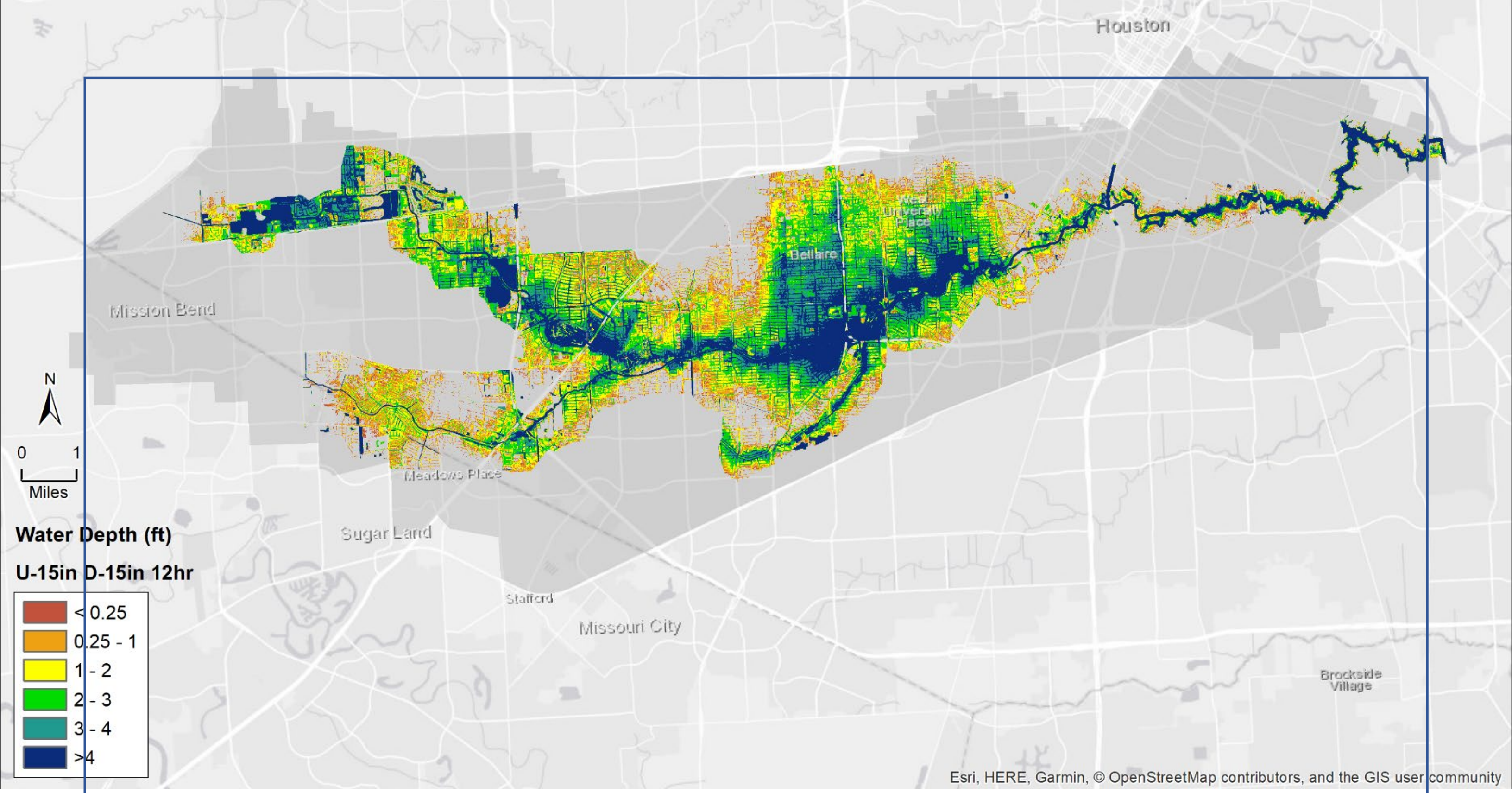


# Flood Information and Response System for the City of Houston, Texas (FIRST)

*Project Report*

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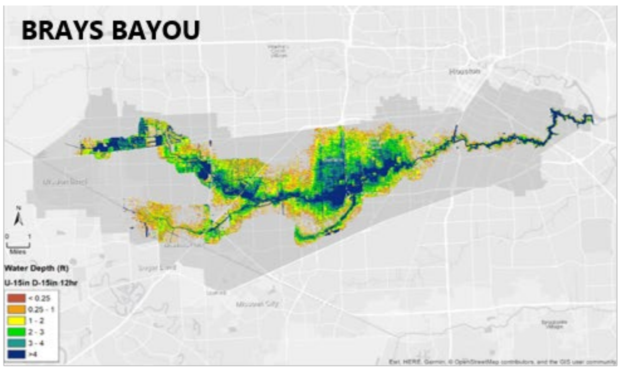
# EXECUTIVE SUMMARY

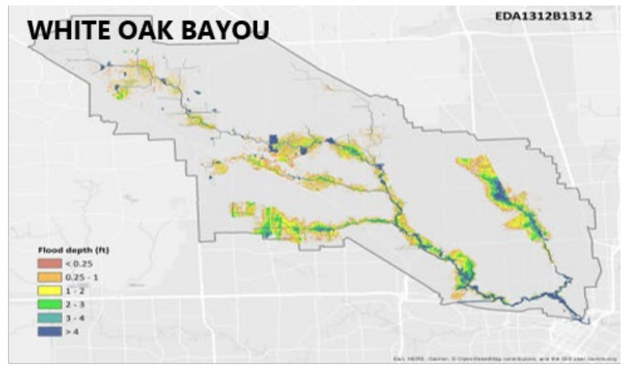
The City of Houston (COH) has funded Rice University and the SSPEED Center (through the CARES Act) with developing an initial flood warning system for four watersheds within the city. This would provide the COH with real-time rainfall and flood information for its use in assessing critical facilities, such as hospitals, nursing homes, shelters, and WWTPs during the spread of the SARS Covid-2 virus. This report summarizes the effort undertaken to develop this system, known as the Flood Information and Response System (FIRST), with funding in October 2020.

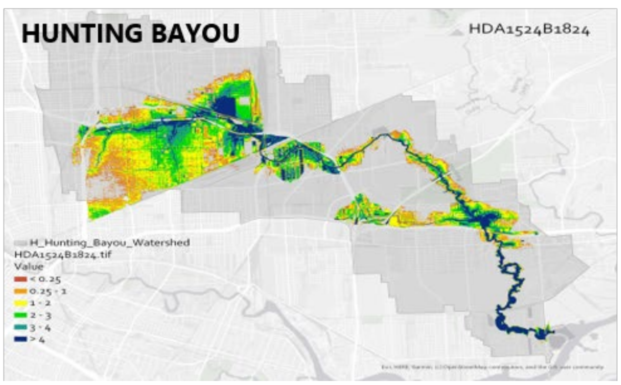
The FIRST has been developed by a joint research team directed by Dr. Bedient from the SSPEED Center at Rice University and the Fang Research Group (FRG) at the University of Texas at Arlington (UTA). The project team consisted of consultants, post docs, and students at both universities. The system currently covers four major watersheds: Brays Bayou, White Oak Bayou, Hunting Bayou, and Sims Bayou at Sunnyside. The state-of-the art of this FIRST system can (A) display rainfall intensity for all the sub-catchments of the four major watersheds in real time, and (B) forecast the flood inundation maps over the watersheds using NEXRAD radar rainfall data provided by Vieux & Associates, Inc., one of the best radar rainfall data providers in the nation.

