeling techniques for simulating both storm surge and overland flooding, and ongoing research in modeling, mapping, and public dissemination of flood risk.

2.1 Storm Surge

Storm surge causes the most damage, deaths, and recovery expenses associated with hurricanes. The phenomenon can be thought of as a wall of water that approaches the shoreline as a hurricane makes landfall. Created from the winds and pressure differentials in a hurricane, storm surge is worse when the radius of maximum winds is large and the central pressure is low. Figure 2-1 is a diagram from the National Oceanic and Atmospheric Administration (NOAA) and represents the different components and causal mechanisms of storm surge. Notice that if the astronomical high tide coincides with the arrival of the storm surge, the approaching wall of water is essentially higher by the change in sea level associated with the high tide. Storm surge is generally highest in the northeast quadrant of a hurricane in the northern hemisphere and in the southwest quadrant of a hurricane in the southern hemisphere.

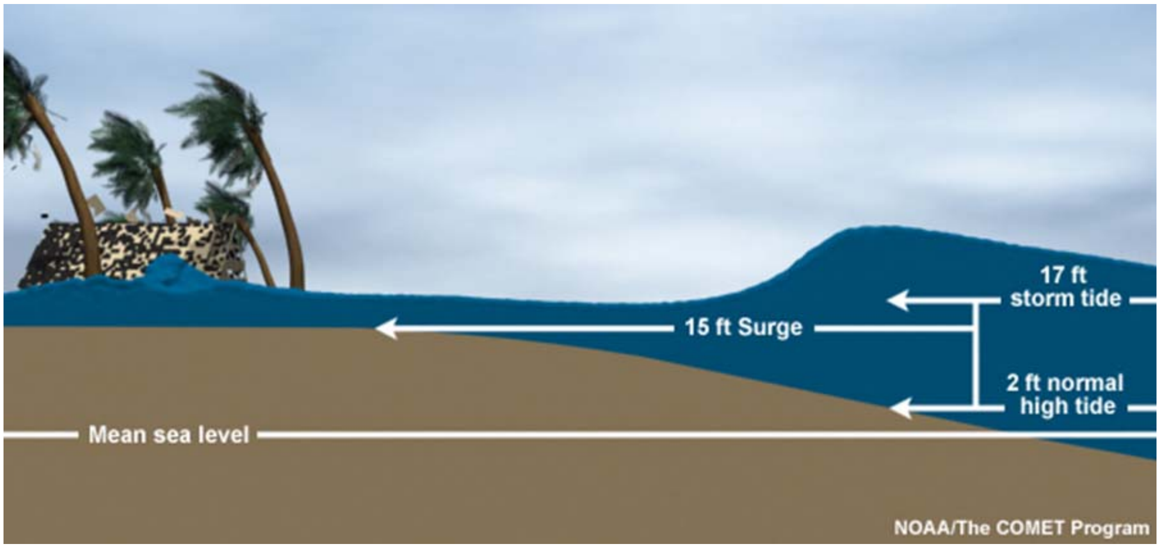


Figure 2-1: NOAA graphic illustrating what storm surge is

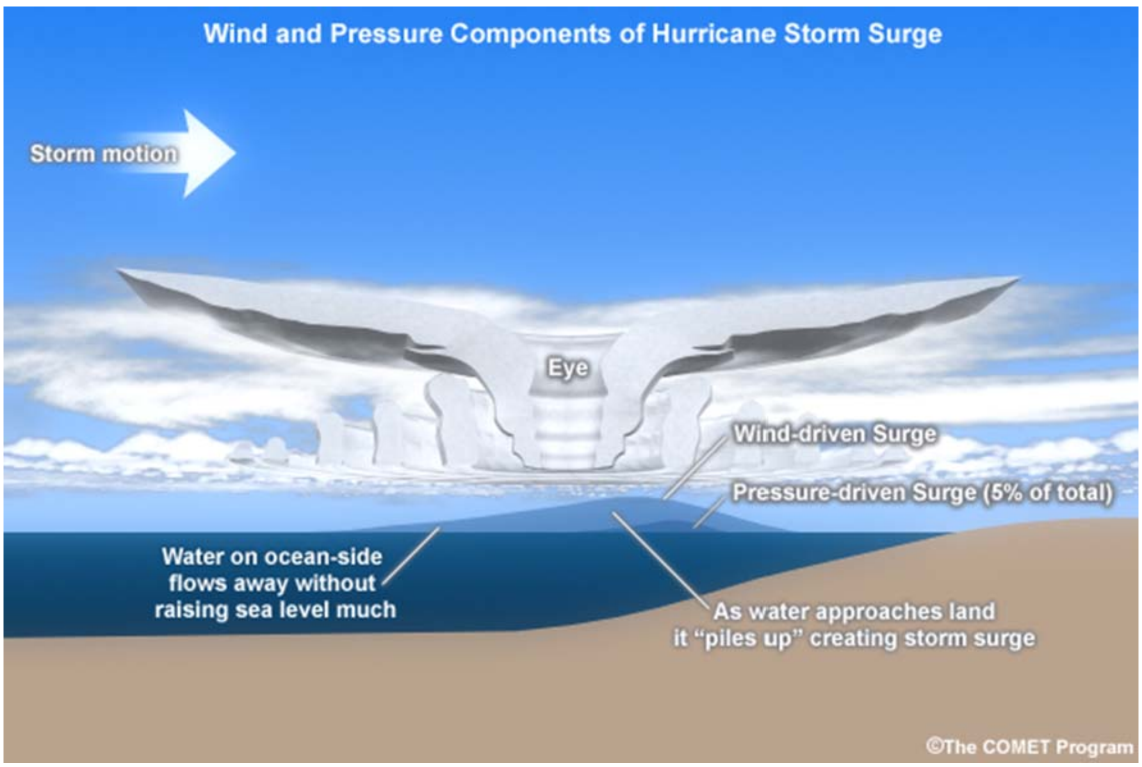


Figure 2-2: NOAA graphic illustrating the causal mechanisms of storm surge

As Figure 2-2 illustrates, storm surge is driven by both pressure changes and wind speeds in a hurricane. The lowest pressure and highest wind speeds are located in the center of the storm. Thus, the highest surge levels are generally located closest to the eye of the hurricane, as is represented in Figure 2-2. However, many other factors also determine the potential storm surge. The forward speed of the hurricane, radius of maximum wind speeds, angle of approach, and coastal characteristics also have an effect on how severe the resultant surge will be. Thus, it is important for storm surge to be analyzed on a case-by-case basis. In an effort to better understand the effects of different levels of storm surge, this study models the inland impacts of the Hurricane Ike surge in addition to modeled "worst case" storm surge scenarios. Combining surge model forecasts with inland flood models is a relatively new concept in the field of hydrology. This study works to experiment with and verify the methodology of simulating surge forecasts in a riverine model. If put into real-time operation, this research could have wide-reaching impacts in both the United States and abroad.

Significant historical storm surge events include Hurricane Katrina (2005) with surge elevations 25-28 ft above normal tide levels, Hurricane Camille with 24 ft of storm surge, and the Galveston Hurricane of 1900, which killed at least 8,000 people with its storm surge of 8-15 ft (with astronomical tides). The impacts that a particular level of storm surge can have on a coastal community depend heavily on factors such as population density, economic productivity, and infrastructure (e.g. interstates, arterials, and airports). According to NOAA, population density from 1990-2008 increased "by 32% in Gulf coastal counties, 17% in Atlantic coastal counties, and 16% in Hawaii" (NOAA, 2012). Over half of all US economic productivity is located along the coast

(NOAA, 2012), and as global climate change decreases the recurrence intervals of extreme events, local and federal costs due to hurricanes are rapidly increasing. As a response, the Federal Emergency Management Agency (FEMA) recently conducted a massive study to delineate standard storm surge recurrences (e.g. 1%, 10%, etc.) in an effort to improve coastal construction standards, community awareness, and the likelihood of widespread implementation of restrictions for coastal development (FEMA, 2012). Given the amount of research dollars currently being invested in storm surge risk analyses, the level of damage resulting from Hurricane Ike, and the high vulnerability associated with its location, the Clear Creek Watershed will undoubtedly benefit from a detailed storm surge analysis.

2.2 Weather and Climate in the Houston Area

The vulnerability of Clear Creek to storm surge is enhanced by the local climate. Located near Houston, Clear Creek is situated in a humid subtropical climate. On average, the annual precipitation totals 54 inches, with the wettest month being June and the driest month being March (NOAA, 2012). Though supercell thunderstorms sometimes cause tornadoes in the area, flooding is the largest concern. The intense rainfalls, flat slopes (characteristic to coastal areas), and drainage limitations can create extreme flash flooding hazards during all times of the year. Hurricanes are also common along the Texas Coast, and according to Needham (2012), the upper Texas Coast is historically one of the two most vulnerable areas to storm surge along the Gulf Coast, second only to the Mississippi and upper Louisiana coastlines. By clustering historical storm surge data along the Gulf Coast, Needham calculated that the 1% storm surge return period is just over six meters (~ 20 feet) for the upper Texas Coast, and about 7.6 meters (~25 feet) for the Mississippi and upper Louisiana coastline (Needham, 2012).

The Houston area has been impacted by numerous storms over the years that have taken many lives and devastated the local economies. Tropical Storm Allison, Hurricane Rita, and Hurricane Ike are three disastrous storm events that have occurred since 2001. Hurricanes and tropical storms, however, are not the only threat to the region. Several extreme rain events, such as those in April 2009 and January 2012, have brought severe flash flooding to local communities (NWS, 2012).

Since their inception, flood-alert systems such as the third generation of the Texas Medical Center Flood-Alert System (FAS3) have helped local officials to make important decisions about flood prevention and management (FAS, 2012). For instance, the Texas Medical Center, the largest medical center in the world, monitors the FAS3 website during storm events. The system helps emergency managers determine when to close the flood gates in the garages and tunnels that connect all of the medical institutions. Such a system is helpful in preventing a disaster such as the flood from Tropical Storm Allison (2001), which brought over $2 billion in damage to the medical center alone (NOAA, 2001). As a next step in this project, research is currently being undertaken to develop a flood-alert system that will not only make flood predictions during rainfall events, but also during hurricanes when storm surge is a threat. This type of system would incorporate real-time storm surge predictions from the ADCIRC storm surge model and provide information on the severity, timing, and potential impacts of a threatening hurricane.

Hurricane Ike was the first hurricane to directly affect the Galveston and Houston areas since Alicia made landfall as a Category 3 hurricane on the southwestern tip of Galveston on August, 18, 1983 (NOAA, 1983). Creating $24.9 billion in damage in the United States, Hurricane Ike was the third most expensive storm ever to hit the US coast and is often compared to the great "Galveston Hurricane" of 1900.

The highest recorded water mark during Hurricane Ike was 17.5 ft and was located roughly 10 nautical miles inland in Chambers County. However, many sensors failed during the storm and experts estimate that the storm surge on Bolivar Peninsula reached 20 ft and higher in some locations (NOAA, 2009). Figure 2.3 illustrates the damage that occurred on Bolivar Peninsula. If one compares this number to the highest surge values felt during Hurricane Alicia, which brought a maximum water level of 9 ft to Galveston Island, the contrast is shocking. Hurricane Alicia was the first hurricane to hit the Houston area since the Category 1 hurricane of 1943 (July 25-29) (NOAA, 1983). The cities of Galveston and Houston were therefore unprepared for the disaster that ensued during Hurricane Ike.

Figure 2-3: Bolivar Peninsula after Hurricane Ike made landfall on the Texas Coast (FEMA, 2008)

Experts' failure to forecast Hurricane Ike's severe surge prompted the National Hurricane Center to release the new Saffir-Simpson Hurricane Wind Scale, which removed the association of storm surge categories with certain ranges of wind speed that existed in the previous scale. Since the surprisingly large storm surge of Hurricane Ike, storm surge is now predicted on a storm-by-storm basis (NOAA, 2012). The wide availability of observed and modeled data during Hurricane Ike have also motivated researchers to evaluate causal mechanisms of storm surge, storm surge modeling, and coastal evaluations of risk, to name a few (Weaver, 2009; Callaghan, 2012; Rego and Li, 2010).

Hurricane Rita occurred about a month after the disaster in New Orleans from Hurricane Katrina. Though it did not directly affect Galveston and Houston as Hurricane Ike did, the storm threatened the Texas coastline in 2005 and caused massive panic in Houston. Making landfall between Johnson's Bayou, LA and Sabine Pass, TX on September 24, 2005 as a Category 3 storm, Hurricane Rita reached Category 5 winds while in the Gulf of Mexico and maintained that status for close to 18 hours. After it entered the Gulf of Mexico, National Hurricane Center predictions estimated that the hurricane would make landfall near Galveston, TX. While in the Gulf of Mexico, the storm was remarkably similar to Hurricane Katrina, and frightened Houston residents fled the city in record numbers. Emergency managers were confronted with the impossible task of evacuating over two million people from the coastline. At least 55 indirect fatalities associated with the evacuation in Texas were reported (NOAA, 2006). Hurricane Rita awakened the Houston area to how unprepared it was for hurricanes and emergencies in general. Since this event, authorities have been working towards improving evacuation and preparedness for Houston and the coastal counties.

Both Hurricane Ike and Hurricane Rita illustrate the dire need for emergency managers to be better prepared for hurricanes in the Galveston and Houston areas. Products such as zonal storm surge inundation maps and real-time flood-alert systems that predict the impacts from storm surge may help managers determine where to restrict development, design better infrastructure for evacuations, and decide how to temporally and spatially manage the evacuations. Furthermore, since sporadic and intense rainfall events are common to coastal Texas, it is crucial that accurate floodplain maps be developed and flood-alert systems work accurately.

2.3 Existing Modeling Techniques

To simulate aquatic processes in a watershed one uses hydrodynamic models to numerically represent the movement of water. These models have applications for water quality, geophysical fluid dynamics, hydrology, and other water processes requiring numerical solutions for the governing equations of fluid conservation of mass and momentum (NOAA, 2012).

In surface hydrology, hydrologic models (i.e., precipitation-runoff models) such as HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) and Vflo™ are used to simulate how water flows over various terrains, in rivers, and through reservoirs. They may also take into account how the water interacts with both natural and manmade infrastructure, such as diversions, slopes, and land use. Hydraulic models then use the flows determined by the hydrologic model to determine water surface elevations in channels and riverines based on cross-section geometry. Some models, such as XPSWMM, InfoWorks, and MIKEFlood, take into account both hydrologic and hydraulic processes, and are even able to incorporate underground pipelines (Bedient, 2012). See Bedient's Hydrology and Floodplain Analysis (2012) for more information on hydrologic and hydraulic models.

Hydrologic models may be either distributed or lumped. Lumped representations apply uniform characteristics across a subbasin, whereas distributed models divide an area into grid cells and assign unique parameters to each cell. The choice of whether to use a lumped or distributed model is usually based on how homogenous the soil and land use characteristics are across a basin (Vieux, 2004). Both types of models are widely used and accurate if chosen appropriately by the user.

2.3.1 Inland Flood Models

These hydrologic and hydraulic models are also referred to as inland flood models because, as may be expected, they analyze and predict flooding from surface runoff. Storm surge models are generally a separate category and are discussed later.

HEC-HMS is a lumped model that was developed by the United States Army Corps of Engineers (USACE) in 1992. Free to the public, the model has a friendly user-interface and is a derivation of the HEC-1 model, which was originally developed in 1968. Having been perfected and adapted over the last 44 years, the HEC software is widely accepted and used by the engineering community (HEC, 2000).

The HMS model components include a basin, which represents the watershed; a meteorological model, which applies rainfall to the basin; and the control specifications, which provide the model with information on how long to run. Within the basin component exist several elements: subbasins (subwatersheds), reaches (rivers), junctions (joining of any two elements), sources (sources of flow), sinks (exiting of flow, such as an outlet), reservoirs, and diversions (flow leaving the main channel). Not all elements must be present for a complete model. Specific parameters are assigned uniformly to each subbasin and reach. For instance, across a subbasin the user will apply methods for precipitation losses (infiltration), calculating direct runoff, and other optional parameters. In a river reach the user will input both routing and loss methods (HEC, 2010). HEC-HMS can be coupled with hydraulic models such as HEC-RAS to generate floodplains for frequency storms such as the 0.2% (500-Yr), 1% (100-Yr), 2% (50-Yr), and 10% (10-Yr) storms, as well as specific rainfall events. HEC-HMS was used for hydrologic simulations in this study since it was already created during the Tropical Storm Allison Recovery Project (TSARP), is very thorough, and is very widely accepted software. Furthermore, the large size of the Clear Creek Watershed creates computational limitations in most other models.

As mentioned previously, not all models are lumped. Distributed models are sometimes preferred due to their friendly user-interface, their ability to analyze on a smaller scale, and their increased accuracy in variable terrains. Many studies have been completed on the advantages and disadvantages of using lumped and distributed models. Carpenter and Georgakakos (2006) completed one such study comparing lumped and distributed model in basins approximately 1000 km^2, about twice the size of our study watershed. They found that distributed models performed better in 60% of cases, and that lumped models performed better in approximately 25% of cases. Most cases in which the lumped model performed better than the distributed model were when soil parameters and rainfall were relatively uniform.

One example of a physics-based fully distributed model is Vflo^{TM}, which was created by Vieux and Associates in Norman, Oklahoma. The model solves the conservation of mass and momentum equations (kinematic wave) to compute hydrologic fluxes and to take into account hydraulic conditions in a watershed. For ease of use, the model assigns parameters to the grid cells based on imported raster datasets (i.e. grids) from ESRI's ArcGIS software. Some examples of parameters include effective porosity, hydraulic conductivity, and imperviousness, all of which are created from grids of land use and soils data. This methodology makes the program simple and accurate. Smaller grid cells provide higher accuracy, but also increase the computation time required (Vieux, 2002). Other models that are similar to Vflo^{TM} include XPSWMM, InfoWorks, and MIKE Flood. See Bedient's Hydrology and Floodplain Analysis (2012) for more information on these models.

Since the Clear Creek Watershed is relatively large, grid cells in a distributed model would have to be of courser resolution to obtain timely results, thereby negating the increased accuracy sometimes given by distributed models. Thus, it was more logical to try to improve the existing (calibrated) HEC-HMS model than to create a new model from scratch. To update the HEC-HMS model used in this study, terrain and soil parameters, which are relatively uniform across each subbasin, were averaged across each subarea to achieve a semi-distributed approximation.

Hydraulic models, such as HEC-RAS, calculate solutions to the equations of mass and momentum, as well as the one and two-dimensional versions of the St. Venant equations, to determine water surface elevations under given flow scenarios. Some models, such as XPSWMM, are both hydrologic (overland and riverine flows) and hydraulic (water surface elevation models). HEC-RAS is a hydraulic model that was first released by the USACE in 1995. Originating from HEC-2, a FORTRAN-based program first released in 1966 under the name "Backwater Any Cross-Section," USACE employees and engineers have been using the hydraulic software for decades. The HEC-RAS software was a significant improvement over the old HEC-2 model and brought hydraulic engineering to a new level. The software is extremely stable, can run under subcritical, supercritical, and mixed flow regimes, and is able to perform complex calculations modeling bridges, weirs, culverts, outflow gates, and more. Using these modeling methods, HEC-RAS is widely used to delineate floodplains, perform dam breach analyses, and analyze channel modification possibilities (HEC, 2010; Bedient, 2012). HEC-RAS was the particular model chosen for the work presented here because of its longstanding reliability and ability to analyze on a large scale.

Both steady-state and unsteady-state modeling is performed in HEC-RAS. Steady-state HEC-RAS uses only peak flows from HEC-HMS or another hydrologic model to calculate a maximum water surface elevation that represents a "worst case scenario" for the area being modeled. This is the standard method for delineating floodplains such as the 0.2% (500-Yr), 1% (100-Yr), 2% (50-Yr), and 10% (10-Yr) floodplains. For steady-flow analyses HEC-RAS calculates the one-dimensional (1D) energy and mass equations.

In unsteady-state analyses, entire hydrographs, rather than just peak flows, are used as inputs for the model. This allows the user to develop a temporal representation of water surface elevations in the channel during specific storm events. Solving the 1D St. Venant equations, and prone to instability, unsteady-state simulations require more expertise by the user. Particular difficulties that one may encounter during the simulation include a stream drying up, water surfaces being calculated above the cross-sections, and instability that is caused by bridges, weirs, and outflow gates. However, if performed correctly, unsteady-state simulations provide invaluable insight into the impacts from specific storm events. One may use unsteady simulations for performing hindsight analyses, evaluating the effectiveness of flood gates, and determining how certain structures may affect water surface elevations (HEC, 2010). Additional applications are being discovered as technology and computer capabilities progress. See the HEC-RAS User's Manual (2010) for additional information on steady- and unsteady-state modeling.

In order to create floodplain maps from the HEC-RAS output, one may use HEC-GeoRAS. HEC-GeoRAS is a tool within the ArcGIS software that provides a set of tools and procedures to build a HEC-RAS model within a graphical user interface, and to analyze the output from an existing HEC-RAS model. The software uses a digital elevation model (DEM) to extract elevations along user-defined cross-sections and utilizes additional shapefiles, such as Flow Path Centerlines and Bank Lines, to provide important geometric data for the HEC-RAS model. Furthermore, HEC-GeoRAS may be used after a HEC-RAS model run to map inundation depths using the calculated water surface profile data. The tool subtracts the DEM from the water surface profile to develop a depth of inundation for a given model area. HEC-GeoRAS was used in this project to develop floodplain maps for both HEC-RAS steady- and unsteady-state output.

2.3.2 Storm Surge Models

Storm surge models have historically been used separately from inland flood models. One of the first reliable storm surge models was the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model created by NOAA. SLOSH results are accurate to within 20 percent when the track forecast is known and accurate. However, if the track forecast is inaccurate, as often happens, the storm surge predictions will also be incorrect (NOAA, 2012).

The Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters (ADCIRC) is a newer model that creates a coastal triangular network (i.e. a “mesh”) to model storm surge from hurricanes. The network is tighter closer to shore, and becomes increasingly coarse as one moves away from the coast. ADCIRC solves the equations of motion for fluid that is rotating on a large scale (i.e. Earth) using the finite element method spatially, and the finite difference method temporally. The ADCIRC model can operate at resolutions finer than 50 meters, simulate overland flooding, and perform well in areas with convoluted shorelines (IHRC, 2012). ADCIRC is currently being used by FEMA in the Map Modernization program, and is considered one of the best models of its kind. This work presented here uses modeled ADCIRC storm surge hydrographs to represent pseudo “worst case” surge levels at points in Galveston Bay and the Clear Creek Watershed. See the Methodology section for additional information.

2.4 Floodplain Mapping Policy

Floodplain mapping is one of the primary ways in which hydrologic modelers and FEMA communicate flood risk to clients and to the public. Most current methods of mapping rely on steady-state modeling. That is, they model the worst case flooding scenario for an area by only taking into account peaks in overland and riverine flows. However, unsteady-state modeling, which takes into account the full temporal representation of flow in a river or over land, is considered more accurate, is rapidly becoming more cost efficient, and has many applications. This study, for instance, utilizes unsteady-state modeling to analyze the impacts of storm surge on a coastal community. Other applications include structure vulnerability, mitigation techniques, and dam breach analyses. Some modeling methods, such as two-dimensional (2D) modeling, allow engineers to simulate and map flooding on the street level. This, however, requires enormous computer power and is not feasible on a large scale. See Stepinski's thesis (2011) for additional information on 2D modeling. While unsteady-state modeling was used for analyzing impacts in this study, the mapping discussed in the following paragraphs is regarding large-scale communication of flood-risk, and therefore is based on steady-state modeling.

Flood Insurance Rate Maps (FIRMs) are currently used to map floodplains and delineate flood insurance boundaries as part of the National Flood Insurance Program (NFIP) under FEMA. There are several different flooding zones associated with FIRMs. For instance, the AE zone is defined as the area that is expected to be inundated from the 1% annual chance flood event. The AE zone presents Base Flood Elevations (BFEs), which are determined by the modeled 1% annual chance flood event and represent the level to which all buildings and structures must be built in order to “floodproof” the structure. The flood zone also determines the NFIP cost of flood insurance for a particular property. Other zones include the A, AH, AO, AR, V, VE, and X zones. For more information on these zones, refer to the FEMA website (FEMA, 2012). The FEMA Map Modernization program is a new effort to develop Digital Flood Insurance Rate Maps (DFIRMS) for all areas in the United States that have a high risk of flooding. FEMA has produced DFIRMS for areas that contain 80% of the US population and is expected to complete the map modernization in 2014. One additional component of the Map Modernization study is to produce coastal maps of the 1% annual chance storm surge height by modeling hypothetical hurricanes with the ADCIRC storm surge model (FEMA, 2012). Once completed, this will prove very useful for coastal standardization of levees and structures.

The production of a floodplain map library (FPML) is common in present-day research practice. Such a library displays the resultant floodplain from standardized frequency storms that are statistically determined from historical data on a local scale. For instance, a FPML might present the 0.2%, 1%, 2%, and 10% annual chance flood events on a local scale. These are currently determined using rainfall only. However, the release of standardized FEMA annual percent chance storm surge events may allow coastal communities to incorporate storm surge into their localized floodplains. The theory behind FPMLs suggests that a user compare the approaching storm to a similar frequency storm event. The corresponding floodplain map is then to display the “worst case” flooding event that could occur from the respective frequency storm at any particular location (Bedient, 2012). A FPML for the Clear Creek Watershed has been created and will be incorporated into a flood-alert system in the future.

2.4.1 Tropical Storm Allison Recovery Project

The Tropical Storm Allison Recovery Project (TSARP) was conducted with the support of FEMA and the Harris County Flood Control District (HCFCD) after Tropical Storm Allison (2001) caused the worst urban flood in US history in Houston, Texas, with damage costs totaling over $5 billion. The goal of the project was to assess the causes of major flooding and the associated risks in Harris County, Texas (HCFCD, 2012).

This multi-year project analyzed 22 major watersheds (Figure 1-1), developing detailed hydrologic and hydraulic models for each watershed in order to comprehensively re-map the Harris County floodplains and create more accurate FIRMs. HEC-HMS and HEC-RAS models were used in conjunction with Light Detection and Ranging (LiDAR) data (high resolution elevation data) to perform this modeling (HCFCD, 2012). For the study presented here, the TSARP models were adapted to run in unsteady-state, as described above. See the Methodology section for more information.

2.5 Ongoing Research in Modeling and Mapping

One of the future goals associated with this project is that the models developed in this study be used to implement a comprehensive flood-alert system, which will incorporate real-time ADCIRC storm surge predictions. Many real-time flood-alert systems currently exist, but none predict what inundations will result from an approaching storm. This can have applications for the analysis of damage costs, as well as the time management of evacuations. For instance, knowledge of when water levels will rise and subside will help emergency managers determine when to evacuate certain zones and when to admit access to essential personnel and residents once the storm has passed. The primary difficulty with this task will be running HEC-RAS in real-time in conjunction with HEC-GeoRAS, which will likely require heavy scripting. Research is still ongoing to determine whether or not accomplishing this task will be feasible, as there are no documented attempts to date. However, since Bedient's research group at Rice University has experience in flood-alert system development, this ambitious goal may not be so farfetched.

Bedient's group has created numerous flood-alert systems (TMC FAS and Sugarland FAS) that run HEC-1 in real time. These systems are well accepted and extremely effective. For instance, from 2002 to 2010 the TMC FAS has achieved an r^2 value of 0.90 when comparing predicted and observed flows (Fang, 2011). Since Bedient's established methods are proven effective, and because creating a flood-alert system from existing methodology is much more efficient than learning new methods, the flood-alert system for the Clear Creek Watershed is to be initially created using HEC-1. This will require the manual conversion of the existing HEC-HMS model to HEC-1, and it is anticipated that such a project may be completed in the duration of a summer. Once the FAS is functioning smoothly, the challenge of incorporating storm surge and running HEC-RAS in real-time will be undertaken. One potential method of accomplishing this task may be through HEC-RTS (Real-Time Simulation). HEC-RTS is a public version of the Corps Water Management System (CWMS) Control and Visualization Interface (CAVI). The model works through HEC-DSS (Data Storage System) and may be able to be connected to other databases through an API (Application Programming Interface) in future versions. Version 1 is currently available on request and version 2 is currently in the development stage (HEC, 2010). Furthermore, HEC-RTS has the capability to map inundation depths as well. Other successes in modeling HEC-RAS in real-time have not been documented.

Chapter 3: METHODS

The models described in the previous section were used to identify the appropriate methodology for this project. Selections were made based on the models' theoretical equations and approaches used in calculations, economic expense and computing power requirements, acceptance in the engineering community, and previous work accomplished using such models. According to these considerations HEC-HMS was chosen for hydrology, HEC-RAS for hydraulics, ADCIRC for storm surge, and HEC-GeoRAS for floodplain mapping.

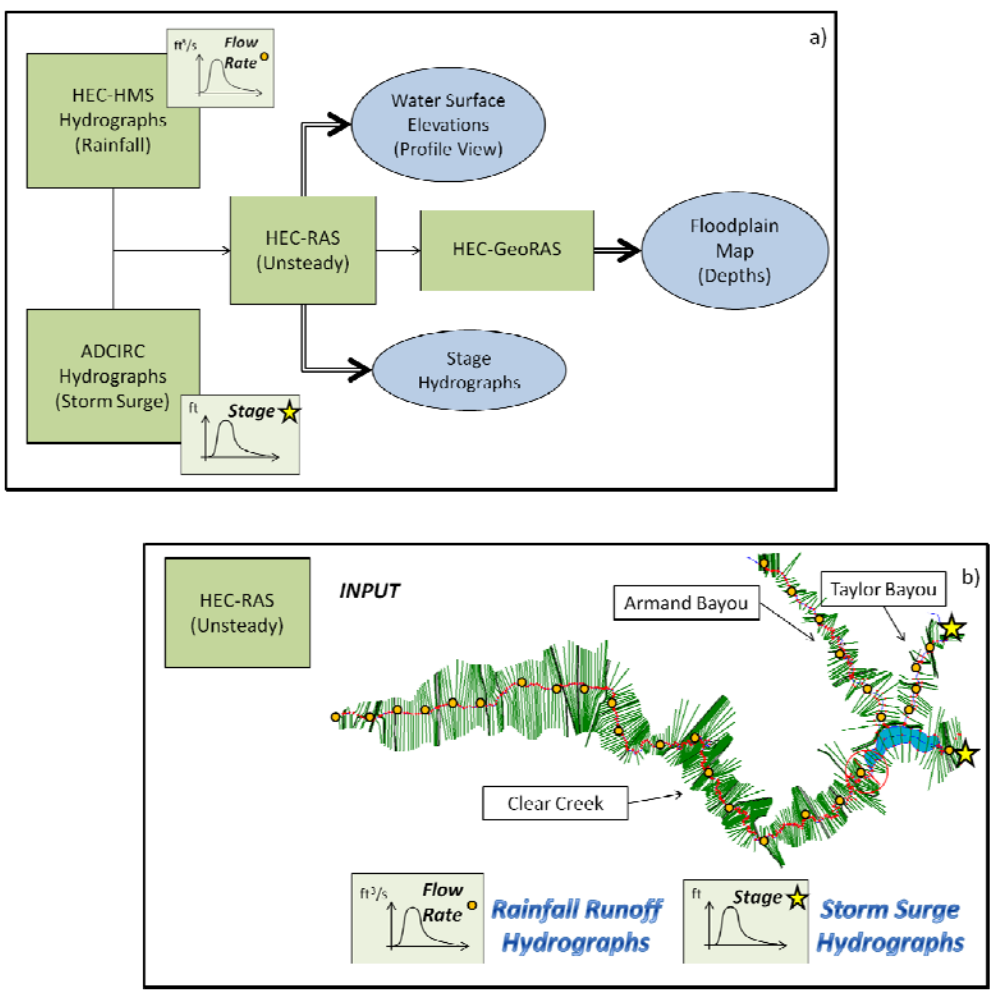


Figure 3-1: a) Flow chart of methodology; b) HEC-RAS geometry file and model inputs

As Figure 3-1 illustrates, output from HEC-HMS and ADCIRC were input into HEC-RAS, which was then run in unsteady-state. Two storm surge stage hydrographs were used in each model run: one as the upstream boundary condition for Taylor Bayou and the other as the downstream boundary condition for Clear Creek. Rainfall-runoff hydrographs (flow rate) were input at various points along the stream to represent locations where either a tributary or subbasin drains into Clear Creek. Section 3.3.1 expands upon this process. Most of the results will be in the form of stage hydrographs, profile views of water surface elevations in the channel, and HEC-GeoRAS floodplain maps.

3.1 HEC-HMS Model Setup

For this project, HEC-HMS was chosen as the hydrologic model for several reasons. The model, having been created by the United States Army Corp of Engineers (USACE), is freeware and widely accepted in the engineering community. A lumped model, HEC-HMS operates well over large areas and can incorporate a significant amount of detail. For example, HEC-HMS models can include reservoirs, diversions, manmade channels, and certain drainage structures. The Tropical Storm Allison Recovery Project (TSARP) created HEC-HMS models for every major watershed in Harris County, including the Clear Creek Watershed. Dannenbaum Engineering later updated the Clear Creek Watershed model for areas outside of Harris County (Dannenbaum, 2011). The updated models from Dannenbaum Engineering were used in this project, and their generous donation saved months of work.

Figure 3-2 shows the complete HEC-HMS model for the Clear Creek Watershed and Armand Bayou. Though Armand Bayou is recognized as its own watershed by the

Harris County Flood Control District (HCFCD), it drains into Clear Creek and is thus included in the Clear Creek Watershed HEC- HMS model. In Figure 3-2 the subbasins, junctions, and reaches are represented by the respective labeled icons. The user simply clicks on an icon and enters the parameters for that element in a user-friendly interface. The Green and Ampt and the Clark Unit Hydrograph loss and transform methods were applied to each subbasin, and modified Puls routing was used in the reaches (referencing the pre-existing storage discharge tables). For more information on these methods, please refer to Bedient's Hydrology and Floodplain Analysis (2012).

Using NEXRAD radar rainfall, three different storms were run in the HEC-HMS model to verify the model was working correctly. Figure 3-3 shows the cumulative rainfall for each event in the Clear Creek Watershed. Tropical Storm Allison was the largest event with an average total rainfall of 17.8 inches over the Clear Creek Watershed. The April 2009 event produced an average total of 15.8 inches over the basin. However, the event actually occurred in four different waves over the course of 12 days. Finally, because it is the primary focus of this project, Hurricane Ike rainfall, bringing an average total of only 8.7 inches to the Clear Creek Watershed, was run in HEC-HEMS. Table 1 compares these three storm events.

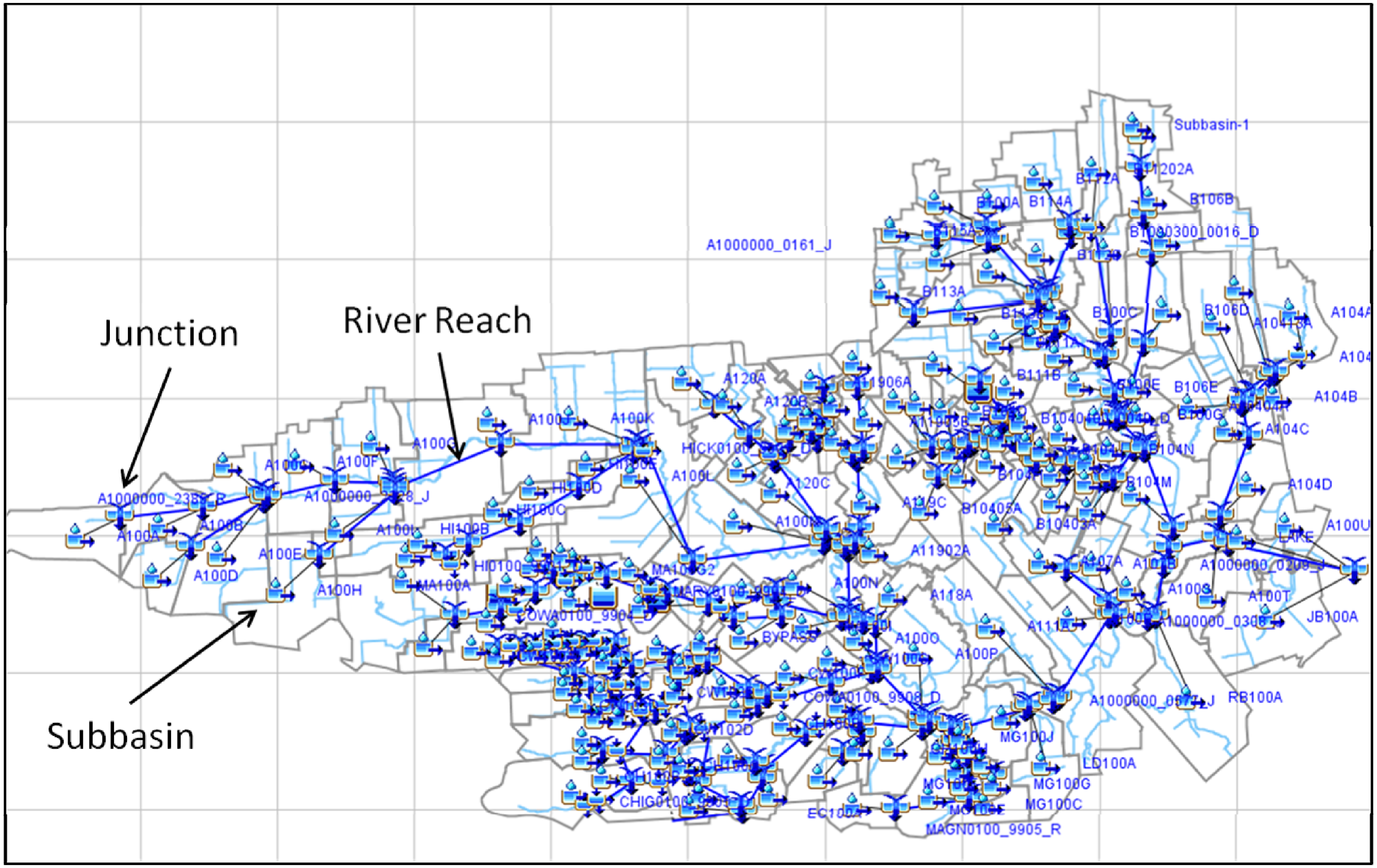


Figure 3-2: HEC-HMS model of the Clear Creek Watershed and Armand Bayou

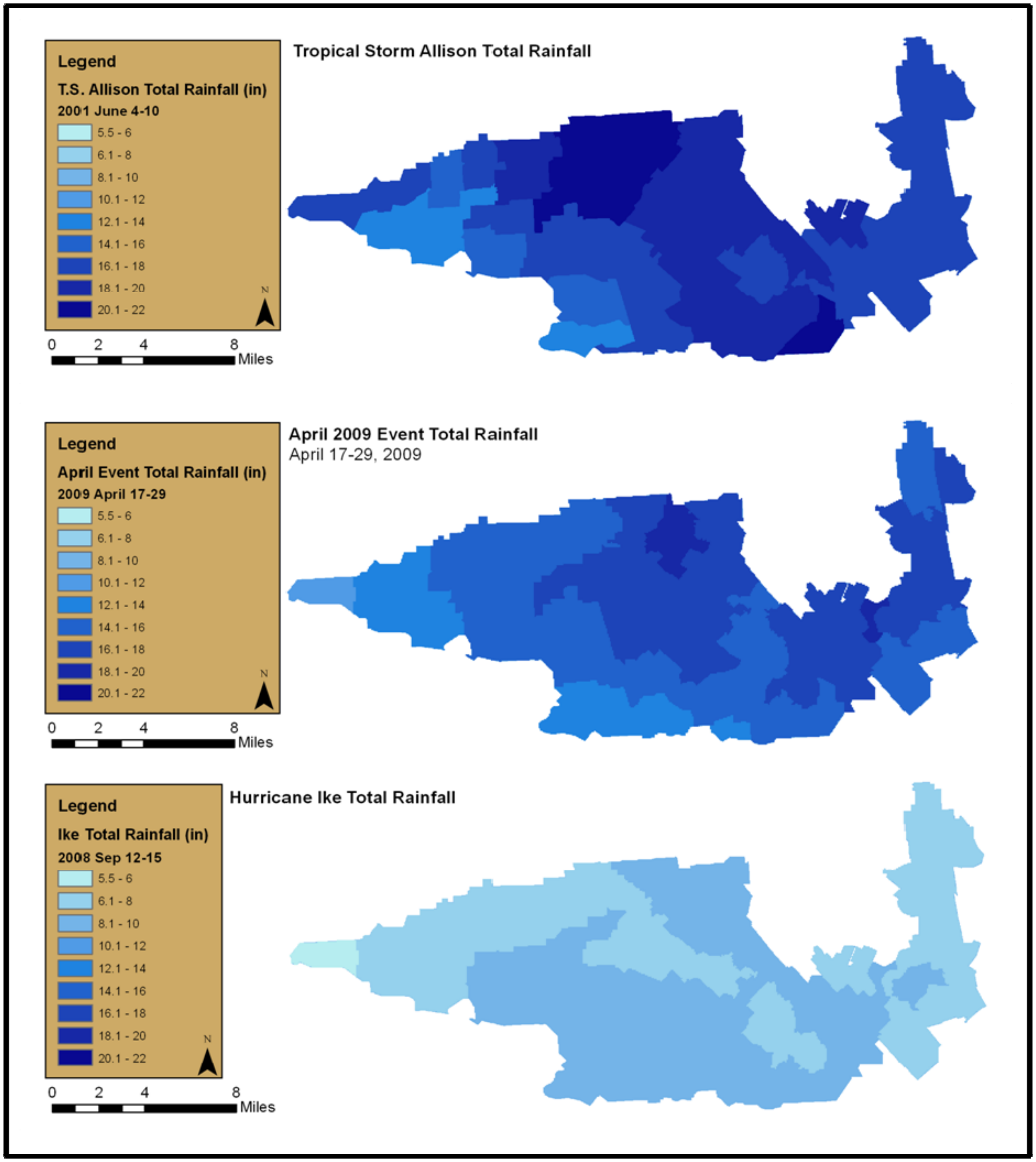


Figure 3-3: Three different storms run in HEC-HMS to verify the hydrologic model

Figure 3-4 shows the cumulative rainfall during Tropical Storm Allison (2001), which actually occurred in two waves of rain (Dannenbaum, 2012). During the first wave, about 6 inches fell in 12 hours, making it close to a 10% annual chance rainfall event (Tables 3-1 and 3-2). However the second wave, which brought 10 inches in 24 hours, was closer to a 4% annual chance rainfall event. Just northeast of downtown Houston, where approximately 28 inches fell in 12 hours, Tropical Storm Allison was greater than a 0.2% annual chance rainfall (HCFCD, 2012).