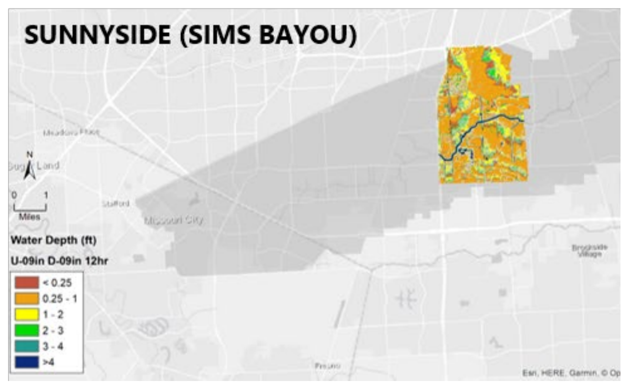
Given the popularity of ArcMap Online, a web-based mapping application provided by ESRI, the FIRST system is able to display the floodplain inundation maps within the ArcMap online map frame, serving as the main platform. Computer models (HEC HMS and HEC RAS) were obtained from the Harris County Flood Control District's M3 Library that had been used to develop the floodplain maps adopted by FEMA for the Harris County floodplain mapping program as part of its Tropical Storm Allison Recovery Project (TSARP) in the early 2000s. These models were then updated as needed to reflect recent flood control projects that had been implemented since that TSARP work, such as Project Brays and the White Oak Flood Reduction Project. In addition, for the Sims Bayou watershed, since the focus of this project in that watershed was on the community known as Sunnyside, a 2D HEC-RAS model was also developed to simulate the hydrologic and hydraulic response to excess rainfall over that specific area of the watershed. All of these models were validated by simulating recent tropical storm events, such as Harvey (2017), Imelda (2019) or Beta (2020), and comparing the results to observed data at selected stream gages along the various bayous in these four watersheds.

These updated and validated models were then used to simulate a suite of rainfall patterns from 5 inches up to 18 inches over 6 to 24 hours that might occur over the upper and lower portions of each watershed in order to develop a library of floodplain inundation maps to be displayed by the ArcMap on-line map frame as radar rainfall is collected and analyzed in real-time. Approximately 75 maps (Floodplain Map Library FPML) were generated within ESRI GIS, so that they can be selected based on real time 15 min rainfalls crossing the Houston areas. By then evaluating critical facilities slab elevations, it is possible to predict inundation (within 1.0 ft) based on this highly accurate system. THE figures below shows a sample of the FPML maps for the four watersheds based on months of analyses.



# I. INTRODUCTION

Flash flooding is not new to Houston. Rapid urbanization of the region, however, has exacerbated the local flood vulnerability, especially in recent years (e.g., 2010, 2015, 2016, 2017, and 2019). Most recently, the devastating flood caused by Hurricane Harvey (2017) raised a great deal of attention and concern from the City as well as the public. The potential flood impacts on wastewater treatment plants as one of Houston's critical infrastructure pose a significant threat on the City's current and future resilience goals. While additional improvements to existing structural measures are necessary to reduce risks for future flooding in the Houston watersheds, non-infrastructural solutions such as real-time flood information and mapping systems are necessary to provide timely data for facility operators, emergency personnel, and the general public during severe storm events.

The performance and reliability of urban flood warning and mapping systems have improved substantially over the last decade, owing to the availability of NEXRAD radar precipitation and advancements in GIS. As a result, real-time, spatially-distributed rainfall that is rapidly updated can be used by hydrologic/hydraulic models to estimate surface runoff, peak discharge, and inundation levels more accurately for specific areas of interest. One particular system, the Rice/Texas Medical Center FAS (see **Figure 1.1**), has been providing reliable hydrologic and flood warning information for the Texas Medical Center since 1997 for over 60 storm events with a forecast $R^2$ value of 90%. The system utilizes the NEXRAD Level II radar/rainfall data coupled with hydrologic/hydraulic models, and a floodplain map library (65 maps) that delivers vital flood information with up to 2-3 hours in advance. It has a user-friendly dashboard that allows users to visualize rainfall progression, Google Maps-based inundation extents, flood alert levels, hydrologic predictions, and real-time monitoring via cameras at the bayou.

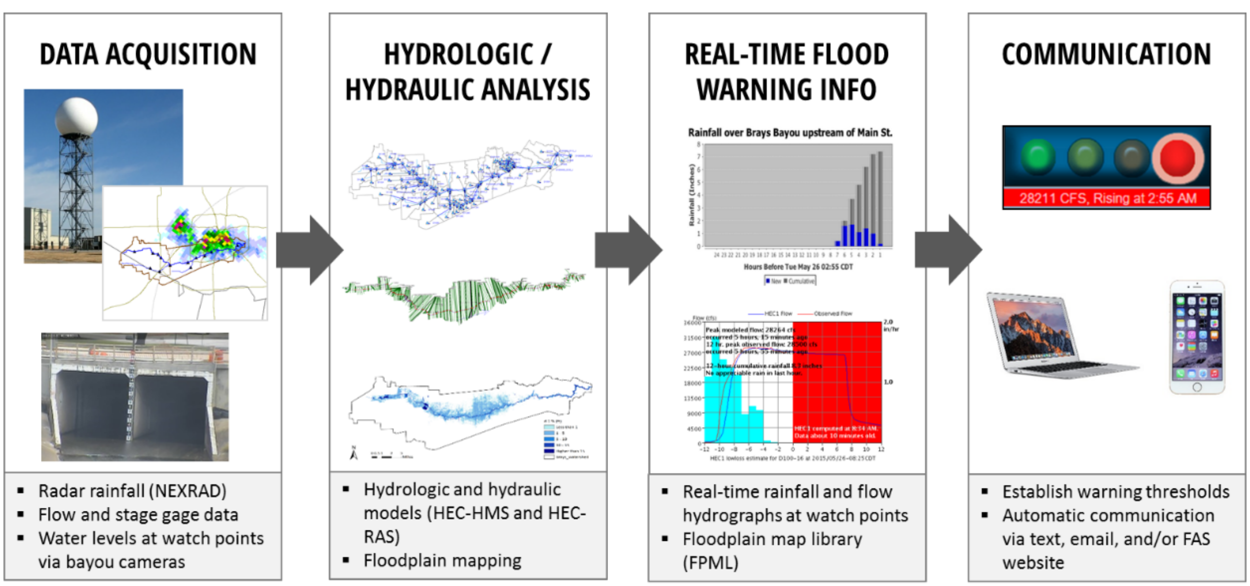



**Figure 1.1** The Rice-Texas Medical Center Flood Alert System flowchart

At the request of the Houston Health Department (HHD), City of Houston (COH), the SSPEED Center at Rice University was tasked with developing an initial flood warning system for 4 watersheds within the city that would provide the city with real-time rainfall and flood information. This report summarizes the effort undertaken to develop this system, known as the Flood Information and Response System (FIRST).

## PROJECT GOAL

The goal of this project was to develop and implement an end-to-end radar-based flood information and response system (FIRST) as a flood assessment and mapping tool for critical infrastructure within the City of Houston (COH). This system allows for early warning of potential flooding with real-time visualizations of critical hotspots and/or inundated areas during storm events. The system will assist the City of Houston (COH) in addressing emergency management/operations, including emergency closures and evacuation, as well as rescue operations. The system utilizes the results of calibrated hydrologic and hydraulic models, the local rain gauge network, NEXRAD radar precipitation data in real time, and the existing flood warning framework developed by the SSPEED Center at Rice University to provide reasonably reliable, real-time flood information.

The project developed this Flood Information and Response System (FIRST) for four watersheds: Brays Bayou, White Oak Bayou, Hunting Bayou, and Sims Bayou/Sunnyside (see **Figure 1.2**), which include many of the neighborhoods and facilities of interest to the COH, such as hospitals, nursing homes, fire stations, and wastewater treatment plants (WWTPs). The successful implementation of this flood information system will serve as a template to later expand to other flood-prone locations in the COH.

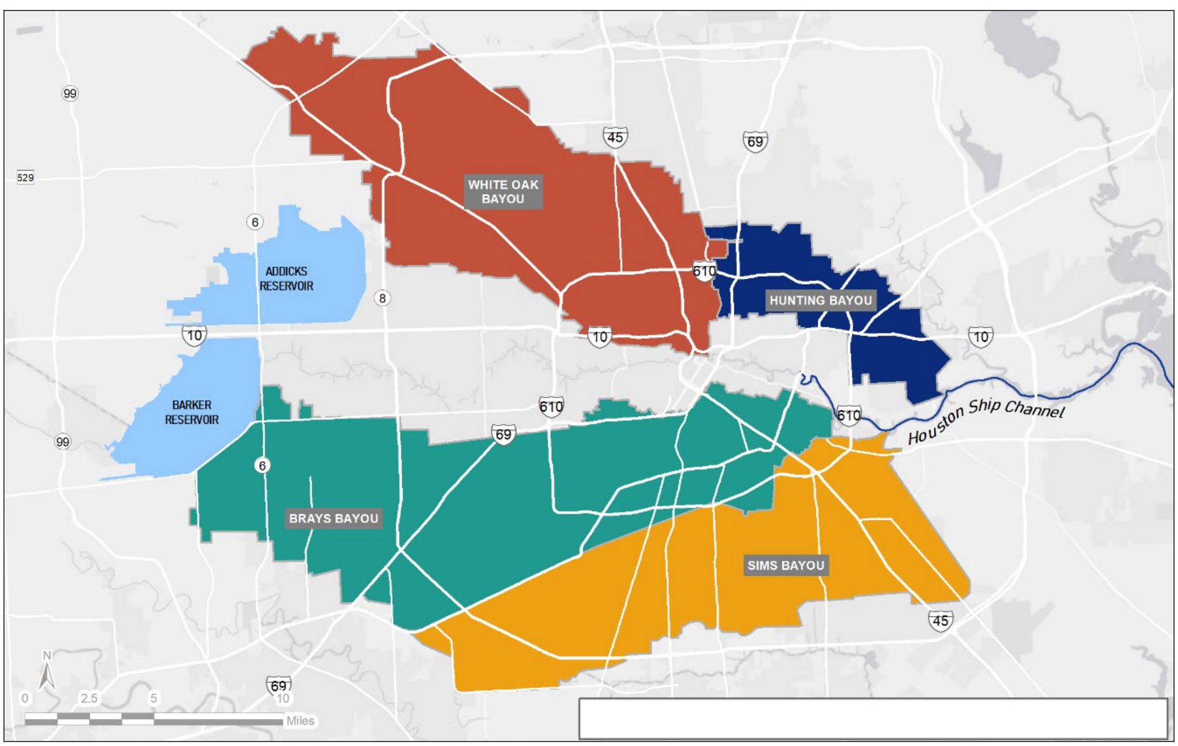



Figure 1.2 Location of the Four Watersheds Included in the FIRST Project

## WORK TASKS

The various tasks performed during this FIRST project, and discussed in more detail in this report, are outlined below.

### TASK 1 | MEET WITH HEALTH DEPARTMENT AND OTHER COH OFFICIALS

Conduct a meeting with primary stakeholders, including emergency management officials, environmental and health experts, and first responders from the COH to discuss project objectives, scope, timeline, and logistics (e.g., establish points of contact, communication and distribution of warning information, operation / emergency response procedures, etc.).

### TASK 2 | COLLECT & ANALYZE RELEVANT DATA

Obtain the necessary data from available gauges, existing H/H models, radar rainfall data, topographic/spatial datasets, land use, historical flood data, and other pertinent information for model development and calibration. The data collection process will also be used to assess whether currently available data are sufficient to develop accurate H/H models for the selected areas of interest as outlined in **Tasks 3-5**, and also help identify high-risk areas that lack measured data for model validation. We will collect data from various bayous, watersheds, sources and agencies (HCFCD, COH, NWS, USGS, USACE, etc.) to identify the high risk wastewater lift stations/facilities that could overflow and pose risk of exposure to communities. The Stadler Team at Rice will complete the SARS-CoV-2 Assessment.

### TASK 3 | EVALUATE HYDROLOGIC & HYDRAULIC MODELS

- Develop, validate, and/or calibrate hydrologic models for the project;
- Evaluate the validated / calibrated hydrologic models using the rainfall information from recent floods such as Hurricane Harvey (2017), Tropical Storm Imelda (2019), and Tropical Storm Beta (2020);
- Evaluate radar rainfall and gauge rainfall data. An additional software routine will automate the input of radar rainfall into a Data Storage System (DSS) file as input into the flood information system.

### TASK 4 | PERFORM DETAILED HYDRAULIC ANALYSES FOR THE SELECTED WATERSHEDS

- Perform hydraulic analyses for the selected watersheds and validate hydraulic performances (i.e. stage) against observed data from recent historical events;
- Develop correlations for critical elevations for the selected communities within the watersheds of interest and establish alert (water elevation) thresholds for emergency responses (e.g., road closures), structural flood damage, and/or other critical flood levels.

### TASK 5 | DEVELOP & TEST THE PROPOSED FLOOD INFORMATION SYSTEM

- Develop the proposed flood information system by integrating various modules (i.e., rainfall, flood prediction, and warnings/communication) using the established FAS4 framework;

- Evaluate statistical analyses to investigate rainfall patterns, durations, and intensities of historical rainfall events (e.g., past 20 years) over the selected watershed. The results will be used to generate the corresponding hydrographs, floodplain maps, and cross-section water profiles;
- Associate particular rainfall patterns, floodplain maps, and water surface profiles triggered by real-time rainfall measurements during actual rainfall and watershed conditions;
- Generate a database of pre-simulated floodplain maps (Floodplain Map Library), and cross-sectional water-surface profiles for the flood information system;
- Validate the determined thresholds at selected points of interest with recent events. Adjustments will be made as necessary to improve system performance.

### TASK 6 | DEVELOP WEB-BASED FLOOD INFORMATION SYSTEM

- Develop and test the proposed wastewater overflow information system by integrating the different modules as shown in **Figure 1.1**. The proposed assessment will include the overflow Floodplain Map Library (FPML), a tool that demonstrates inundation extents under various spatial / temporal and overflow conditions;
- Design and develop a centralized web system using the data platform at HHD and one at Rice University to assess overflow levels for the selected facilities and neighborhoods by integrating real-time access to local overflow and stream gauges and at least one bayou camera.
- Provide a list of facilities which are currently most at risk of wastewater overflows, and thus spread of SARS-CoV-2 and other pathogens in waste, due to flooding, failure of wastewater treatment plant, or other similar events. The Stadler Team at Rice will complete the SARS-CoV-2 Assessment.