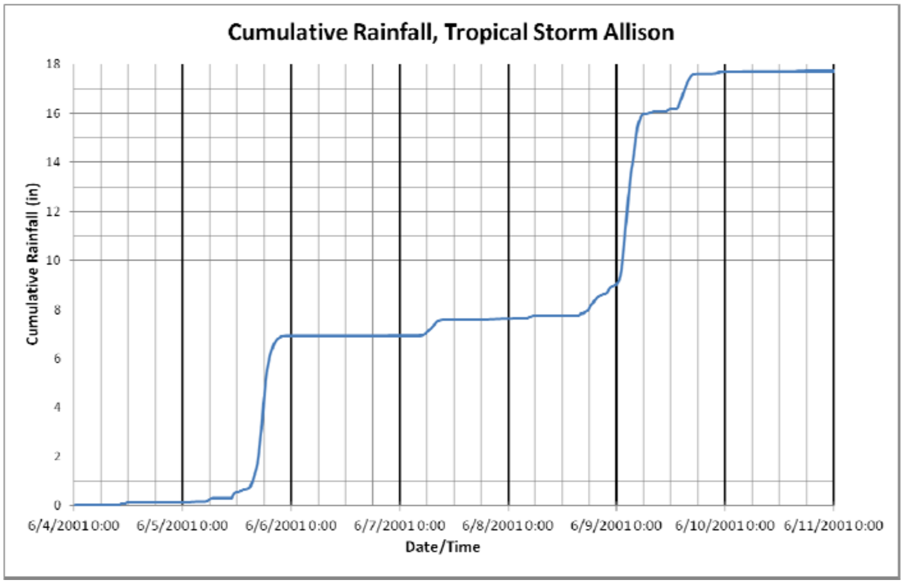


Figure 3-4: Tropical Storm Allison cumulative rainfall over the Clear Creek Watershed

Table 3-1: HEC-HMS Storms –cumulative rainfall and storm duration

Storm Event	Cumulative Rainfall (inches)	Storm Duration (days)
Tropical Storm Allsion	17.8	5
April 2009	15.8	12
Hurricane Ike	8.7	0.5

Table 3-2: Rainfall frequency totals for Harris County Hydrologic Region 3 (HCFCD, 2009)

Harris County Hydrologic Region 3 – Rainfall Frequency Totals (inches)					
Storm Duration	0.2% Storm	1% Storm	2% Storm	4% Storm	10% Storm
2 - Hour	7.7	5.7	5.0	4.4	3.7
3 - Hour	9.4	6.8	5.9	5.1	4.2
6 - Hour	13.1	9.1	7.7	6.6	5.3
12 - Hour	15.9	11.1	9.5	8.0	6.4
24 - Hour	19.3	13.5	11.6	9.8	7.8

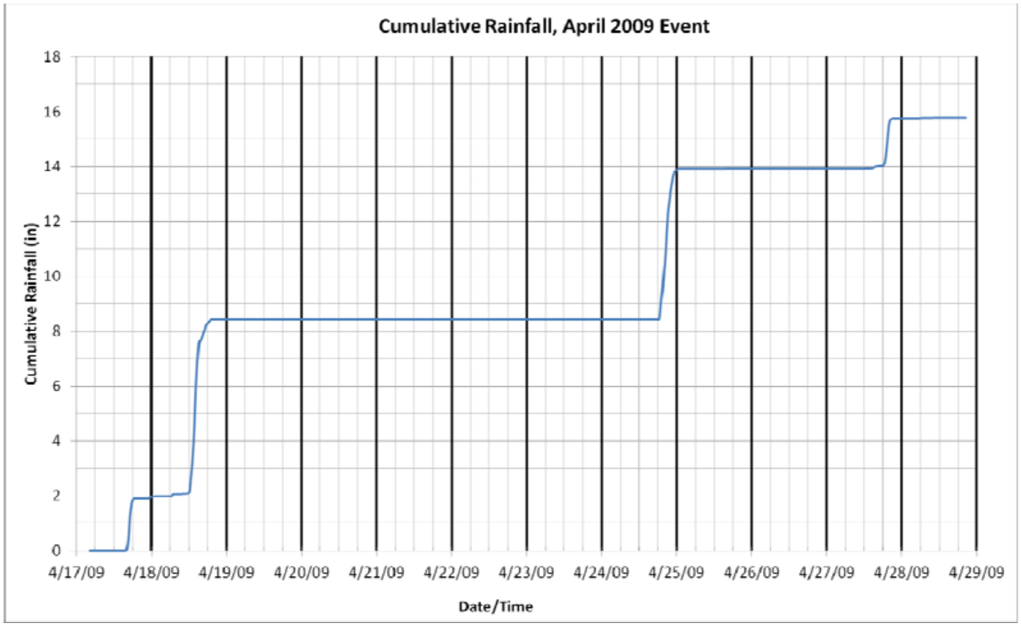


Figure 3-5: April 2009 event cumulative rainfall over the Clear Creek Watershed

3.1.1 Modeled and Observed Flows

The TSARP HEC-HMS model was initially calibrated to Tropical Storm Allison. However, when run with the Hurricane Ike and the April 2009 events, the modeled hydrographs overestimated observed peak flows and storage. One reason for the discrepancy is that the streamflows caused by Hurricane Ike and April 2009 rainfall-runoff were less than the flows caused by Tropical Storm Allison, thereby making calibration more difficult. Model parameters based on soil type, originally assigned uniformly across the basin, were updated to remedy the disagreement between the modeled and observed hydrographs.

Both hydraulic conductivity and wetting front suction parameters were originally assigned uniformly across the entire Clear Creek Basin. Using soils data from the Soil Data Mart (USDA, 2009), hydraulic conductivity and wetting front capillary pressure were averaged over each subbasin and updated in the model. See Bedient et al. (2012)

for more information on these parameters. Table 3.3 was reproduced from Rawls et al. (1983) and was used to estimate hydraulic conductivity and wetting front capillary pressure. The following figures (3-7 to 3-11) represent the observed and modeled flow data after the model was refined. After updating these parameters the model still overestimated storage, but better captured the peak flows.

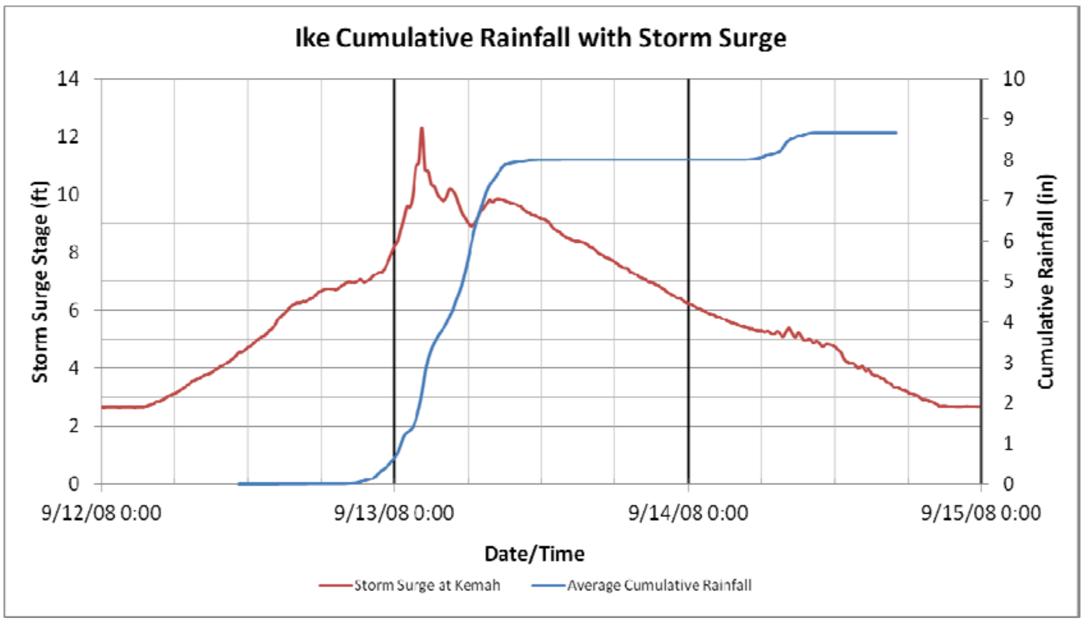


Figure 3-6: Hurricane Ike rainfall and storm surge in the Clear Creek Watershed

Table 3-3 and Figure 3-7 show the locations of the hydrographs discussed in the following paragraphs. Figure 3-8 represents the HEC-HMS modeled and observed flow at FM 528 for Tropical Storm Allison. The figure clearly shows a good match in both peak and timing for the storm. Both Hurricane Ike and the April 2009 event were run in HEC-HMS after the model parameters were updated. Figure 3-9 represents the modeled and observed flow for the April 2009 event much farther upstream at Clear Creek and Mykawa St. Since the rainfall from the worst wave during the April 2009 event and during Hurricane Ike were both on the order of a 10% annual chance storm, comparing the flow at Mykawa St. with the flow farther downstream can help us better characterize the watershed during these events. The peak flow from the 10% annual chance storm is about 2,200 cfs at Mykawa St., and 11,200 cfs at I-45—approximately five times greater.

Table 3-3: Rawls et al.'s (1983) wetted front capillary pressure and hydraulic conductivity

Soil Texture Class	Wetted front capillary pressure (cm)	Hydraulic conductivity (cm/hr)
Sand	4.95	11.78
Loamy Sand	6.13	2.99
Sandy Loam	11.01	1.09
Loam	8.89	0.34
Silt Loam	16.68	0.65
Sandy Clay Loam	21.85	0.15
Clay Loam	20.88	0.10
Silty Clay Loam	27.30	0.10
Sandy Clay	23.90	0.06
Silty Clay	29.22	0.05
Clay	31.63	0.03

Table 3-4: Locations for modeled and observed hydrographs

Location	Description
1	Clear Creek and I-45
2	Clear Creek and W. Bay Area Blvd.
3	Clear Creek and FM 528
4	Clear Creek and Mykawa Rd.

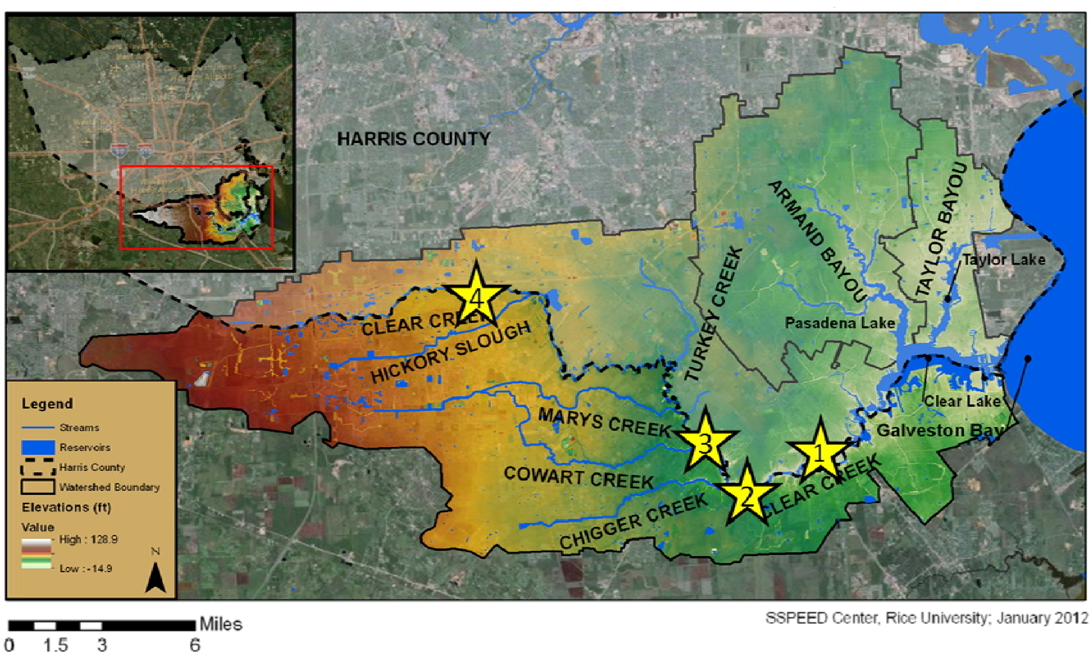


Figure 3-7: Locations corresponding to Table 3-4

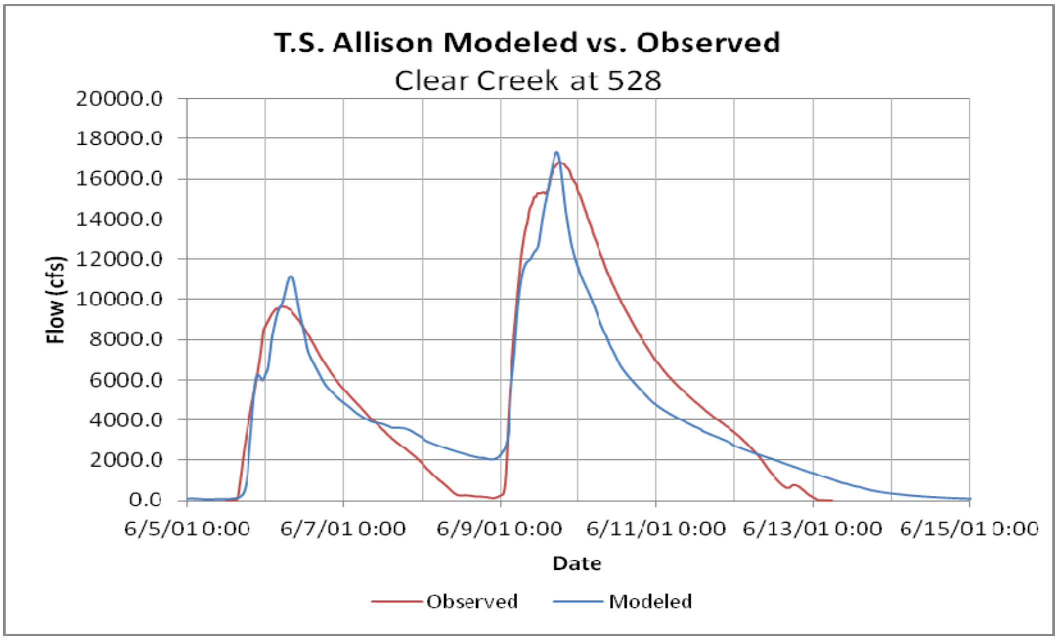


Figure 3-8: Modeled and observed flow at FM 528 during Tropical Storm Allison

As mentioned earlier, the observed peaks for the April 2009 event were matched in Figure 3-9, but excess storage was still present. The storage differential present in Figure 3-9 may be due to the Clark Unit Hydrograph transform method, which is based on the assumption that the area is well-drained (i.e. drains quickly). Since the area upstream is mostly undeveloped, this assumption is most likely violated. The Clark Unit Hydrograph method will therefore overestimate both peak and volume of runoff in poorly drained areas because such areas will inherently have more storage detention/retention than this method assumes (Dunbar, 2012). If we move farther downstream, where Clear Creek crosses Bay Area Blvd for instance, we notice that flows were much higher for the April 2009 event (Figure 3-10). Here, we see that the storage match was much better, though the peaks were not matched quite as well. However, because the model overestimated the peaks, and given the previously discussed issue with the unit hydrograph methodology, the difference is not a large concern.

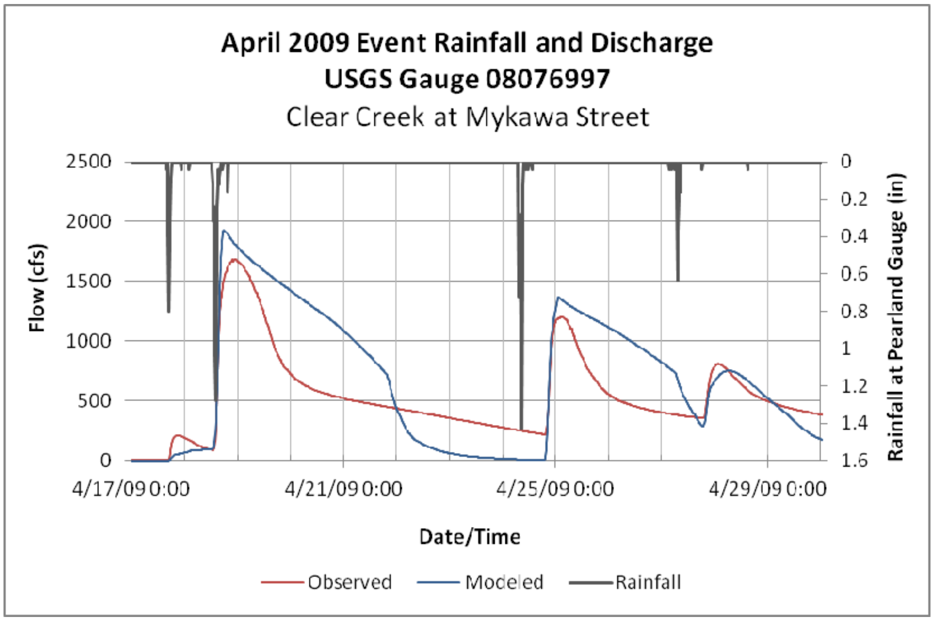


Figure 3-9: Modeled and observed flow at Mykawa St. during the April 2009 event

The amount of rainfall that fell during Hurricane Ike, averaged over all of Clear Creek, was about that of a 4% annual chance storm. Figure 3-11 shows the observed and modeled flows from Hurricane Ike rainfall at Clear Creek and Bay Area Blvd. The HEC-HMS model was able to capture the peak, but there still appear to be some storage issues.