## TASK DEADLINES

| Tasks | | OCT '20 | NOV '20 | DEC '20 |
|---|---|---|---|---|
| 1 | Meet with Health Department and other COH Officials | ■ | | |
| 2 | Collect & Analyze Relevant Data | ■ | ■ | |
| 3 | Evaluate hydrologic & Hydraulic Models | ■ | ■ | |
| 4 | Perform detailed Hydraulic Analyses for the Selected Watersheds | | ■ | |
| 5 | Develop & Test the Proposed Flood Information System | | | ■ |
| 6 | Develop Web-Based Flood Information System | | | ■ |

**This report represents the methods and completed tasks for the FIRST project funded through the City of Houston Health Department as of December 21, 2020.**

# II. DATA COLLECTION

## HYDROLOGIC AND HYDRAULIC MODELS FOR THE 4 WATERSHEDS

Hydrologic and hydraulic models were needed for this FIRST project and were obtained from the Harris County Flood Control District (HCFCD) (see Reference). The District developed and calibrated/validated these models as part of its Tropical Storm Allison Recovery Project (TSARP) in the early 2000s and used them to prepare the FEMA floodplain maps for Harris County. The District maintains these models in its M3 library and that is the source from which the hydrologic and hydraulic models used for this project were obtained. The following references relate to general and urban hydrology: Bedient, Philip B., et al., 2019; Brody, Samuel, et al., 2014; Brody, Samuel D., et al., 2008; Garner, Morgan, 2020; Gori, Avantika, 2018; Holmes, Cheryl, et al., 2018; Juan, Andrew, et al., 2020; Klijn, Frans, et al., 2015; Sebastian, Antonia, et al., 2019. The following reference relates to hydrologic models: Hydrologic Engineering Center, 2019, 2020.

## RADAR RAINFALL DATA

Gage-adjusted radar rainfall (GARR) data is provided from Vieux and Associates, Inc. (VAI), a firm that specializes in obtaining, calibrating and disseminating radar rainfall data for various agencies, including the HCFCD. This radar rainfall data was obtained from VAI for the storm events used for calibration/verification of the hydrologic and hydraulic models for the 4 watersheds analyzed for this project. Radar rainfall data will also be collected from VAI in real-time and used to establish the magnitude and duration of rainfall in the 4 watersheds so that the appropriate floodplain maps can be selected for display. This radar rainfall data will also be provided by VAI directly to the COH for its use in real-time. The following references relate to radar rainfall conversion to runoff: Bedient, Philip B., et al., 2000; Bedient, Philip B., et al., 2003; Vieux, B. E., et al., 2005; Vieux, Baxter E., 2006.

## SPATIAL DATASETS (TERRAIN / LIDAR, LAND USE, STREAM GAGES)

Additional datasets were obtained as needed for this project. For example, ground elevation data (terrain data) for these 4 watersheds were obtained from the 2018 LIDAR dataset available for Harris County from TNRIS (https://tnris.org/). In addition, 2016 land use data for the Sunnyside 2D model were obtained from the USGS National Land Cover Database (NLCD). Finally, stream gage data for the historic storms analyzed were obtained both from the HCFCD Flood Warning System (https://www.harriscountyfws.org/) and from the USGS (https://maps.waterdata.usgs.gov/mapper/index.html)for their respective gages in the 4 watersheds. The following references relate to data collection: HCFCD, 2019; Perica, Sanja, et al., 2018; McCuen, Richard H., et al., 2006.

## CRITICAL FACILITIES IN THE COH

Various critical facilities located in the City of Houston were identified using a national database known as Homeland Infrastructure Foundation Level Data (HIFLD). Such facilities include hospitals, fire stations, nursing homes, and storm shelters.  From this list, a handful of critical facilities were selected for use as "watch points" at which pertinent flood information will be provided as part of the FIRST project.

# III. HYDROLOGIC AND HYDRAULIC ANALYSES

## METHODOLOGY OVERVIEW

The hydrologic and hydraulic analyses that were conducted for this FIRST project were based on the M3 models obtained from the HCFCD, which use the Corps of Engineers' HEC suite of computer model software developed over the years for such analyses. For the hydrologic analyses, the model used is based on the software program for a Hydrologic Modeling System (known as HEC-HMS); and for the hydraulic analyses, the model used is based on the program for a River Analysis System (known as HEC-RAS).

### HEC-HMS

The HEC-HMS flood hydrograph package was developed by the Corps' Hydrologic Engineering Center (HEC) beginning in 1973. HEC-HMS can be used to transform historical rainfall events or design rainfall into runoff via standard unit hydrograph (UH) methods. The process of converting precipitation to direct runoff can be simulated for either small subbasins or large complex watersheds. A typical HEC-HMS model for any river basin has basic components for subbasin runoff, channel and reservoir routing, and hydrograph combining. Subarea boundaries are delineated so that lumped precipitation loss and watershed parameters can be used. The computations proceed from upstream to downstream in the watershed, and hydrograph data or plots can be provided for any subbasin or junction point. The flood routing component in HEC-HMS requires input parameters to define the specific routing characteristics of a river reach or reservoir. An example of a typical HEC-HMS model set-up for a watershed is shown in **Figure 3.1**. The latest version of HEC-HMS is referenced HEC-HMS, 2020.

The HEC-HMS input parameters, such as rainfall and subbasin characteristics, as well as the transformation methods used, are described in more detail in Appendix A. The primary output from this model consists of flow hydrographs at the downstream junctions. These flow hydrographs were then used both to compare to historical storms to validate the model, as well as to determine peak flows for input into the HEC-RAS model (**Figure 3.2**).