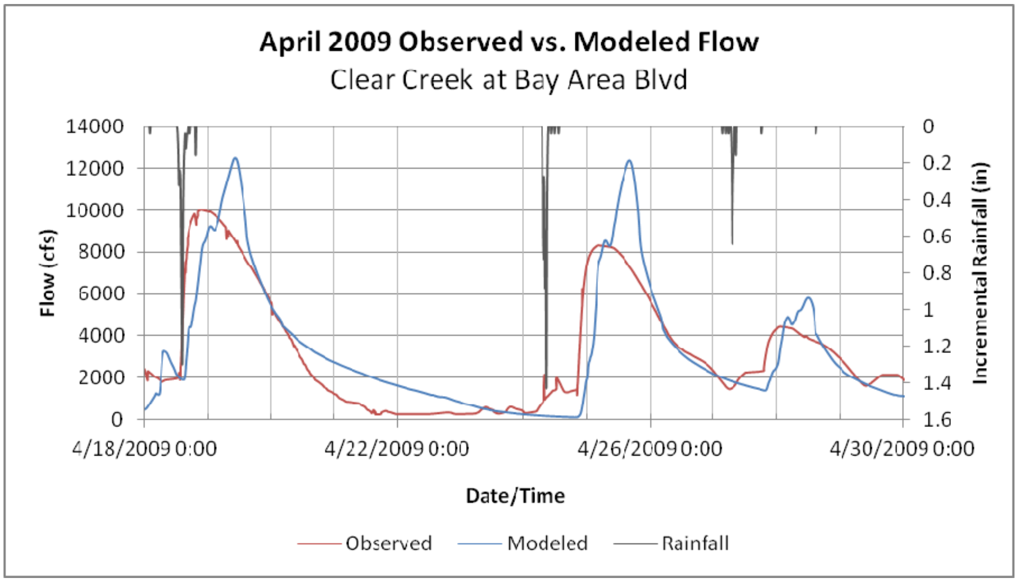


Figure 3-10: Modeled and observed flow at Bay Area Blvd. during the April 2009 event

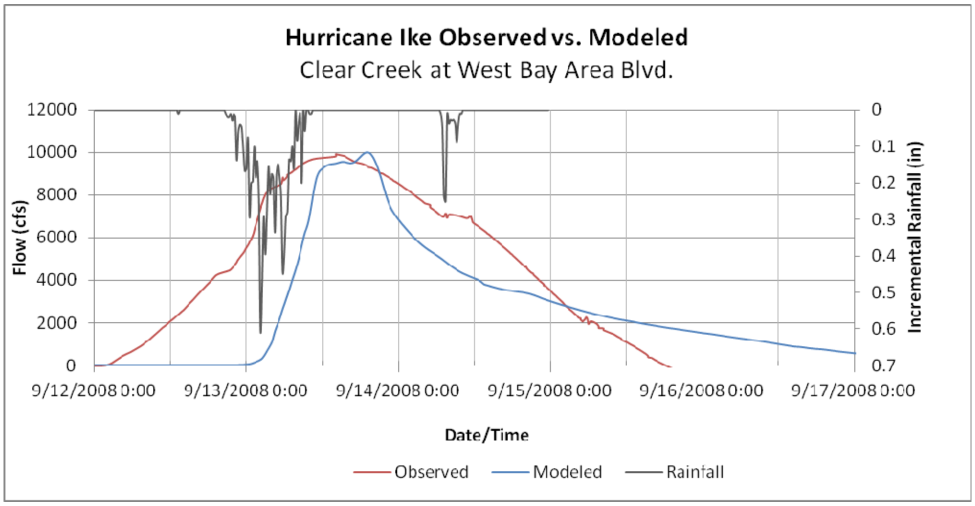


Figure 3-11: Modeled and observed flow at Bay Area Blvd. during Hurricane Ike

If we look at the observed and modeled flow at Clear Creek and I-45 (Figure 3-12), we notice a large difference in timing and peak, signifying that rainfall was not the only source of flow. HEC-RAS modeling, which is discussed later, shows that both the storage issues in Figure 3-11 and the peak/timing differences in Figure 3-12 are due to storm surge. Thus, we can hypothesize that the effects from storm surge reached at least up to I-45, and that excess storage made it even up to Bay Area Blvd. This "ballooning" effect from storm surge was also observed in Ray et al. (2011).

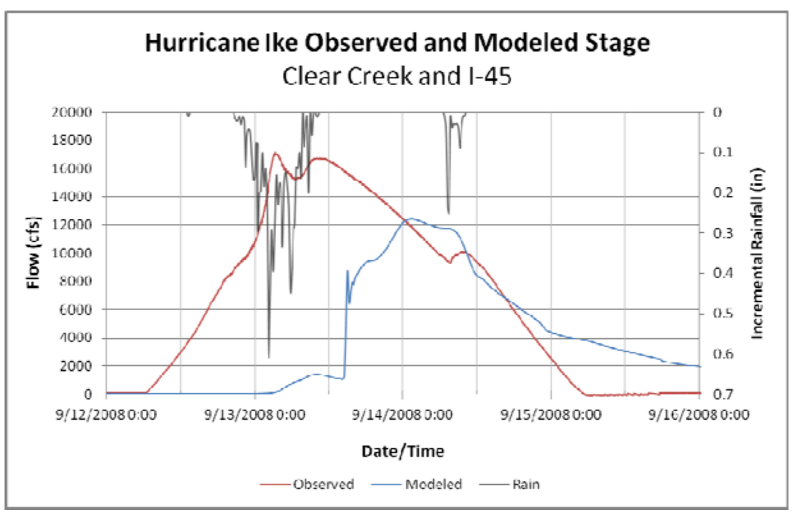


Figure 3-12: Modeled and observed flow at I-45 during Hurricane Ike

3.2 ADCIRC Storm Surge Stage Hydrographs

As mentioned in Chapter 2, the Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters (ADCIRC) model was used to simulate two hurricane scenarios. First, Hurricane Ike was simulated for model reanalysis. Since the worst storm surge is generally seen on the east side of a hurricane in the northern hemisphere, and because Hurricane Ike made landfall on the southern tip of Bolivar Peninsula, Bolivar Peninsula received the worst storm surge (Figure 3-13). However, to really capture the vulnerability of the Clear Creek Watershed and the Houston Ship Channel, we used ADCIRC to simulate scenarios of hurricanes that made landfall farther south, therefore resulting in large storm surges in the Houston area. This second scenario is referred to as Hurricane Ike125 near San Luis Pass.

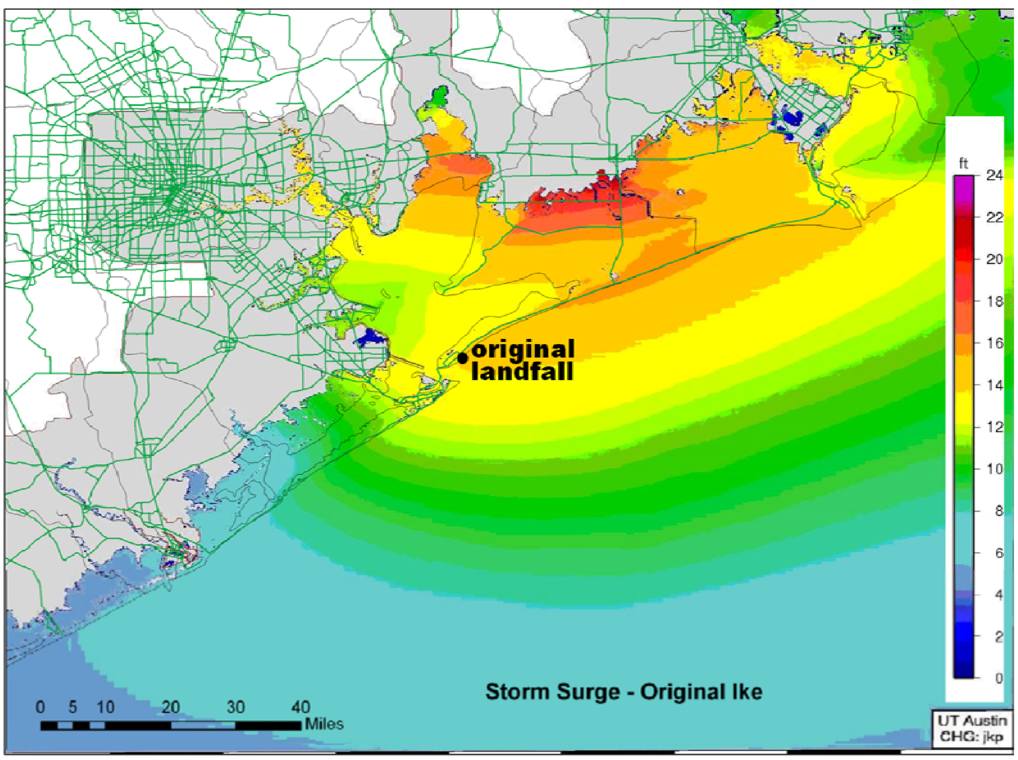


Figure 3-13: ADCIRC simulated storm surge for Hurricane Ike original landfall

Hurricane Ike125 represents Hurricane Ike with its winds multiplied by 1.15, thereby resulting in a hurricane with Category 3 winds of 125 mph at landfall (Dawson, 2011). For the sake of simplicity, Hurricane Ike rainfall was used when modeling Hurricane Ike125 near San Luis Pass. There is some error associated with not shifting the rainfall to the southwest as would naturally be the case. However, since storm surge is of greatest interest, and because the rainfall during Hurricane Ike was minimal compared to other more intense rainfall events, the error associated with the rainfall is not a large concern. To simulate a worst case surge scenario, the landfall of Hurricane Ike125 was moved from the southern tip of Bolivar Peninsula to a location farther south near San Luis Pass (dotted line in Figure 3-14). Hurricane Ike125 near San Luis Pass would be a Category 3 hurricane causing tide levels to reach 16.8 feet in Kemah.

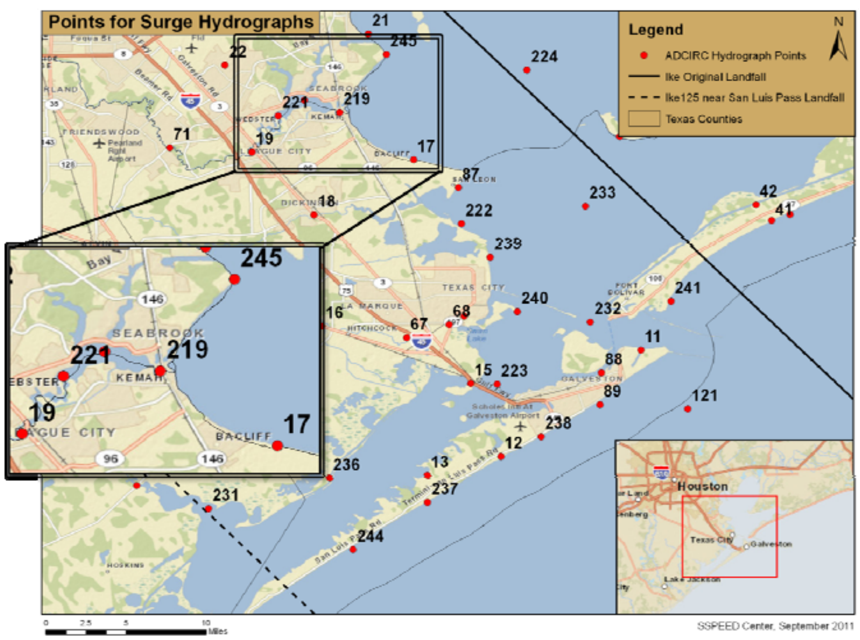


Figure 3-14: ADCIRC storm surge hydrograph points

The points in Figure 3-14 represent the locations where the SSPEED Center has received ADCIRC storm surge stage hydrographs (Dawson, 2011). When modeling

Hurricane Ike, an observational stage hydrograph near point 219 was used as the downstream boundary condition for Clear Creek, and the modeled hydrograph at point 245 was used as the upstream boundary condition in Taylor Bayou. The same methodology was used to model Hurricane Ike125 near San Luis Pass, except that the modeled data at point 219 was used in place of the observational data. The peak stage at the outlet of Clear Creek for Ike125 near San Luis Pass is 16.8 feet, compared with 12.32 feet for Hurricane Ike. A Category 4 hurricane could cause even higher sea levels. Modeled data for Hurricane Ike145 near San Luis Pass (Hurricane Ike rainfall, Hurricane Ike winds*1.3, landfall at dotted line) are currently being processed and will be available for analysis soon.

3.3 HEC-RAS Model Setup

Like the HEC-HMS model, the HEC-RAS model used in this study was also adapted from the TSARP models. The HEC-RAS models from the two largest tributaries of Clear Creek, Taylor Bayou and Armand Bayou, were added to the main channel (Figure 3-15). Between Clear Creek and the two tributaries, the combined model has 527 cross-sections, 34 bridges, 6 culverts, and 1 inline structure. When the geometry data from the models were initially combined, the cross-sections (green lines) overlapped around the river junctions. Though HEC-RAS can run with overlapping cross-sections, the user should always adjust them so that they no longer overlap. HEC-RAS makes the assumption that flow is perpendicular to every cross-section, and by having cross-sections overlap the user is violating this assumption. The cross-sections on the main channel of Clear Creek, rather than those on the Armand and Taylor Bayou tributaries, were therefore shortened to avoid making alterations to the NASA Road 1 Bridge that

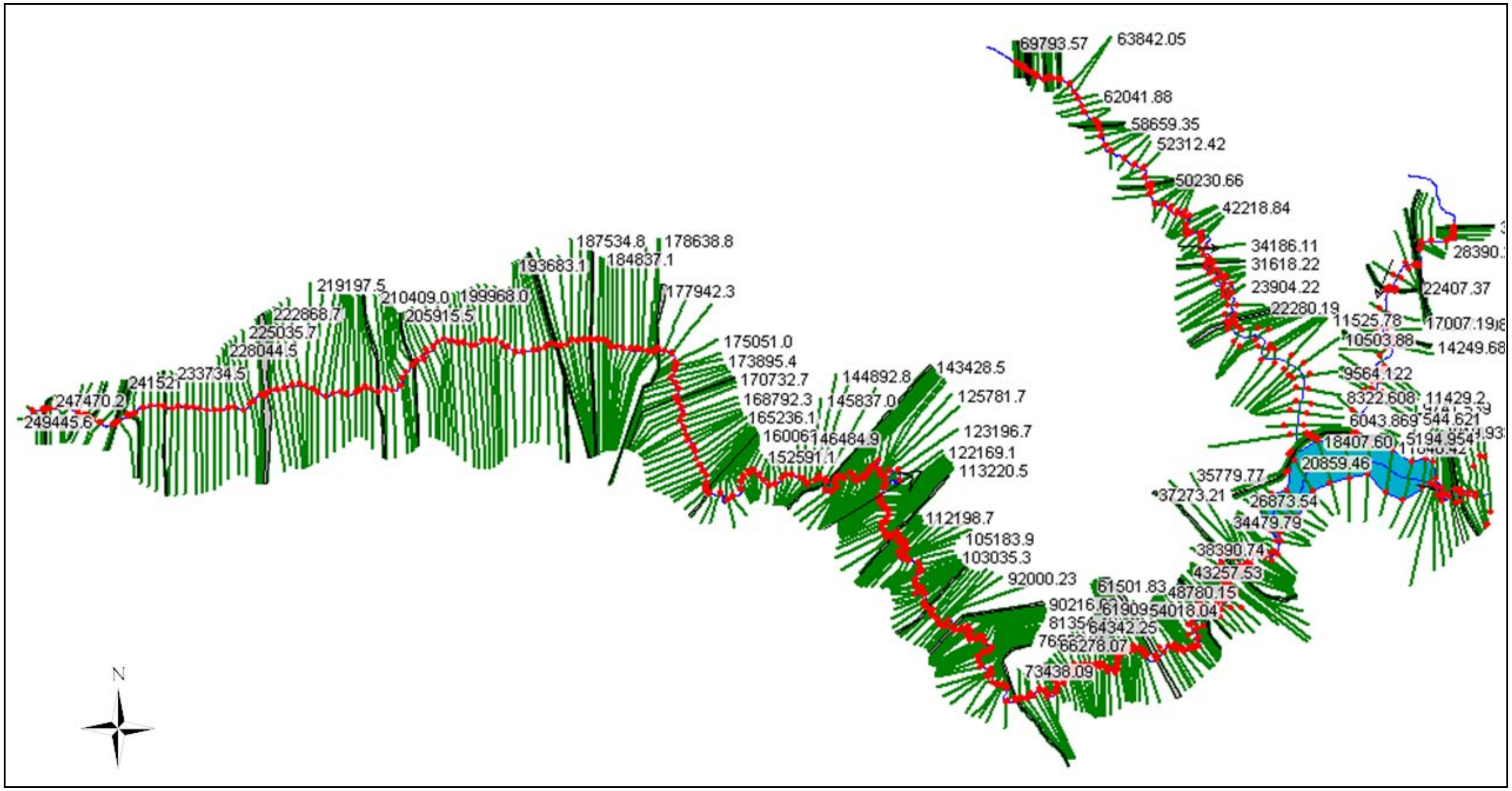


Figure 3-15: HEC-RAS model geometry

crosses both tributaries. The original Manning's roughness values and steady flow data were kept for all three reaches. Furthermore, a storage area was added to represent Clear Lake, and storage was calculated using the area times depth method. Both Armand Bayou and Taylor Bayou were then connected to this storage area.

3.3.1 Unsteady-State Modeling

As mentioned in Chapter 2, unsteady-state HEC-RAS solves the continuity equation and the one dimensional (1D) full dynamic wave momentum equation (i.e., the St. Venant equations). The continuity equation, which represents the conservation of mass in a one-dimensional system, is:

$$\mathrm{V}\frac{\partial \mathrm{y}}{\partial \mathrm{x}} + \mathrm{y}\frac{\partial \mathrm{V}}{\partial \mathrm{x}} + \frac{\partial \mathrm{y}}{\partial \mathrm{t}} = 0 \qquad (1)$$

where V is the channel velocity, y is the water depth, x is the horizontal location along the channel, and t is the simulation time. The 1D full dynamic wave momentum equation, representing the conservation of momentum in a system, is:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g\left(S_0 - S_f\right) = 0 \qquad (2)$$

which can also be expressed as:

$$-\frac{1}{g}\frac{\partial V}{\partial t} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{\partial y}{\partial x} + S_0 = S_f \qquad (3)$$

where S_0 is the slope of the channel, S_f is the friction slope, and g is gravitational acceleration. The first term in equation (2) is the local acceleration term, the second is the convective acceleration term, the third is the pressure force term, the fourth (gS_0) is the gravity force term, and the fifth (gS_f) is the friction force term. Unsteady-state non-uniform flow calculations use all the terms in equation (3). However, in steady-state non-uniform flow, the first term is eliminated (no time component, but the velocity varies in the fluid). In steady-state uniform flow, the first two terms are eliminated (because there is no time component, and the velocity is the same at every point) (HEC, 2010).

Because unsteady-state simulations keep the first term in (3) (change in velocity with time), they require that the user input the entire hydrograph, rather than just the peak flows as in steady-state HEC-RAS computations (because steady-state computations eliminate the temporal component). Hydrographs must be added along the main channel of the stream where subbasins and tributaries flow into the main channel (Figure 3-16). This is a crucial step because the channel will go dry if it is not completed, and HEC-RAS becomes very unstable when the channel goes dry. The user may add two types of flow hydrographs: a lateral inflow hydrograph, or a uniform lateral inflow hydrograph. The lateral inflow hydrograph represents a point where a tributary joins with the main channel, and a uniform lateral inflow hydrograph is divided evenly across a defined area to represent overland flow draining into a river across a subbasin. Usually both types are necessary for an accurate model. HEC-HMS and Geographic Information Systems (GIS) were used to judge where hydrographs should be input along the stream.

In order to correctly input uniform lateral inflow hydrographs, outflow hydrographs from subbasins draining directly into the channel were attached to the cross-sections that best corresponded with the upstream edge of each respective subbasin (Figure 3-16). Then downstream cross-sections representing the downstream edges of the respective subbasins were specified, signaling HEC-RAS to divide the hydrograph evenly across the length of river covered by the subbasin. In ESRI’s ArcGIS software, a

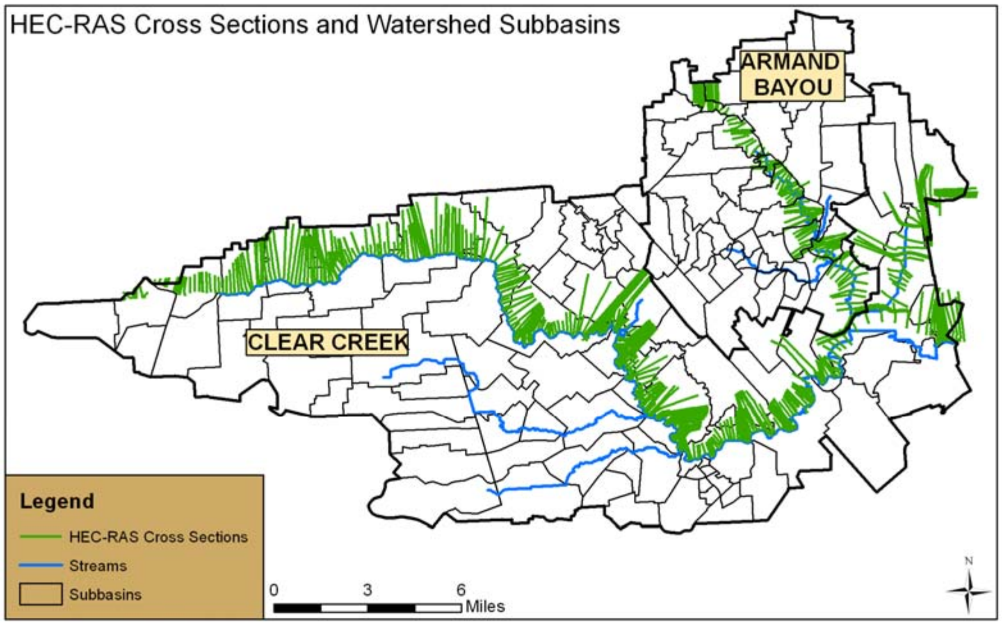


Figure 3-16: HEC-RAS cross-sections overlaid onto Clear Creek subbasins

shapefile of subbasins was overlaid onto the HEC-RAS cross-sections to determine which cross-sections best corresponded with the subbasin's upstream and downstream boundaries. Subbasins far away from the stream do not drain directly into the river but into other basins. Since each basin drains into one farther downstream, the effect was cumulative and it was not necessary to add hydrographs for subbasins located away from the stream. HEC-HMS provided the connectivity between the basins needed to determine where hydrographs needed to be added.

Lateral inflow hydrographs were inserted at the joining of a tributary and a modeled river reach. In order to determine which cross-sections corresponded with the river reach junctions, a shapefile of rivers was overlaid onto the model cross-sections. The closest cross-section to the junction of the two streams was chosen as the appropriate location to insert a lateral inflow hydrograph, which was taken from the HEC-HMS outflow hydrograph at the corresponding junction. Please note that lateral inflow hydrographs were not used at the junctions of Armand Bayou and Taylor Bayou to Clear Creek because these tributaries were also modeled in HEC-RAS.

HEC-RAS is often used to simulate inland flooding due to rainfall-runoff, but less often used to simulate the effects from storm surge. One reason storm surge is often not included may be because of the difficulty in obtaining the storm surge hydrographs where they are needed for model input. Another reason could be that a large storm surge will almost certainly cause the water surface to reach the edge of the cross-sections, meaning that elevations are not calculated in locations outside of the model area. However, modeling storm surge in HEC-RAS can still provide valuable information on where the most severe flooding is, where more study is needed, and where how far upstream storm surge may cause flooding.

Simulated storm surge hydrographs from the ADCIRC model were obtained and entered at two locations: the outlet of Clear Creek and the most upstream cross-section of Taylor Bayou. These two locations were chosen for their proximity to Galveston Bay. Points 219 and 245 from Figure 3-14 were chosen as the appropriate corresponding locations for the modeled storm surge hydrographs. When modeling Hurricane Ike, the observed stage hydrograph at Kemah during Hurricane Ike was used as the downstream boundary condition for Clear Creek (Ray et al., 2009), and the modeled stage hydrograph from point 245 was used to estimate the storm surge at the upstream end of Taylor Bayou since no observed data were available. The ADCIRC storm surge hydrographs were used at both points when modeling Hurricane Ike125 with landfall near San Luis Pass.

As mentioned earlier, it is crucial that the HEC-RAS channels do not run dry in order for the model to run properly. The only source of water flowing into the channel is that which is specified by the user. Thus, initial flows and baseflow are usually added in unsteady-state models to simulate water that is present under normal circumstances. Another method to prevent the channel from going dry is to add a pilot channel, which introduces a narrow channel at the bottom of each cross-section. A negligible amount of volume is added, but the channel reaches deeper so HEC-RAS calculates a water surface at every cross-section. In order to make the unsteady-state model stable for this project, baseflow was added at all locations along Clear Creek, Armand Bayou, and Taylor Bayou, and pilot channels were added in Armand Bayou and Taylor Bayou (HEC, 2010).

Even if the user is sure that there is flow in the channel during all time steps in the simulation, stability issues may still persist. The HTAB parameters (hydraulic table properties) are also extremely important in unsteady-state modeling. As illustrated in Figure 3-17, HEC-RAS makes calculations at horizontal lines in each cross-section. The closer the lines are together, the more accurate the simulation. When the water surface elevation is calculated above the highest horizontal line, the model may become unstable. To remedy the instability, the user may add more lines (up to 100) or increase the interval between each line. The smaller the interval is, the more accurate the simulation will be. However, since the user is only allowed a maximum of 100 lines, larger intervals are sometimes necessary. The same concept also applies to bridges. If HEC-RAS calculates the water surface above the user-defined elevation at the bridge, the model will become unstable (HEC, 2010).

An unstable model will often produce water surface elevations in the thousands of feet. Apart from the obvious error in having a water surface elevation of 1,000 feet in Houston, TX, the error means that water surface elevations will be calculated above the highest horizontal line in a cross-section. The instability could be caused by the simple fact of not having enough lines in the cross-section. However multiple factors can

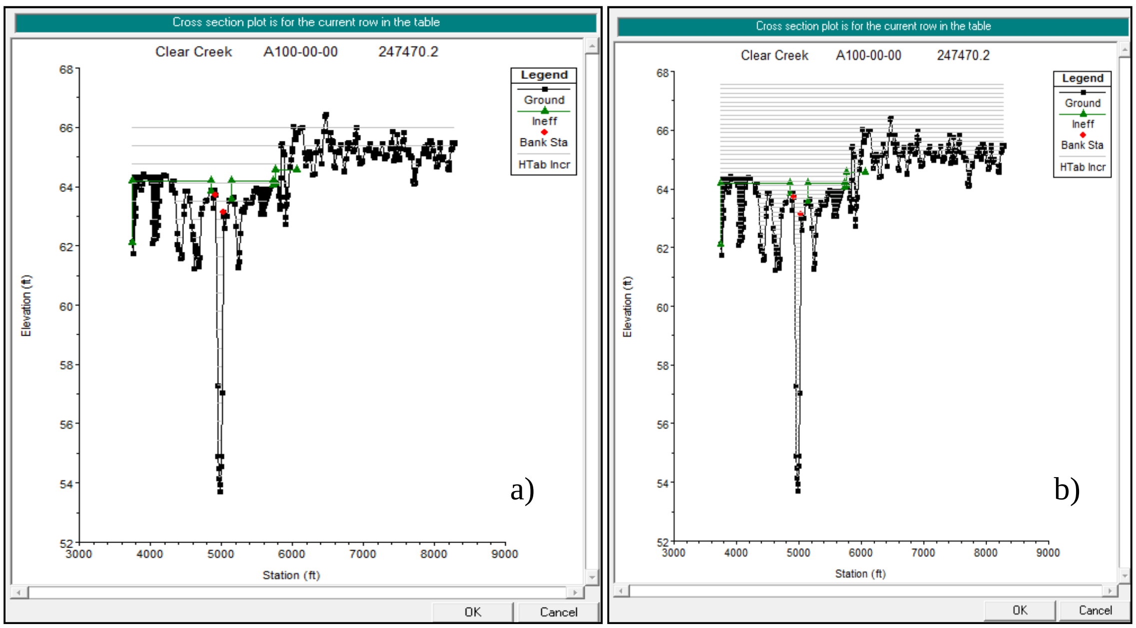


Figure 3-17: A cross-section in the HEC-RAS hydraulic table parameters (HTAB)

cause instability. Though it is not conclusive, Table 3-5 outlines a few rules of thumb determined by experience in this study that one may follow when developing an unsteady HEC-RAS model. Junctions, bridges, and high stage levels can all cause model instability when large stage gradients are present between tributaries, and when the headwater maximum elevations at bridges are calculated above a user-defined level. For instance, the user may need to add a pilot channel to keep the channel from going dry, increase the number of lines in a cross-section, or increase the maximum elevation that a model calculates on a bridge. Thus, attempting to model HEC-RAS in unsteady-state is an iterative process of changing one aspect, rerunning the model, and observing the effects of the change. The large number of bridges (34), the size of the basin (197 sq mi), the Armand and Taylor Bayou junctions, and the high storm surge boundary conditions used in this project all contributed to making the HEC-RAS model particularly difficult to run in unsteady-state.

Table 3-5: Steps to take when attempting unsteady-state HEC-RAS modeling

Steps to take in unsteady modeling	
1.	Verify that channel has flow at all locations along the stream. The user may add a pilot channel or baseflow along the stream.
2.	Check HTAB parameters (hydraulic table properties) for cross-sections. Make sure horizontal lines reach well above the cross-section and that distances between lines are small.
3.	Check HTAB parameters for all bridges and structures. In particular, make sure the maximum headwater elevation for bridges is sufficiently high.

Four different scenarios, specified in Table 3-6, were modeled in unsteady-state. Hurricane Ike125 near San Luis Pass was run with and without rainfall (Scenarios 2 and 3) to determine how far upstream the storm surge alone would reach in a worst-case storm surge scenario. The Results section expands upon this process. Scenarios 2 and 4 are designed to predict worst case flooding scenarios in the Clear Creek Watershed. See the Results section both for graphs of modeled and observed stage for Hurricane Ike and for stages from each model run.

Table 3-6: Storms run in unsteady-state HEC-RAS

Storms run in Unsteady-State HEC-RAS	
1.	Hurricane Ike
2.	Hurricane Ike125 near San Luis Pass with Ike Rainfall
3.	Hurricane Ike125 near San Luis Pass without rainfall
4.	Hurricane Ike125 near San Luis Pass with 0.2% annual chance rainfall

3.4 Mapping using Geographic Information Systems

Mapping in Geographic Information Systems (GIS) is a great way to put the results in media that can be easily understood by the public. The main purpose of using GIS in this study was to map floodplains using software that easily communicates with HEC-RAS: the HEC-GeoRAS software.

HEC-GeoRAS is a tool within GIS that acts as an interface between HEC-RAS and GIS. To create a floodplain map from the HEC-RAS output, the user must first export the data in GIS format. Once the data are exported, HEC-GeoRAS is able to import the data. The tool utilizes a user-provided digital elevation model (DEM) to subtract the land elevation from the water surface elevation, thereby giving an inundation depth of water (HEC, 2011).

A DEM from the United States Geologic Survey (USGS) was used with 1/9th arc second resolution (about 3 meters) (USGS, 2011). The maximum inundations from all four unsteady-state scenarios were mapped, in addition to those from four steady-state scenarios (0.2%, 1%, 2%, and 10% annual chance rainfall events). By mapping the maximum inundations, we were able to compare the flooding from Hurricane Ike against potential worst-case storm surge and rainfall scenarios, thereby providing emergency managers and city officials with an idea of what to prepare for. Furthermore, these inundation maps can be used in the future to develop damage risk maps using the depth-damage curves for specific types of structures (Mays, 2011).

Chapter 4: RESULTS

The results presented in this section discuss the model output from the HEC-HMS hydrologic model, the HEC-RAS hydraulic model, and the HEC-GeoRAS floodplain delineations. In particular this section discusses the results from a HEC-HMS analysis of Hurricane Ike rainfall, and an unsteady HEC-RAS analysis simulating both Hurricane Ike rainfall-runoff and storm surge. Four scenarios were run in HEC-RAS, described in Table 3-6. Using the first three scenarios, hazard zones were identified along the stream for areas vulnerable to storm surge, rainfall, and both. The fourth scenario simulates a worst case scenario by using rainfall-runoff from a 0.2% annual chance storm and storm surge from Hurricane Ike125 near San Luis Pass. Two stage hydrographs were entered in the model for each storm surge scenario: one at the downstream end of Clear Creek, and another at the upstream end of Taylor Bayou. Rainfall-runoff, if added, was approximated by inputting hydrographs along the stream, which were simulated using HEC-HMS. In addition, this research presents floodplain maps and inundation depths in the Clear Creek Watershed and Armand Bayou from each storm scenario.

4.1 Rainfall-Runoff Modeling Results

Flooding due to rainfall-runoff is first analyzed using a hydrologic model. Scientists and engineers use surface hydrology to calculate the flow rate of water over land, in reservoirs, and in rivers. These flow rates are useful in determining the vulnerability of a watershed to flooding and how much water may be supplied by surface water systems in a particular region. Engineers may also analyze water velocities in a channel by inputting the flow rates produced by the hydrologic model into a hydraulic model. Both hydrologic and hydraulic analyses are often extremely useful for day-to-day flood forecasting.

Table 4-1: Streamflow at various junctions along Clear Creek

Peak Flows at Various Locations along Clear Creek (cubic feet per second)							
Location	0.2% Storm	1% Storm	2% Storm	10% Storm	T.S. Allison	April 2009	Hurricane Ike
1. Channel Outlet	71,692	46,278	37,913	16,373	48,566	12,846	21,181
2. Taylor Bayou Junction	72,611	46,954	38,777	16,443	50,361	12,947	22,247
3. Armand Bayou Junction	64,311	41,939	35,188	16,065	45,927	12,673	22,402
4. I-45	32,047	22,997	19,680	11,206	24,400	12,824	12,404
5. W. Bay Area Blvd.	29,371	21,061	18,366	10,739	22,449	12,389	11,764
6. F.M. 528	24,894	17,906	15,795	9,297	16,858	11,332	10,000
7. Turkey Creek Junction	17,182	10,933	10,635	6,116	12,132	7,932	6,600
8. Hickory Slough Junction	7,673	4,233	4,453	2,541	5,341	3,027	2,453
9. Highway 288	3,917	1,745	1,901	903	1,425	1,047	660

Engineers sometimes compare a particular storm event to frequency storms in order to better characterize the flow in the channel. For instance, Table 4-1 compares the peak flows produced by the 0.2%, 1%, 2%, and 10% storms with those from the three calibration storms at various points along the stream. The numbered locations in Table 4-1 are identified on a map in Figure 4-1 by a star and the corresponding number. Upstream of Bay Area Blvd, Table 4-1 indicates that streamflow during Hurricane Ike due to rainfall-runoff is most similar to that from a 10% annual chance rainfall. Downstream of Bay Area Boulevard., however, streamflow from Hurricane Ike rainfall-runoff is analogous to the streamflow that would be caused by a rainfall in between a 10% and 2% annual chance storm. Comparing this to Tropical Storm Allison and the April 2009 event, we see that the streamflow caused by Allison was closest to that from a 1% annual chance rainfall event, and that the April 2009 can be most closely compared to the streamflow from a 10% annual chance rain event.

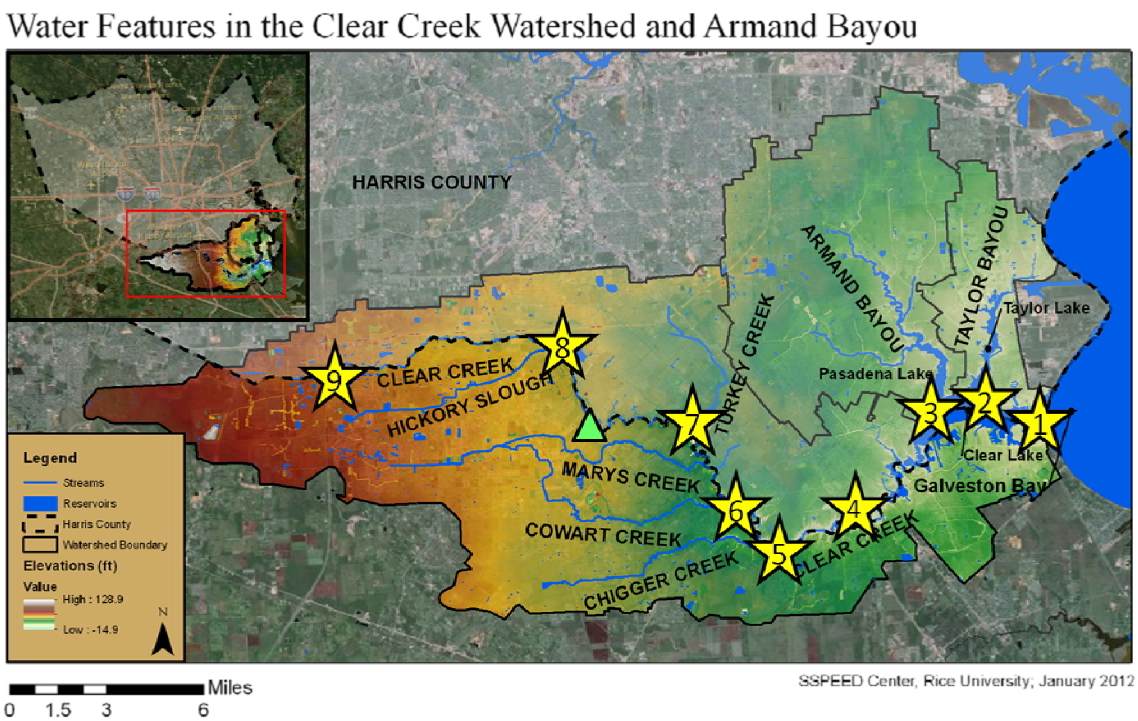


Figure 4-1: Locations (stars) corresponding to points in Table 4.1

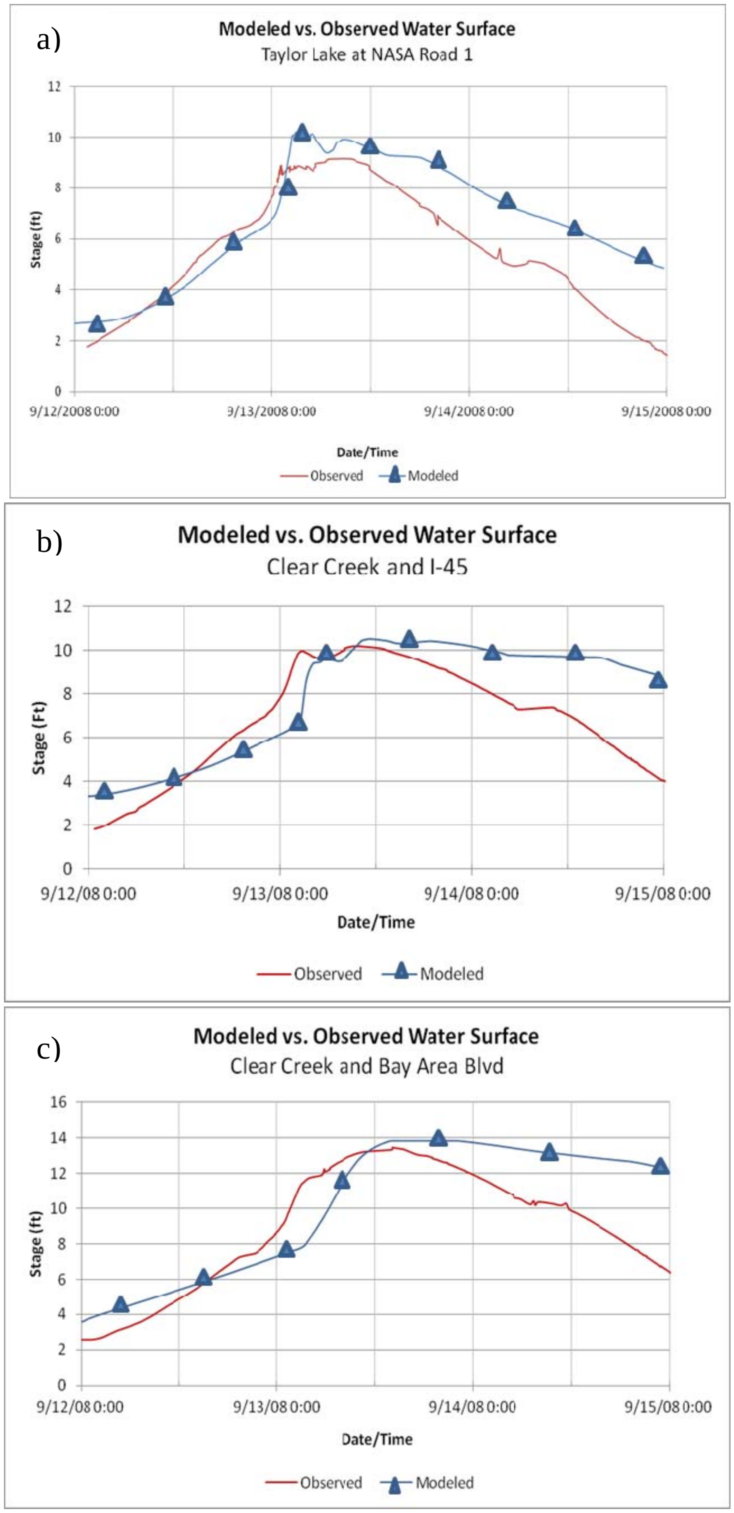
Peak flows for frequency events can be used in real time to characterize the approaching storm and match it to an appropriate corresponding floodplain map (see Section 3.4 for description). Thus, by knowing the potential flood danger from frequency events, emergency managers and local residents can estimate the flood danger from the present threat. Similarly, floodplain maps can be created for various storm surge scenarios, providing potential victims of storm surge with a similar method of estimation to deduce how much storm surge will inundate their home during a hurricane. FEMA recently derived 0.2%, 1%, 2%, and 10% frequency storm surge levels in Texas coastal areas. Once these data are available, frequency storm surge floodplains will be delineated in the Clear Creek Watershed.