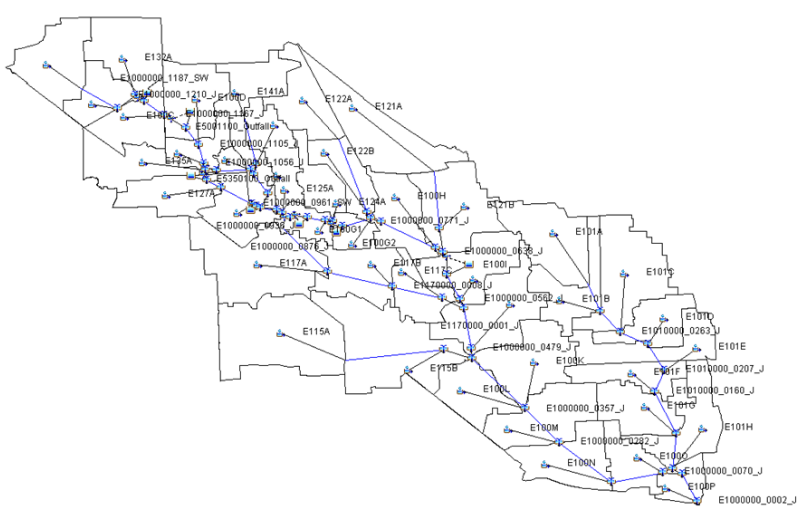


Figure 3.1 Example of Typical HEC-HMS Model Set-up

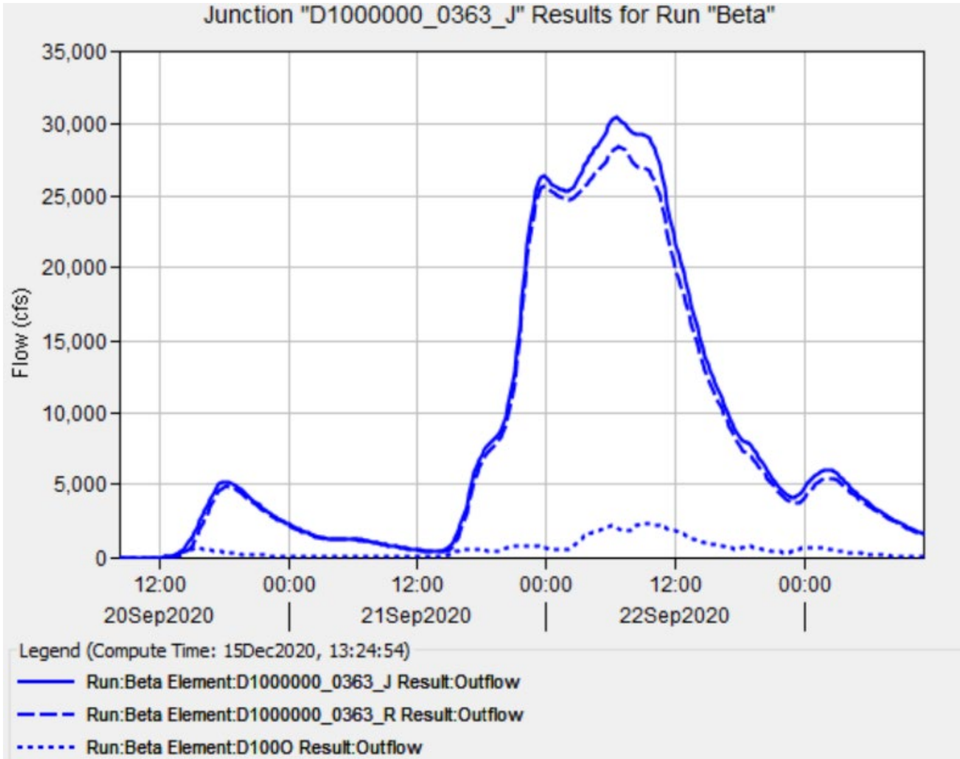



Figure 3.2 Example of Output Flow Hydrograph from HEC-HMS

## HEC-RAS

HEC-RAS was developed in 1995 as an upgrade to the old HEC-2 hydraulic model created by the Corps' HEC. This software program is designed to perform hydraulic modeling in order to calculate water surface profiles for steady, gradually varied flow in natural or man-made channels. The hydraulic modeling program can be applied to floodplain management and flood insurance studies to evaluate floodway encroachments and to delineate flood hazard zones. This model can also be used to evaluate effects on water surface profiles due to channel improvements and levees, altered flow values, and the presence of bridges or other structures in the channel or its floodplain. The latest version of HEC-RAS is referenced HEC-RAS, 2019.

The main objective of the HEC-RAS program is to compute water surface elevations at cross-section locations of interest along a river or stream, for given flow values. Data requirements include flow regime, starting downstream water elevations, flow rates, loss coefficients, channel and floodplain roughness, cross-sectional geometry, and reach lengths. Water surface profile computations begin at the downstream channel cross- section with known or assumed starting conditions and proceed upstream for subcritical, steady-state one-dimensional (1D) flow, which is most often the case for Houston watersheds.

The HEC-RAS program is often used in association with the HEC-HMS program for determination of both flood flows and flood elevations within a particular watershed. Peak flows at various locations along the main channel are computed by HEC-HMS for a given rainfall. These peak flows are then used in HEC-RAS to calculate the steady-state, nonuniform water surface profile along the stream. For example, the 100-

year rainfall could be inputted into HEC-HMS to calculate 100-year flows, which then could be inputted into HEC-RAS to predict the 100-year flood levels and floodplain extent. More information on the computations used in HEC-RAS can be found in **Appendix A**.

HEC-RAS requires the user to select all the cross-sections along a stream reach where a change in flow occurs. These changes in flow are often based on the peak flows found at different junctions in the HEC-HMS output for that watershed. Once a flow is selected for a cross-section, that flow is used on all cross-sections upstream of the first until the model encounters a different flow. **Figure 3.3** shows a typical RAS model set-up of cross-sectional data to determine the floodplain for a stream.

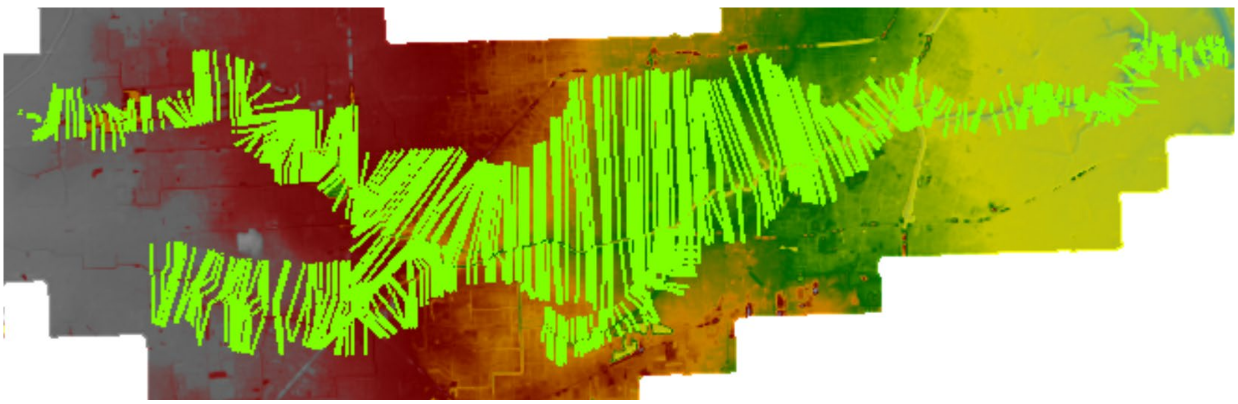


Figure 3.3 Example of Typical HEC-RAS Model Set-up

For simpler hydraulic analyses, only the energy equation is used, and the flow is assumed to be steady because time-dependent variables are not included in the energy equation. The typical output of a steady flow hydraulic model is the maximum flood profile along the channel for producing its associated floodplain, based only on the peak flows at selected cross-sections, and does not reflect variations of flood depth with time (See **Figure 3.4**). When flow conditions do vary with time at a discrete location, the flow is classified as unsteady.

The latest version of HEC-RAS allows for the analysis of unsteady 1D flow along a channel and its floodplain, allowing the user to view the change of flood depth as a function of both space and time. The Unsteady NETwork simulator (UNET) was modified for HEC-RAS to allow for this analysis of one-dimensional unsteady flow through a full network of open channels. In this way, one can visualize a complete flood event as it moves downstream.

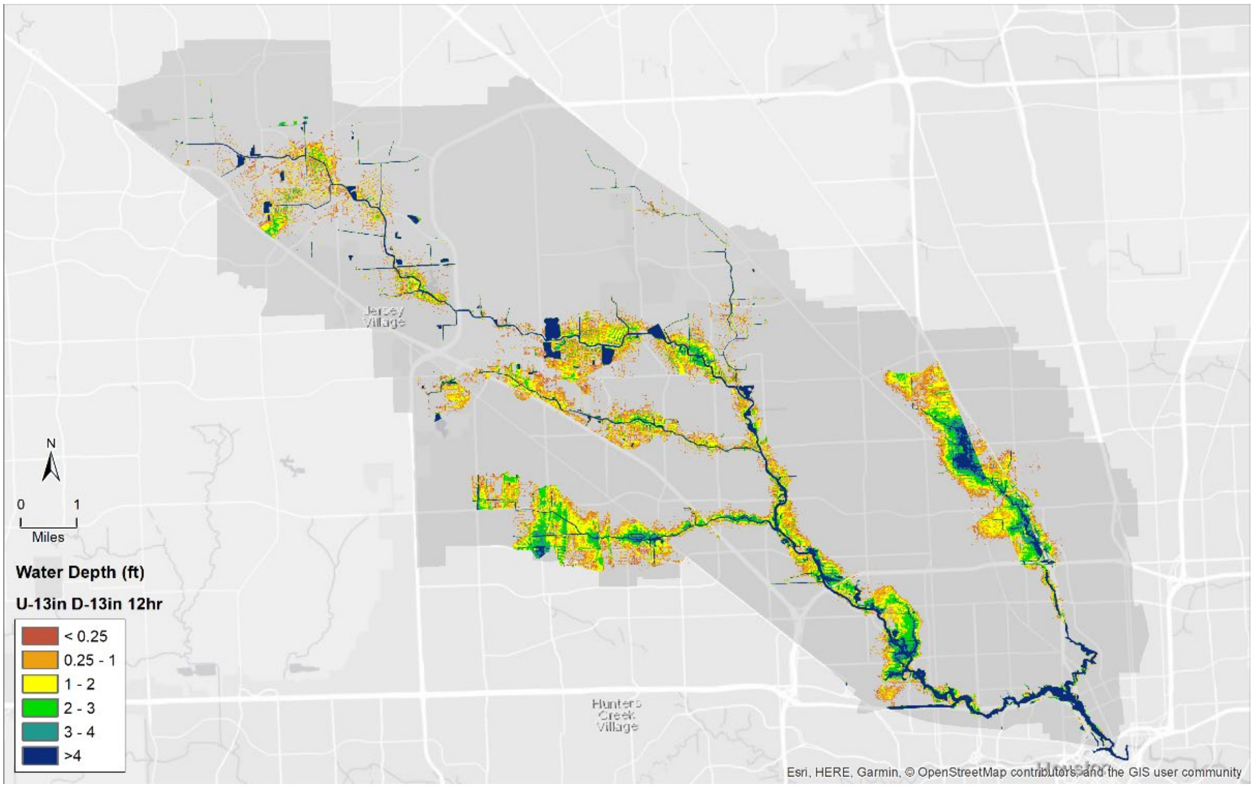


Figure 3.4 Example of Typical HEC-RAS Produced Floodplain

## HEC-RAS 2D

In 2016, the HEC released an updated version of HEC-RAS (5.0), allowing for two-dimensional (2D) modeling of flow. This FIRST project uses HEC-RAS version 5.0.7 for conducting both the 1D and 2D hydraulic analyses. In 2D modeling, flows and velocities are calculated in two dimensions (both the x and the y directions at each cell face, allowing for lateral flows in addition to the traditional downstream flows). Unlike in 1D, where hydraulic calculations are completed only for representative cross-sections of the channel and its floodplain, calculations in 2D are computed in every cell of a grid-like computational mesh. This means that a water surface elevation is computed throughout the entire 2D domain, being at every point in the channel and its floodplain, whereas in 1D a single water surface elevation is computed only at every cross-section. A 1D hydraulic model can only simulate riverine flooding, but a 2D model can analyze both riverine and pluvial (overland) flooding since a computational mesh is created across the entire model domain. **Figure 3.5** shows the difference in the two model results.

Unlike in one dimensional modeling, HEC-RAS 2D requires that the model be run only as unsteady. In the unsteady flow input file, users enter upstream and downstream boundary conditions and any rain-on-grid precipitation (if desired). The 'rain-on-grid' feature of HEC-RAS 2D combines certain hydrology concepts with hydraulics by allowing the user to directly input precipitation (hyetographs) onto the 2D mesh area. It is important to note that HEC-RAS version 5.0.7 and earlier do not have the ability to calculate for infiltration losses, so a hydrologic program such as HEC-HMS will need to be utilized beforehand to calculate the losses and the resulting excess rainfall for use as the appropriate precipitation input.

Behind the scenes, HEC-RAS 2D is simultaneously solving the continuity and momentum equations. More information on the computations associated with HEC-RAS 2D can be found in **Appendix A**.

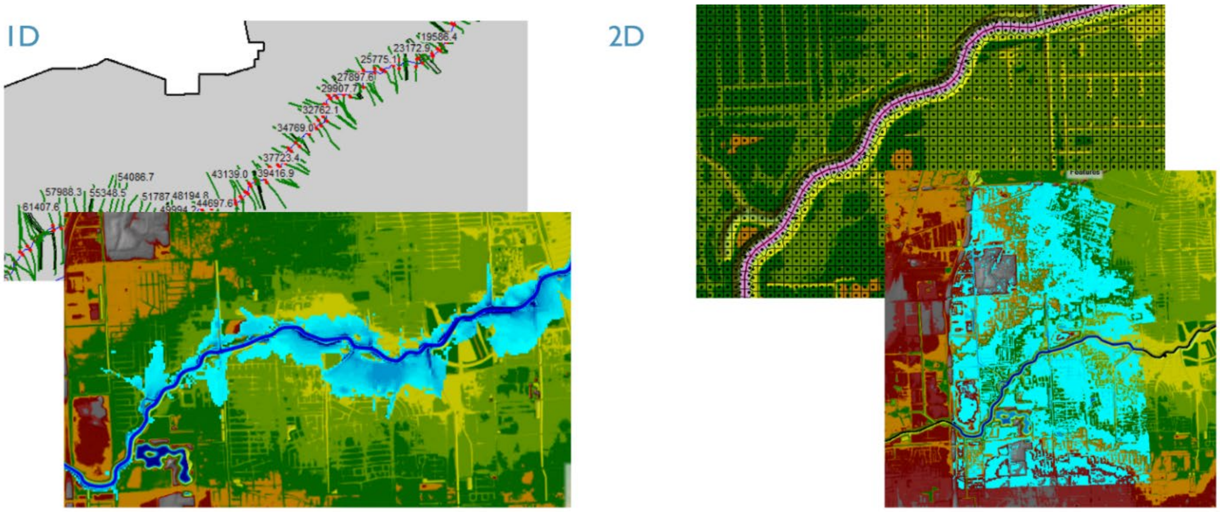



Figure 3.5 Display of 1D vs 2D HEC-RAS Modeling Differences

## BASELINE MODEL SETUP AND VALIDATION/CALIBRATION

The models that were obtained from the HCFCD had been developed and calibrated during the TSARP effort in the early 2000s. Since then, we have had significant rainfall events in the Houston area, especially associated with hurricanes or tropical storms, such as Harvey (2017), Imelda (2019) and Beta (2020). As part of the FIRST project, these HCFCD models were run for these three storm events to determine if there needed to be any significant adjustments made to these models so that they would be able to provide reasonably reliable flood information for use in this FIRST project, including updates due to flood reduction projects that have been implemented since TSARP (such as Project Brays and the White Oak Bayou Project). Below is a discussion of this calibration/verification effort for each of the 4 watersheds analyzed for this project.

## HISTORICAL STORMS FOR CALIBRATION

Three historical storms were used to validate both the HEC-HMS and HEC-RAS models: Hurricane Harvey (2017), Tropical Storm Imelda (2019), and Tropical Storm Beta (2020). These three storms caused major flooding in the past three years and had a variation in magnitude and duration to be suitable for model validation. Recent storms like these are important for validation since land use and channel morphology can change over time. The models for Brays Bayou, White Oak Bayou, and Hunting Bayou were validated using all three storms above, while Sims Bayou was only validated using both Imelda and Beta.

Hurricane Harvey caused devastating flood events in Houston in August 2017. The flooding led to an unprecedented total damage of $125 billion, the highest in the history of flooding nationwide. Hurricane Harvey first made landfall in south-central Texas on August 25th, 2017 as a Category 4 hurricane with 130 mph winds. Then, it was downgraded to a tropical by August 26th and continued to dump rain on Southern

Texas and Houston until it began to move north on August 30th. Some areas of Houston received over 60 inches of rainfall, and around one third of the city was completely inundated in flood water.