4.2 Unsteady-State HEC-RAS Modeled and Observed Stages

The majority of the results presented in this chapter are from the unsteady-state HEC-RAS model described in Chapter 3. However, before any conclusion can be made we must first verify the model. For the unsteady HEC-RAS model described in Chapter 3, Figure 4-2 compares the modeled and observed stages. Figure 4-2 is different from Figures 3-8 through 3-12 in Chapter 3, as it presents HEC-RAS model output (riverine stage), and Figures 3-8 through 3-12 presented HEC-HMS model output (flows).

Figure 4-2a shows the modeled and observed stage at Taylor Lake and NASA Road 1 (Figure 4-1, #2). The model appears to capture the timing and peak of the stage fairly well, but then overestimates stage on the receding limb of the hydrograph. This phenomenon appears to be a consistent trend at multiple points along the river. In fact, Figures 4-2a, 4-2b, and 4-2c (located at #2, #4, and #5 in Figure 4-1) all appear to capture the peak well, but match less well on the receding limb. Figure 4-2d (located at the triangle in Figure 4-1) also has a large difference at the beginning of the rising limb between the modeled and observed. This difference is most likely due to baseflow that was added in the stream to prevent the channel from going dry, and adjusting this baseflow will likely cause the model to become unstable.

Figure 4-3 shows a profile view of the main channel using HEC-RAS, and points A, B, C, and D correspond to the stage hydrographs in Figure 4-4. One important aspect of the channel the reader should notice is the adverse slope between Bay Area Boulevard and point B, a distance of about 8.9 miles. The adverse slope in Clear Creek was most



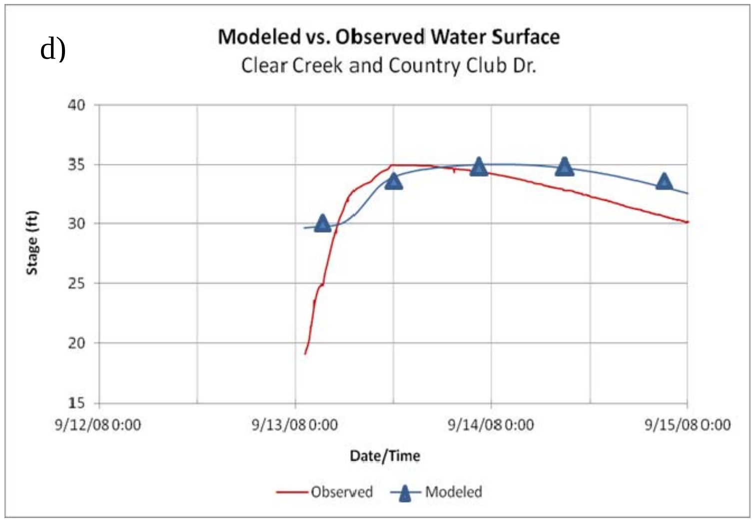


Figure 4-2: Modeled and observed HEC-RAS stage at various points

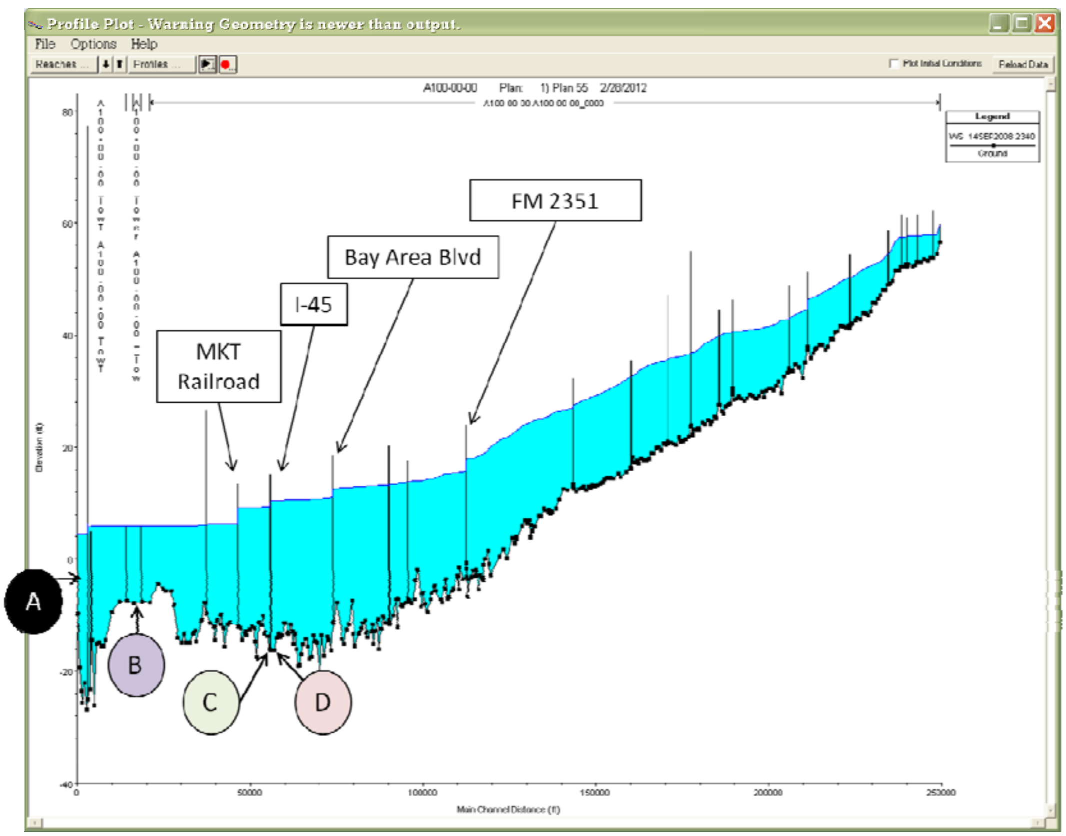


Figure 4-3: Profile view of Clear Creek from HEC-RAS

likely created by the river and its tributaries cutting valleys in the channel (Bedient, 2012). However, since it is not very steep, with about a -0.035% slope (-1.84 ft/mile) from Bay Area Boulevard to point B, and since the water surface elevation in Clear Creek is always greater than the critical depth elevation, the adverse slope present does not cause supercritical flow during Hurricane Ike. In other words, the water in the channel during Hurricane Ike is always draining towards the outlet, and not towards the “bowl” in the river. This may not be the case under low-flow conditions, but the river is deep enough in the depressed region so that any positive backwater effects during low-flow are not a major cause of concern for flooding. The adverse slope may, however, be causing water to drain more slowly out of the river. See Bedient’s *Hydrology and Floodplain Analysis* for more information on adverse slopes (2012).

In Figure 4-3, water surface elevations are graphed from Hurricane Ike at midnight on September 15th. Remembering Figure 3-6, we know that midnight on September 15th was after the storm when both rainfall-runoff and storm surge flows were draining from the stream. There are many locations where the bridges appear to hold back a significant amount of water from upstream, preventing it from draining. At the MKT Railroad, for instance, there is a four-foot difference in water levels between upstream and downstream of the railroad. The extra storage caused by this kind of difference may be one reason why the modeled and observed hydrographs do not match well on the receding limbs. Closer survey and calibration of bridge parameters may be necessary to fix this error, but is outside the scope of this project. To further analyze the effects of bridges, we may also look at stage hydrographs in time and space. A, B, C, and D in Figure 4-3 (and Figure 4-5) correspond with respective profiles in Figure 4-4.

The stage hydrographs in Figure 4-4 demonstrate the propagation of storm surge up Clear Creek during Hurricane Ike. The black line (triangles) represents the measured storm surge at Kemah (opening of channel) over the length of the storm. The red line

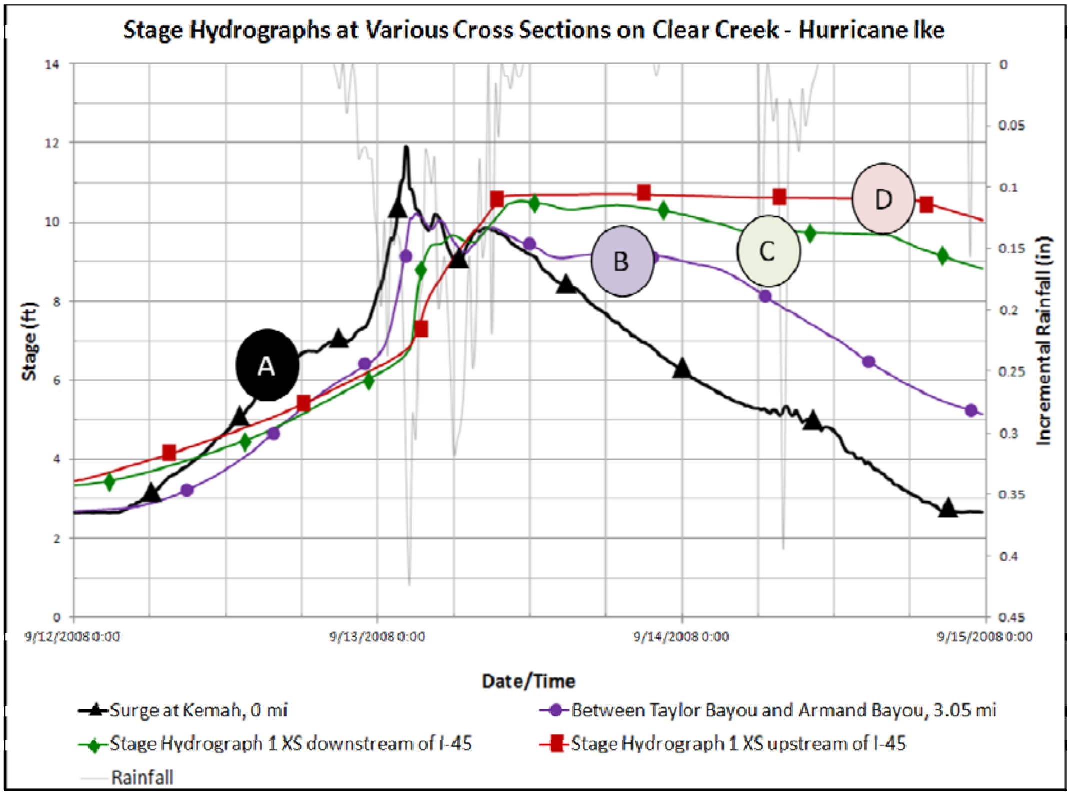


Figure 4-4: Stage hydrographs corresponding to locations in Figure 4.3 and 4.5

(squares) is the stage at the cross-section just upstream of I-45. The peak stage due to storm surge decreases by approximately 1.8 feet from the opening of Clear Creek to a point 3.05 miles upstream in between Taylor Bayou and Armand Bayou (purple line/circles). It also decreases by about 0.8 feet from that point to the cross-section just downstream of I-45 (green line/diamonds) over 8 miles. At the cross-section just upstream of I-45, the direct propagation of the storm surge peak at Kemah is no longer visible. By interpolating in time and space from the green line to the red line, one can estimate that the water surface elevation decreased by about 0.6 feet from the downstream to the upstream end of the bridge, a distance of 245 feet. Compared with a decrease of 0.8 over 8 miles, this analysis clearly illustrates the impact that a particularly large bridge can have on the water surface elevations in a channel.

4.3 Rainfall and Storm Surge Interactions

Storm surge is a potentially devastating threat along the Texas Coast due to powerful hurricanes that often make landfall during the summer. The Clear Lake Watershed is especially vulnerable due to its location on Galveston Bay and the presence of particularly heavily populated areas such as Kemah, Clear Lake, and Taylor Bayou. The effects that storm surge has had on the Clear Creek Watershed can be found in the Background and Literature Review. One of the largest concerns for residents and potential buyers is how far upstream from Galveston Bay they need to be in order to be safe from storm surge. To determine the most threatened areas, several storms were run in unsteady HEC-RAS (Table 3-6). The maximum water surface elevations from four of these storms (Scenarios 1-3) are shown in Figure 4-5. From the profile plots, an analysis was completed to delineate the three zones along the channel: the Storm Surge Zone, the Rainfall/Storm Surge Interaction Zone, and the Rainfall Zone.

The Storm Surge Zone is defined as the area along the stream where storm surge is the dominant causal mechanism behind water surface elevation in the watershed. Likewise, the rainfall zone is the region where rainfall is predominant and storm surge has no effect. Therefore, the Rainfall/Storm Surge Interaction zone is the region where both rainfall and storm surge are variables in determining water surface elevation in the stream. Figure 4-5 illustrates an estimate of the three zones, with the Storm Surge Zone being a conservative estimate.

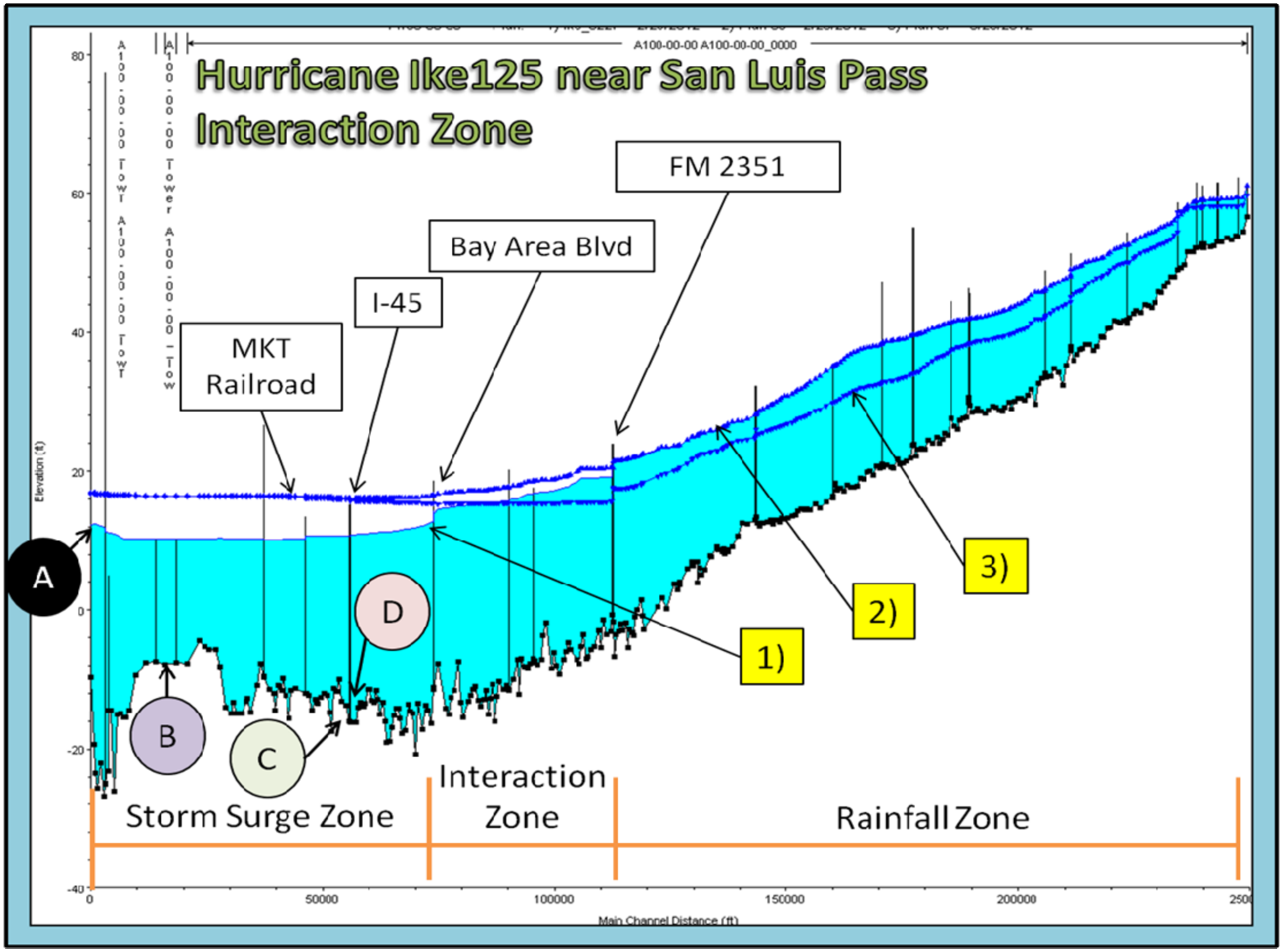


Figure 4-5: 1) Ike; 2) Ike125 near San Luis Pass, Ike rain; 3) Ike125 near San Luis Pass, no rain

To identify the Rainfall Zone, the rainfall was kept constant by comparing profiles 1), Hurricane Ike, with profile 2), Hurricane Ike125 near San Luis Pass with Hurricane Ike rainfall. The rainfall zone is the region in which the water surface elevation in the stream did not change with increasing storm surge. To measure this, the percent increase in stage from Hurricane Ike to Hurricane Ike125 near San Luis Pass was calculated for all of Clear Creek. Every point upstream of FM 2351 in Figure 4-5 had less than a 1% increase in water surface elevation and was thus identified as the rainfall zone because an increase in storm surge had a negligible effect. Downstream of FM 2351 there was a 6.5% increase in stage. It is important to note that if rainfall were to be higher than that from Hurricane Ike, the rainfall zone would extend farther downstream. For instance, if a 0.2% annual chance rainfall fell with Hurricane Ike (16 inches in 12 hours) the rainfall zone would have extended to Clear Lake—encompassing virtually all of Clear Creek. However, since hurricanes generally move too fast to have such a large rainfall associated with them, such an event is highly unlikely. Thus, Hurricane Ike rainfall was chosen for a more realistic estimate.

When defining the Storm Surge Zone, profile 2), Hurricane Ike125 near San Luis Pass with Hurricane Ike rainfall, was compared against profile 3), Hurricane Ike 125 near San Luis Pass without rainfall. By using Hurricane Ike 125, rather than Hurricane Ike, a conservative delineation of the zone is made. Notice that when delineating the Rainfall Zone, rainfall was kept constant, but when delineating the Storm Surge Zone, storm surge was kept constant. Stages from the hurricane without rainfall were subtracted from the hurricane with rainfall to measure the increase in water surface elevation associated with rainfall. Since the Storm Surge Zone boundary was not as apparent as the Rainfall Zone boundary, percent increases of less than 5% (0.7 feet) were chosen to be conservative. Figure 4-6 puts the designated zones in a geographic reference frame.

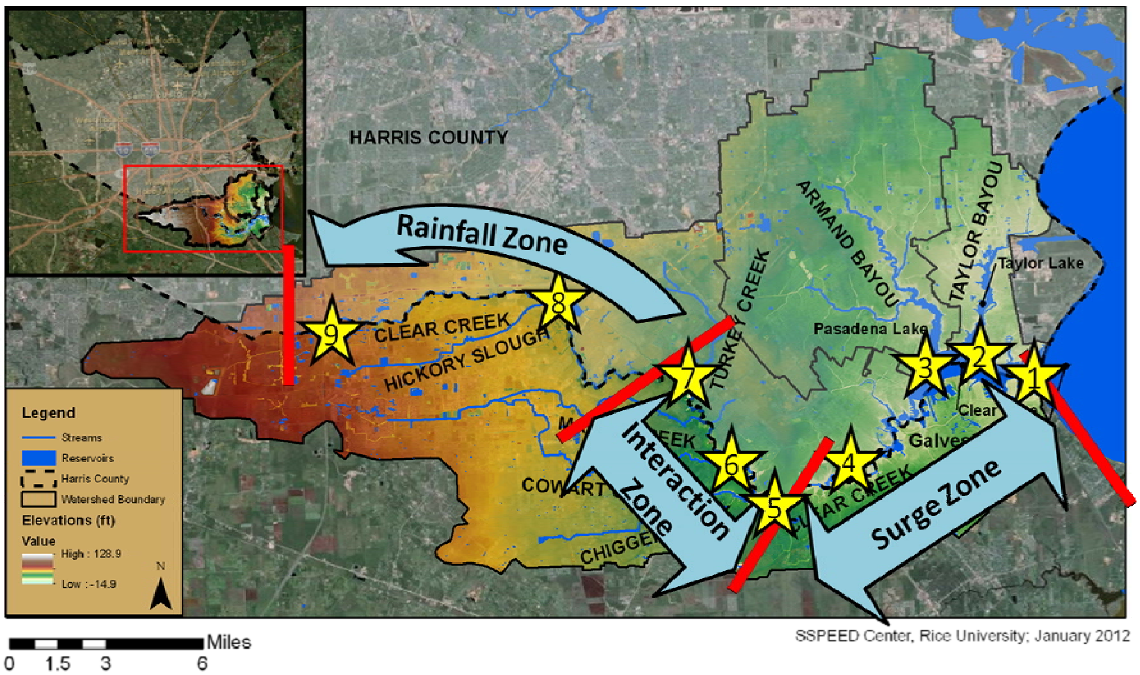


Figure 4-6: Plan view of the zones defined in Figure 4.5

4.4 Floodplain Mapping

After modeling Hurricane Ike in unsteady-state HEC-RAS and using HEC-GeoRAS to delineate a floodplain, a figure representing maximum inundation during the hurricane was produced (Figure 4-7). The figure illustrates that the areas with the most flooding were at the downstream end of Clear Lake and in the upstream end of Taylor Bayou.