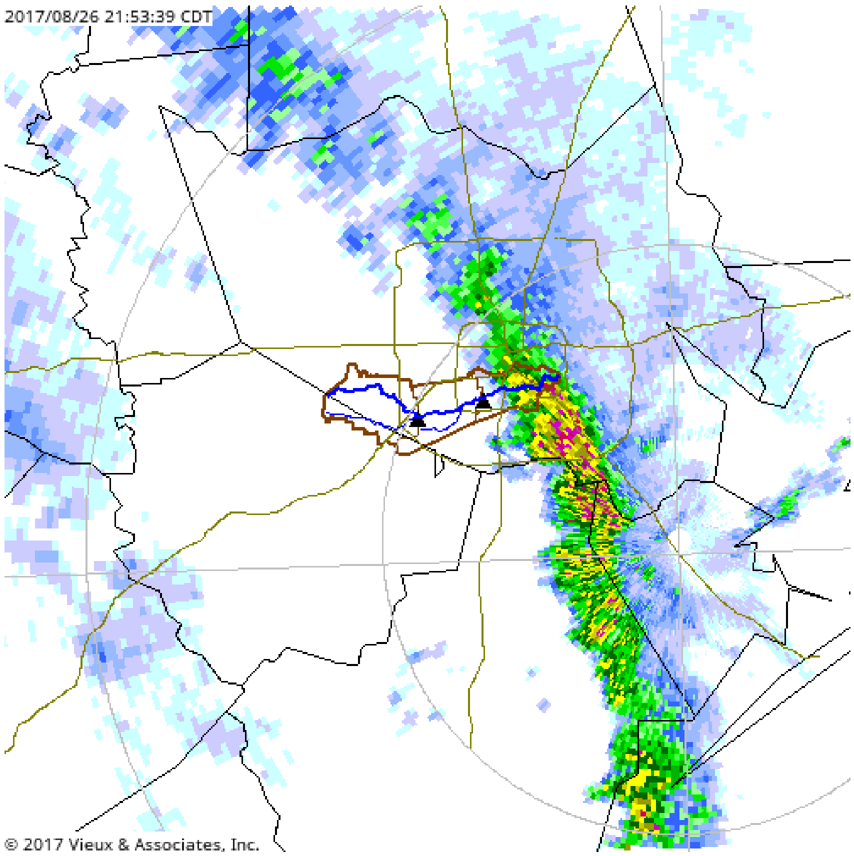



Figure 3.6 Radar Rainfall Image of Hurricane Harvey Hitting Houston in the Evening of Aug 26th, 2017

Tropical Storm Imelda made landfall near Freeport, Texas on September 17th, 2019. It was then downgraded to a tropical depression and dumped significant amounts of rain on the Houston area in the following three days. Imelda was a triple-peak storm event, with some areas in Houston flooded three times. The highest rainfall total was over 44 inches, recorded just east of Houston in Fannett. There was severe flooding in residential neighborhoods and on highways such as the I-10 stretch between Winnie and Beaumont and Interstate 45 north of downtown Houston, submerging vehicles and necessitating evacuations. By September 21st, Imelda had fully dissipated.

Tropical Storm Beta made landfall in Texas on September 21st, 2020. As a slow-moving storm, it caused heavy flooding along the Texas coast through September 22nd, particularly in some southern parts of Houston. Several areas in Houston experienced ten inches of rain and the maximum rainfall of 14.4 inches occurred in Brookside Village just south of Houston. Some neighborhoods and highways (e.g., Highway 288) in Houston experienced local flooding that caused structural and vehicle damage in the morning of September 22nd. The following references relate to flood events in Houston, Texas: Bass, Benjamin, et al., 2017; Bass, B., et al., 2016; HCFCD, 2013.

## SELECTED WATERSHEDS

### BRAYS BAYOU

Brays Bayou is a major tributary to Buffalo Bayou, running from the southwest side of the city to the east. Its watershed is fairly long and narrow, and heavily developed, covering about 130 square miles (see **Figure 3.7**). Its major tributaries include Keegans Bayou and Willow Waterhole Bayou.

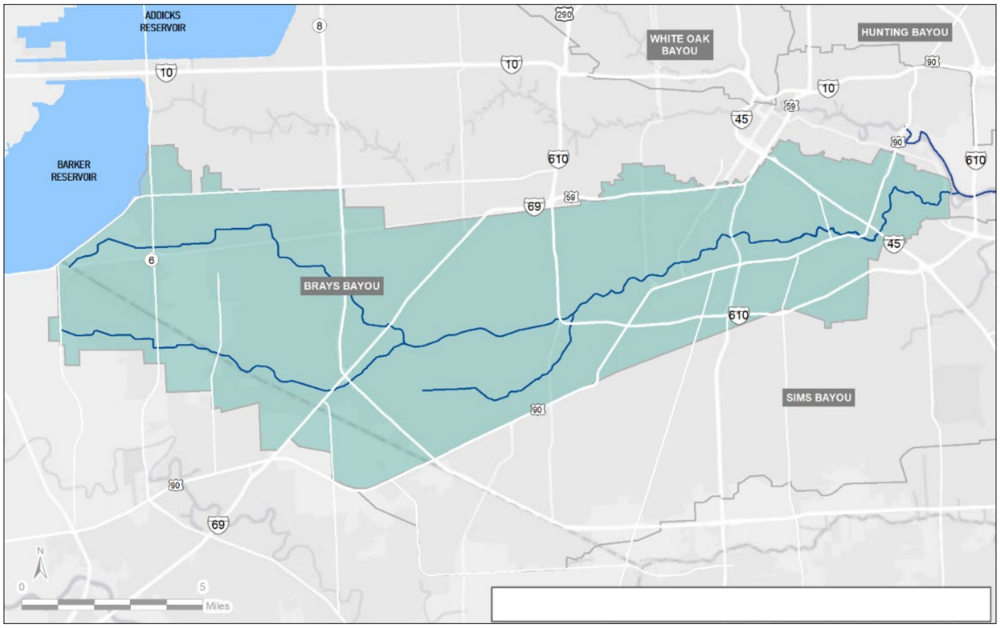



Figure 3.7 Watershed Map of Brays Bayou (ref HCFCD)

*HEC-HMS Modeling*

The hydrologic model used for this project for the Brays Bayou watershed was the HEC-HMS model from the HCFCD M3 Library. This modeling was based on the TSARP work back in the early 2000s and was adopted by Harris County in 2007. The HMS model for this watershed encompasses a number of subareas, as shown in **Figure 3.8**.

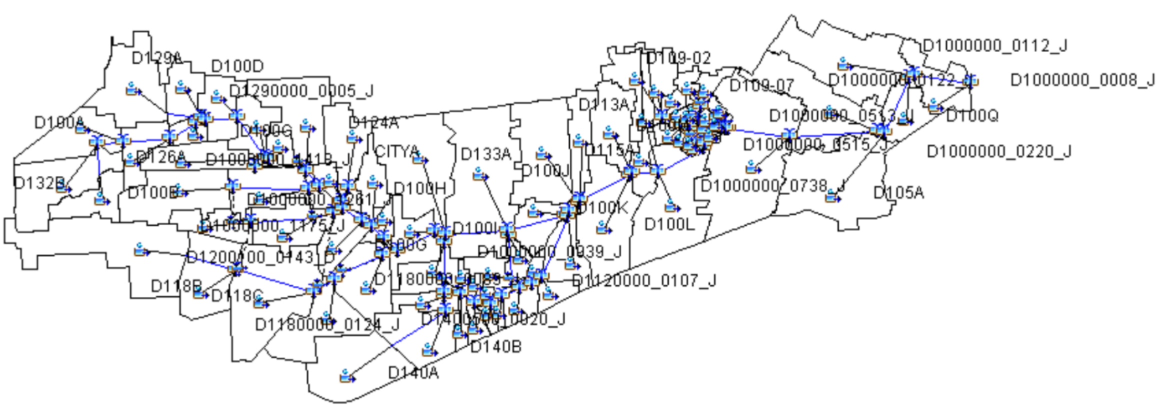



Figure 3.8 HMS Subarea Map of the Brays Bayou Watershed

This HMS model was run for three historic storm events, Harvey (2017), Imelda (2019) and Beta (2020), and the resulting flow hydrographs were compared to the observed streamflow data available from the USGS stream gages located within this watershed. Those USGS gages, as well as the HCFCD gages (that only record water levels), are shown in **Figure 3.9**.