Looking more closely (Figure 4-8), one can see that inundation depths in Taylor Bayou and around Clear Lake reached up to 8 feet in areas outside the channel. These areas have been identified as the primary areas of concern for flooding during Hurricane Ike. The model shows that water elevations upstream did not increase enough to cause flooding. Slight flooding is seen just downstream of Clear Lake and the Lyndon B. Johnson Space Center, but most of the water upstream is contained in the channel.

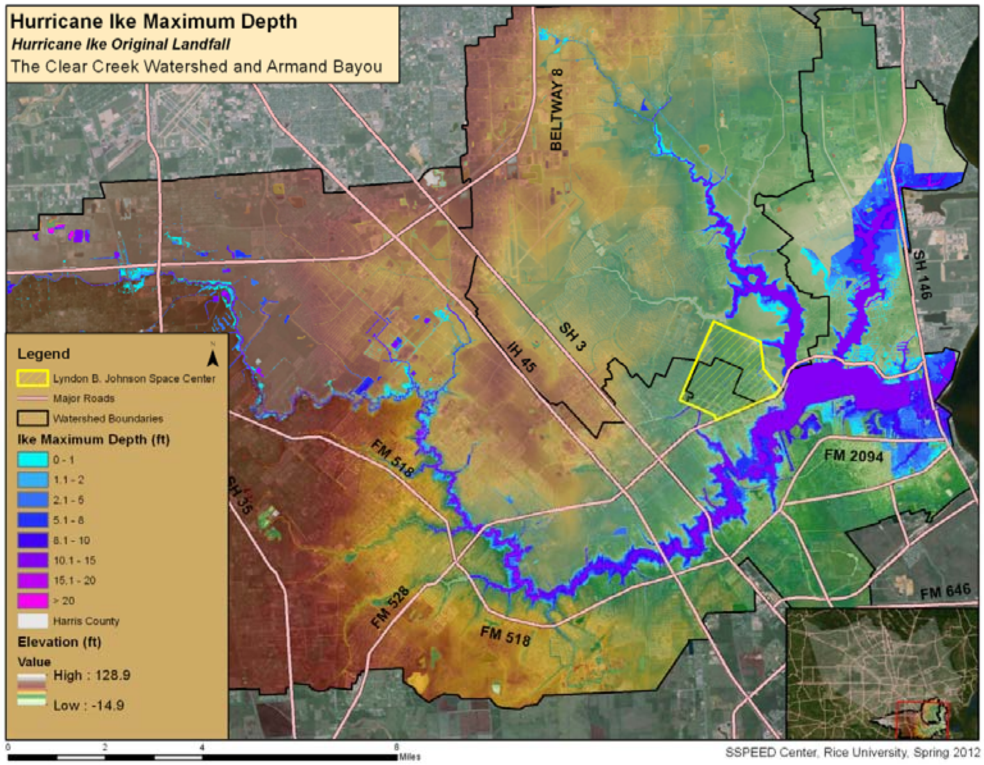


Figure 4-7: Maximum depth during Hurricane Ike (unsteady-state)

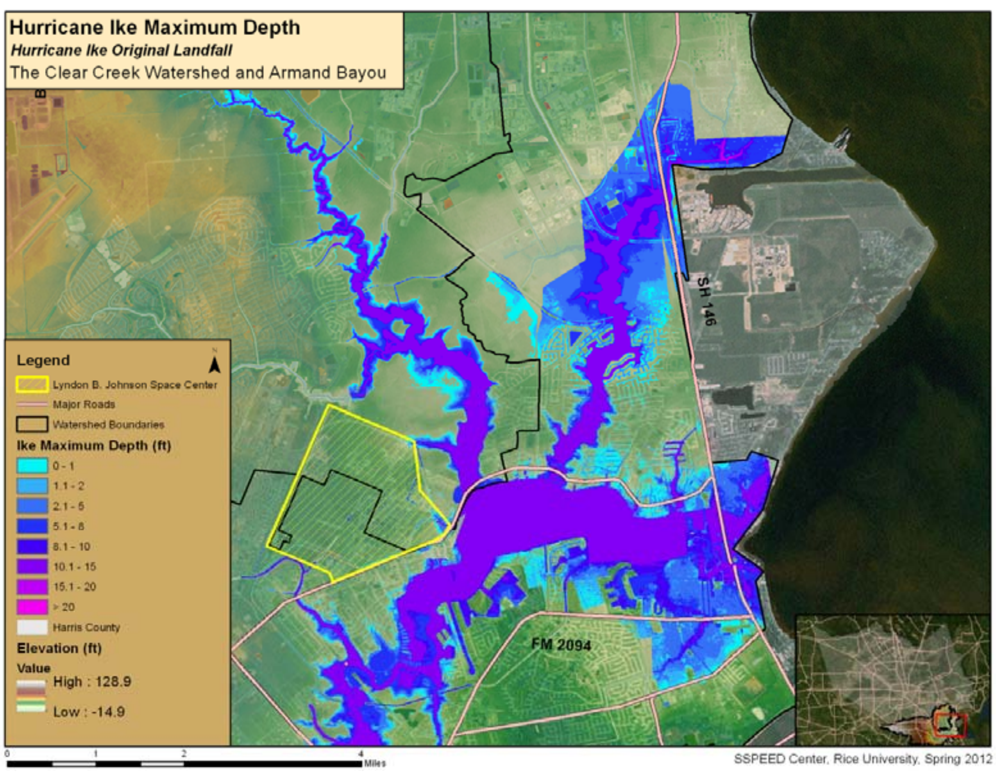


Figure 4-8: Zoom in – maximum depths during Hurricane Ike

This can be attributed to the fact that rainfall-runoff upstream was similar to that from a 10% chance storm (as discussed in Section 4.1), which does not produce much flooding outside the banks of the river (Figure 4-9). Notice that upstream in Figure 4-9, where Clear Creek has been left mostly natural, the 10% chance storm causes 1-2 feet of water outside the banks of the stream. The flooding here may support the proposed notion in Chapter 3 that extra storage in the hydrologic model is caused by poor drainage from natural conditions (see Section 3.1.1).

Figure 4-10 and Table 4-2 identify points where we will investigate inundation depths, and Table 4-3 compares maximum depths for all of the floodplain maps presented in this section. However, because of errors in the terrain model and the inherent variability in depth with changes in point location, it is important to look at the depths in Table 4-3 relatively, and not necessarily as true values.

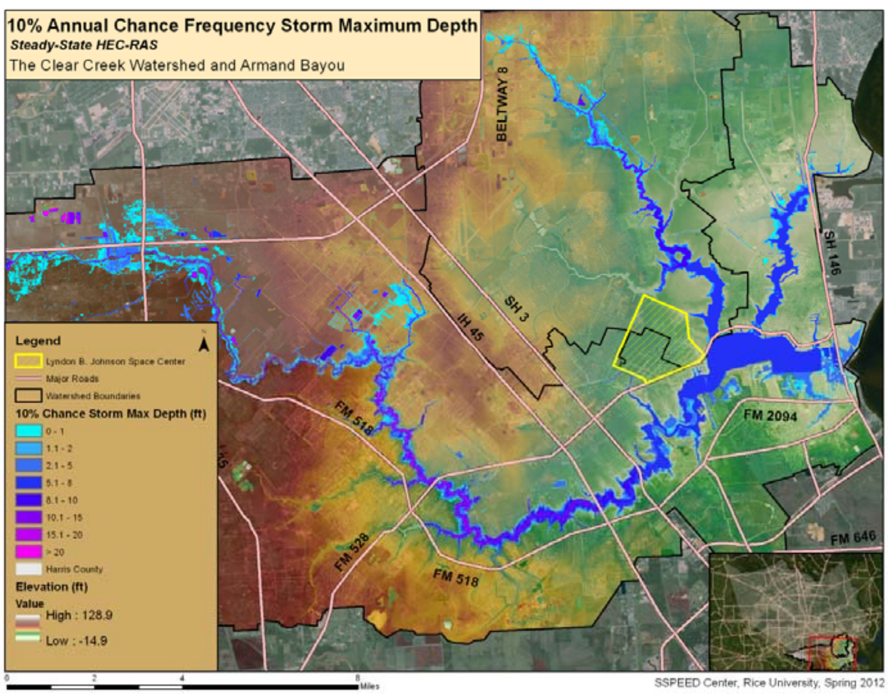


Figure 4-9: Maximum depths – 10% annual chance frequency storm

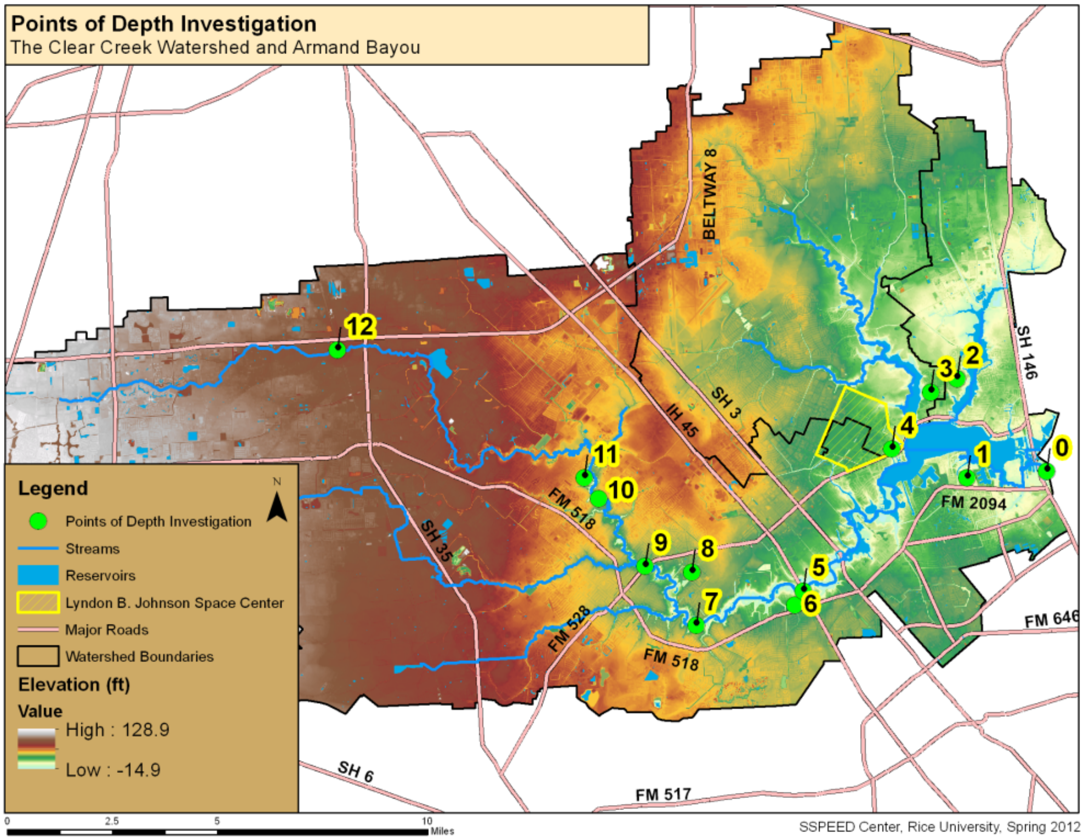


Figure 4-10: Points of depth investigation, corresponding with Table 4-2

Table 4-2: Points of depth investigation in Figure 4-9

Point of Depth Investigation	Description	Point Type
0	Kemah	Commercial
1	Clear Lake	Residential
2	Taylor Bayou	Residential
3	Armand Bayou	Residential
4	Lyndon B. Johnson Space Center at NASA Rd. 1	Governmental
5	Clear Creek at I-45	Channel
6	Near I-45 – Residential	Residential
7	Clear Creek at Bay Area Blvd.	Channel
8	Clear Creek near FM 528	Residential
9	Clear Creek at FM 528	Channel
10	Clear Creek at FM 2351	Channel
11	Clear Creek near FM 2351	Residential
12	Clear Creek at Mykawa Rd.	Channel

Table 4-3: Depths from different runs at points of depth investigation in Table 4-2

Point of Depth Investigation	Ike Depth - ft	Ike125 near San Luis Pass (Ike Rainfall) Depth - ft	Ike125 near San Luis Pass (0.2% Rainfall) Depth - ft	0.2% Depth - ft	1% Depth - ft	10% Depth - ft
0	7.26	11.9	11.9	--	1.2	--
1	0.7	6.9	7.3	--	--	--
2	--	2.9	3.1	--	--	--
3	--	1.5	1.8	--	--	--
4	--	4.2	4.5	--	--	--
5	12.18	17.6	18.7	15.9	13.5	9.9
6	--	1.2	2.7	--	--	--
7	4.6	8.3	11.5	11.5	8.7	4.8
8	--	--	--	0.86	--	--
9	17.36	19.2	23	24.4	22	18.3
10	8.7	10	14.5	17	15	11.6
11	--	--	--	1	--	--
12	2.4	2.4	6.3	7.4	6.6	4.8

The points in Table 4-2 were chosen to make a relative comparison between locations easier to interpret. These points include important sites along the channel, many of which have been used previously for model validation, as well residential and commercial neighborhoods that could potentially be vulnerable to either flooding from rainfall, storm surge, or both. Table 4-3 provides similar conclusions to Table 4-1, but it compares stages and incorporates storm surge. We can see that the flooding caused by Hurricane Ike was close to that which would be caused by a 10% annual chance storm in the Rainfall/Storm Surge Interaction Zone, and less than a 10% annual chance in the Rainfall Zone. At I-45, the flooding caused by storm surge and rainfall was similar to the flooding from a storm in between a 10% and a 1% frequency event. Many of the chosen locations do not show depths for Hurricane Ike and the frequency storms. However, since the depths upstream of Bay Area Blvd. are less than or equal to those caused by the

10% frequency event, Table 4-3 implies that flooding in these locations is dominated by rainfall, thereby reinforcing the previously identified hazard zones.

4.4.1 Larger Wind Events

Though the flooding from Hurricane Ike storm surge was severe, modeling efforts using ADCIRC indicate that it was not a worst case scenario for Houston and the Clear Creek Watershed. Ike made landfall as a Category 2 hurricane on the north end of Galveston Island, causing Kemah to see a peak surge level of just over 12 feet. The highest storm surge levels caused by this landfall occurred on Bolivar Peninsula. However, if the hurricane had been a Category 3 storm (Ike 125) and had made landfall to the south near San Luis Pass, Kemah could have seen surge heights upwards of 16 feet.

To simulate the flooding caused by this storm Category 3 storm, the ADCIRC storm hydrographs from Hurricane Ike125 with landfall near San Luis Pass were set as the boundary conditions in the unsteady HEC-RAS model. Again, a floodplain was delineated for the maximum water surface elevations (Figure 4-11). The results show that if Ike125 near San Luis Pass were to occur, local flooding due to storm surge would occur up to approximately 2 miles upstream of I-45, and about 4 miles farther upstream than would occur with just Hurricane Ike. A closer look at the floodplain (Figure 4-12) shows a significant increase in flooding in Taylor Bayou, Armand Bayou, around Clear Lake, and along Clear Creek moving upstream. Given this scenario, portions of upper Taylor Bayou and around Clear Lake would see depths of 10-15 feet outside of the channel.

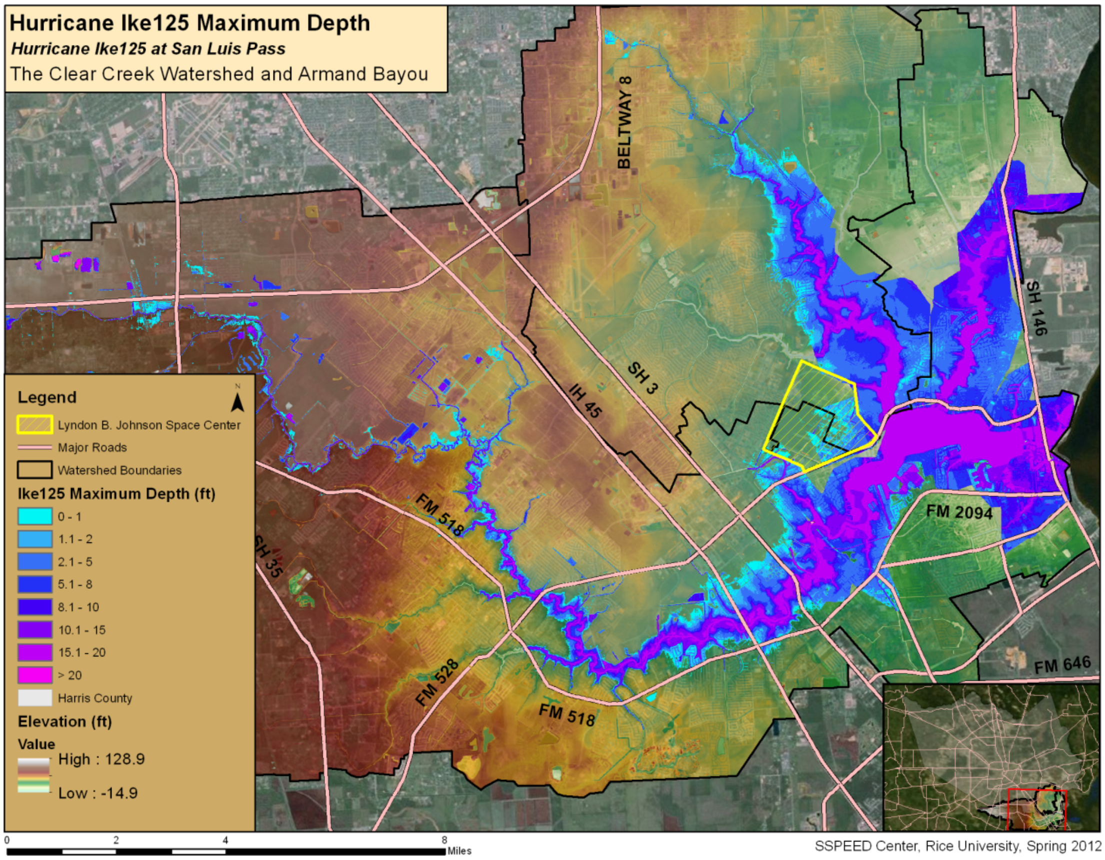


Figure 4-11: Maximum depths – Ike125 near San Luis Pass – Ike Rain

Analyzing Hurricane Ike in comparison with frequency storms has given us a better idea of the scale of the storm as a whole in the Clear Creek Watershed. Furthermore, looking at the inundation depths that would result from Hurricane Ike near San Luis Pass (with Hurricane Ike rainfall) has illustrated the scale of damage that could occur if a hurricane stronger than Hurricane Ike made landfall a little farther down the coast. We have not, however, analyzed what could happen if a heavy rainfall fell in conjunction with the storm surge from Hurricane Ike125 near San Luis Pass, and if the designated hazard zones would still hold true.

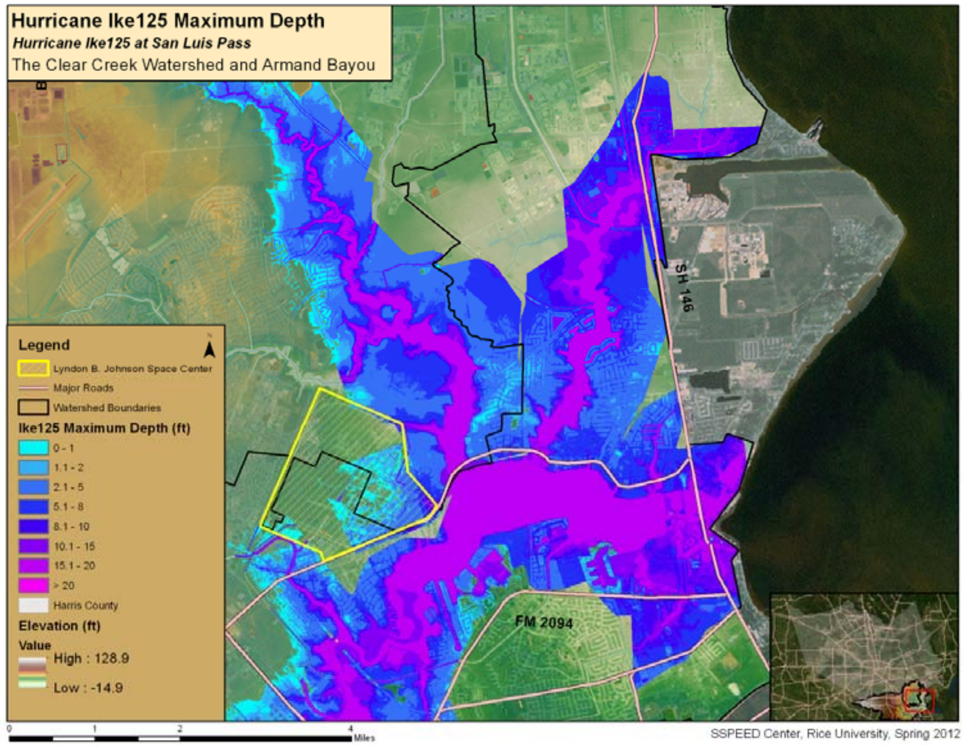


Figure 4-12: Zoom in – Maximum depths – Ike125 near San Luis Pass – Ike Rain

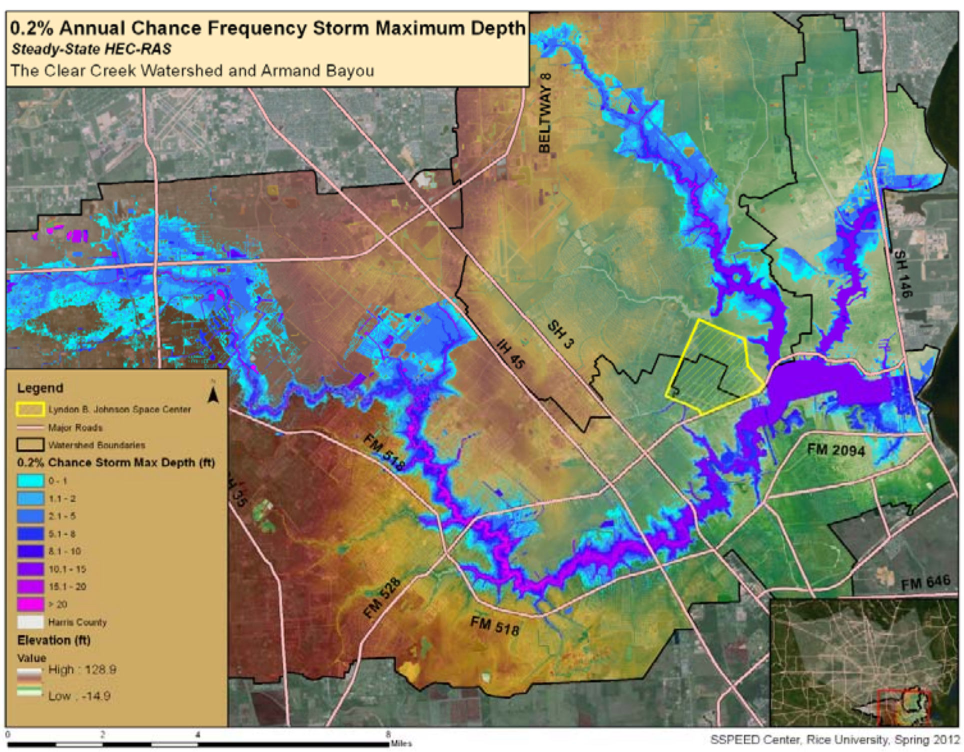


Figure 4-13: Maximum depths – 0.2% annual chance storm

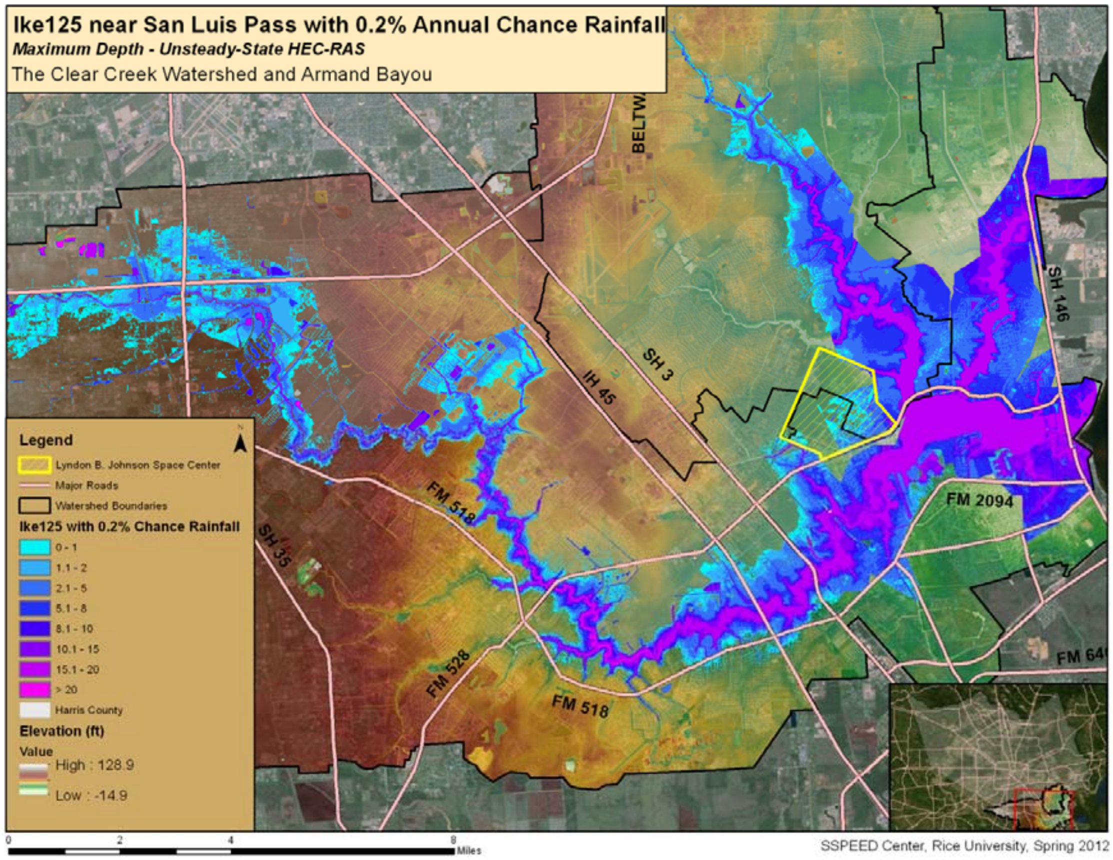


Figure 4-14: Maximum depths – Ike125 near San Luis Pass – 0.2% annual chance storm

Figure 4-13 shows the inundation depths that would result from a 0.2% annual chance storm (steady-state HEC-RAS). Compared with the Hurricane Ike depths, we notice that flooding is similar in Taylor Bayou, has increased in Armand Bayou, and has increased upstream of I-45. Figure 4-14 illustrates what could happen if Hurricane Ike125 made landfall near San Luis Pass and brought with it a 0.2% annual chance rainfall (run in unsteady-state). We notice that storm surge dominates in the Storm Surge Zone, and that rainfall dominates in the Rainfall Zone. By looking back at Table 4-3, it becomes clear that depths downstream of Bay Area Blvd have not increased by much, implying that storm surge is still the dominant process in these areas. The slight increase in depth that appears downstream of Bay Area Blvd. is most likely simply due to the added volume that a 0.2% rainfall brings to the channel. Upstream of Bay Area Blvd the depths are actually less than those that would result from the 0.2% chance storm alone. However, the 0.2% chance storm was run in steady-state when no surge was added, and in unsteady-state with surge. Thus, it is unclear whether these depths would be less in reality, or whether the mismatch is simply a consequence of the inconsistencies in the model runs.

Simulating Hurricane Ike125 near San Luis Pass with a 0.2% frequency storm has served to illustrate the consequences from a worst case rainfall and storm surge scenario and to further support the designated hazard zones. It should, however, be restated that the statistical chances of these combined occurrences are slim because, as mentioned previously, hurricanes generally move too quickly to bring large amounts of rainfall. Nevertheless, it is wise to anticipate about what consequences such a scenario might bring, and this research shows that the hazard zones defined here are confirmed under more intense rainfall.

Chapter 5: SUMMARY AND CONCLUSIONS

Like the East Coast of the United States, the Gulf Coast is extremely vulnerable to hurricanes during the summer months. The section of the Gulf Coast ranging from Alabama to the southern tip of Texas is especially at risk because of the shallow slopes of the continental shelf that resides just offshore. Hurricane Ike made landfall near Galveston, TX, as a Category 2 storm, bringing peak surge levels close to 20 feet on Bolivar Peninsula. Though it brought severe damage, the storm surge caused by Hurricane Ike was not a worst case scenario for the Houston area. This research used an unsteady-state HEC-RAS hydraulic model to analyze the potential flooding that would be caused by a worst-case scenario storm surge in a watershed near Houston, TX.

The Clear Creek Watershed is located just south of Houston and is home to highly populated areas such as Kemah, Clear Lake, Taylor Bayou, Friendswood, and Pearland. It has an area of approximately 197 sq mi, drains into Galveston Bay, and received a surge height of 12.3 feet at the outlet during Hurricane Ike. Modeling efforts using the ADCIRC storm surge model indicate that if Hurricane Ike had made landfall near San Luis Pass and had been a Category 3 hurricane (with landfalling winds of 125 mph), the surge at the outlet of Clear Creek would have been 16.8 feet.

Storm surge modeling and inland flood modeling have historically been separate endeavors. The ADCIRC model has the potential to model overland flooding due to storm surge, but running the model is expensive and rainfall is not taken into account. To model the effects of both storm surge and rainfall, unsteady-state HEC-RAS, which is normally used to model rainfall-runoff, was used in conjunction with simulated ADCIRC storm surge stage hydrographs. The ADCIRC prediction hydrographs were input at the outlet of Clear Creek and the most upstream point in Taylor Bayou to represent the surge that would inundate these areas from Galveston Bay. By using surge as the boundary conditions, the rainfall-runoff and storm surge interactions were analyzed, thereby determining what level of flooding the Clear Creek Watershed should expect with a storm surge of 16.8 feet and Hurricane Ike rainfall.

Many conclusions were drawn when combining these two models. The water surface elevations from the HEC-RAS model were compared against observed stage levels at several points along the stream. Modeled hydrographs matched the observed hydrographs fairly well in timing and peak, but overestimated on the receding limb of the hydrograph. The extra storage present in the modeled hydrograph indicates that the water in the model drains slower than it would in reality. How the 34 bridges were represented in the channel model could be one reason why water is draining more slowly in the model. An animation of the water surface elevations in the channel reveals that the bridges hold back a significant amount of water when the river is draining. The water surface elevation differential at some bridges is as high as 4-5 feet. Future efforts may need to be focused on calibrating the HEC-RAS model based on bridge parameters.

Hazard zones were also delineated based on rainfall-runoff and storm surge interactions from the unsteady HEC-RAS model. Maximum water surface elevations were analyzed in a profile view of the channel for several different storm runs (Table 3-6) to identify the Storm Surge Zone, the Rainfall/Storm Surge Interaction Zone, and the Rainfall Zone. A conservative estimate for the Storm Surge Zone was derived by analyzing Hurricane Ike125 near San Luis Pass with Hurricane Ike rainfall and without any rainfall (keeping storm surge constant). The rainfall zone was determined by comparing Hurricane Ike and Hurricane Ike125 near San Luis Pass with Ike rainfall (keeping rainfall constant). Based on these analyses, the Storm Surge Zone extends from the outlet of Clear Creek up to about Bay Area Blvd., the Rainfall/Storm Surge Interaction Zone extends from Bay Area Blvd. up to FM 2351, and the Rainfall Zone extends from FM 2351 to the most upstream end of the watershed.

Using the HEC-RAS output, floodplain maps for three different storms were developed in HEC-GeoRAS: Hurricane Ike, Hurricane Ike125 near San Luis Pass with Hurricane Ike Rainfall, and Hurricane Ike125 near San Luis Pass with a 0.2% annual chance rainfall. These maps were then compared against floodplain maps for standard frequency events. Results show that flooding from Hurricane Ike was worst around Clear Lake and in Taylor Bayou. Some commercial and residential areas saw depths up to 8 ft outside of the river banks. However, according to the HEC-RAS model and HEC-GeoRAS floodplain delineations, Hurricane Ike125 near San Luis Pass with Hurricane Ike rainfall would result in depths ranging from 10-15 feet in commercial and residential areas.

The floodplain for Hurricane Ike125 near San Luis Pass with a 0.2% rainfall show that in the Storm Surge Zone, inundations depths would be similar to Hurricane Ike125 near San Luis Pass with Hurricane Ike rainfall. In the Rainfall Zone, however, inundation depths would be closer to that of a 1% annual chance rainfall, and in the Rainfall/Storm Surge Interaction Zone, closer to that of a 0.2% annual chance storm. Results may be influenced by errors associated with differences in running HEC-RAS in steady-state and unsteady-state, and future work should investigate and report on the model differences associated with these two methodologies. Nevertheless, simulating Hurricane Ike125 near San Luis Pass with Hurricane Ike rainfall and with a 0.2% annual chance rainfall has served to paint pictures of worst case flooding scenarios and validate the previously outlined hazard zones.

Chapter 6: FUTURE WORK

The work presented in this document is applicable towards many future studies. As part of the future work, the hydraulic model used in this study should be refined to more accurately represent the channel. One method by which the HEC-RAS model may be refined is by altering bridge parameters to calibrate the model and better match the receding limbs of the observed stage hydrographs (see Section 4.2). Furthermore, the cross-sections in the model may also be extended to capture the entire floodplain. In Figure 4-12, for instance, the floodplain suddenly stops when the water reaches the edge of the model cross-sections. Because the floodplain does not extend beyond the edge of the cross-sections as it naturally would, the modeled water elevations are most likely higher than they would be in reality.

Though the shorter cross-sections may have affected the depths of water in the floodplains, they most likely did not have a large effect on the hazard zones delineated. The "bathtub floodplain" is logically a good approximation when modeling high storm surge. A bathtub model would assume that the maximum depth from storm surge would extend up the river until the water reached land, thereby creating a "bathtub" of water everywhere lower than that elevation. Profile 3 in Figure 4-5 shows that the bathtub theory appears to apply for the Ike125 near San Luis Pass simulations, which is the surge scenario that the hazard zones were determined from. Thus, the hazard zones delineated would not change significantly if the bathtub model were applied. Therefore, although the shorter cross sections may not affect the hazard zone delineations, they could be affecting depths in the floodplain and should be extended before further floodplain analyses are completed.

Once the cross sections are extended, further analyses with FEMA flood claims may be completed to verify the HEC-RAS model. Flood modeling is often made more difficult by the lack of observational data available to engineers and researchers. Though the Houston area is blessed with an abundance of hydrologic data, our resources are still limited to channel gauges and surveyed high water marks. Currently there is no way to assess the accuracy of the modeling using publically available damage data outside the channel. However, through a generous and mutually beneficial partnership with Dr. Samuel Brody at Texas A&M University at Galveston, the SSPEED Center has been given access to historical FEMA flood claims from 1999-2009 (Brody, 2012).

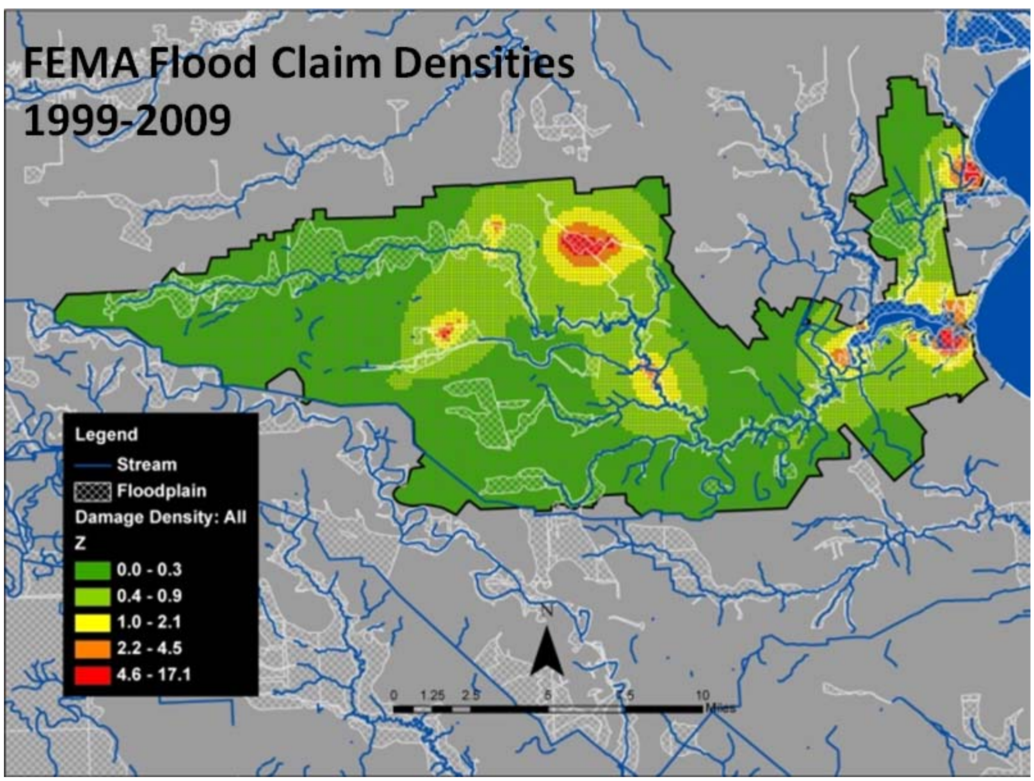


Figure 6-1: Relative Kernel Densities of FEMA Flood Claim Data (Brody, 2012)

Brody performed a kernel density analysis on all of the flood claims in the Clear Creek Watershed, and interestingly enough, most of the hot spots are located outside major channels (Figure 5-1). Access to such data as these opens up a plethora of opportunities for model validation, demographic analyses, and investigation of flood-prone areas. Potential future studies may focus on investigating flood claim hotspots, particularly those outside of the FEMA 1% annual chance floodplain, and determining whether flooding is due to rainfall-runoff, storm surge, or both. A two-dimensional model such as XPSWMM (Bedient, 2012) could additionally be implemented in a subarea between I-45 and FM 2351 to examine rainfall-runoff and storm surge interactions on a street-level, incorporating important factors such as underground drainage systems.

Another area of future study, which has the potential to be very impactful, would be the development of a flood-alert system in the Clear Creek Watershed. The framework of the model would be similar to the Texas Medical Center Flood-Alert System (TMC FAS), which predicts streamflow hydrographs based on current NEXRAD radar rainfall data. Furthermore, storm surge could potentially be incorporated into the flood-alert system to predict inundation depths using a hydraulic model such as the one presented here. Since the ADCIRC storm surge model produces storm hydrographs in real-time, the unsteady HEC-RAS model in this study needs only to be adapted for real-time implementation. The process behind running HEC-RAS for a flood-alert system is currently being researched because it is more complicated than only using HEC-1 (the script version of HEC-HMS). For this reason, most flood-alert systems today focus on hydrology rather than hydraulics (Bedient, 2012). However, the work required to use HEC-RAS in a storm surge flood-alert system would be well worth it if residents and emergency managers can receive real-time information on damage potential, water depths, and times for floodwater recession during a hurricane.

The work presented within has the potential to be very impactful for the Clear Creek Watershed and other areas along the U.S. Coast. Since HEC-HMS and HEC-RAS are freeware and some of the most widely used and reliable inland flood models, and since ADCIRC is already set up to run all along the U.S. East and Gulf Coasts, this research can potentially be applied to any area in the U.S. that is vulnerable to hurricanes. Preparedness is vital in a world prone to increases in weather and climate extremes, and this research brings us one step closer to being aware of and ready for the dangers that lie ahead.

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