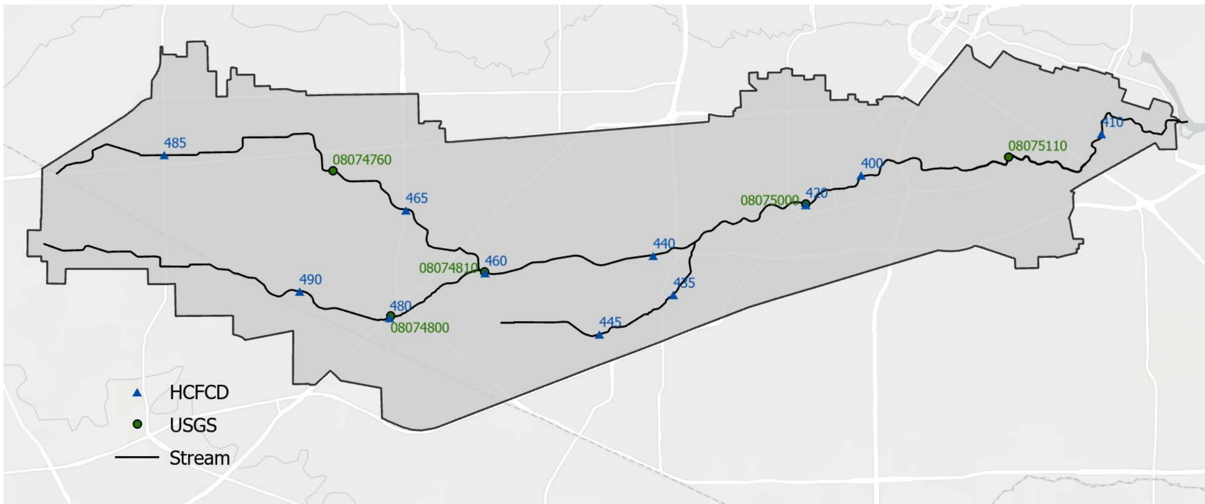



Figure 3.9 Locations of the USGS and HCFCD gages in the Brays Bayou Watershed

The results of the HMS model runs for the three historic storm events using the HCFCD M3 model for Brays Bayou showed reasonable comparisons to the observed data at the USGS stream flow gages. An example of these comparisons are shown in **Figure 3.10** (see **Appendix B** for the complete set of flow comparisons between the modeled results and the observed data).

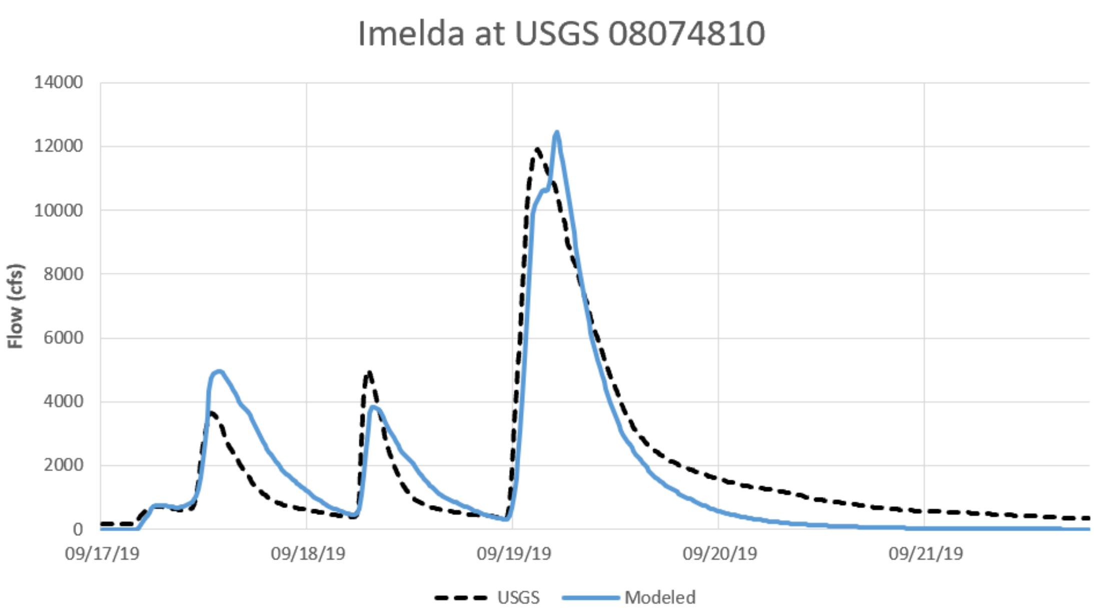



**Figure 3.10a** Comparison of Modeled and Observed Flow Hydrographs for Brays Bayou

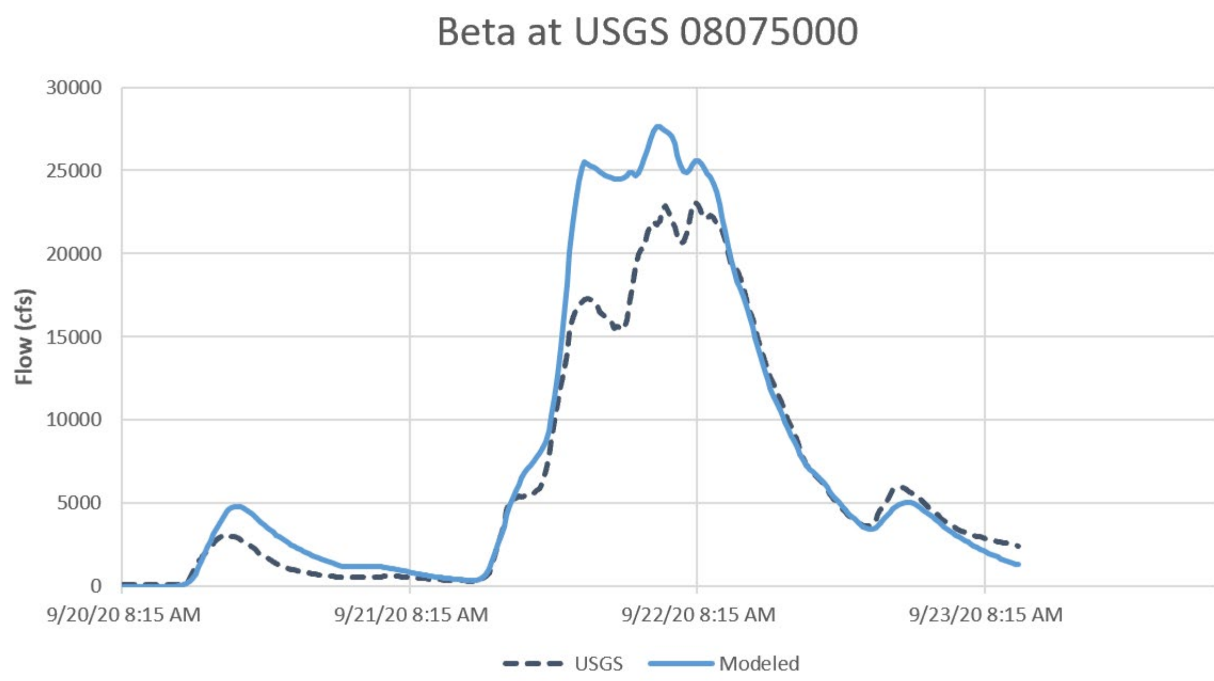



**Figure 3.10b** Comparison of Modeled and Observed Flow Hydrographs for Brays Bayou

An objective analysis was conducted to test the reasonableness of the model results in comparison to the observed data by performing a Nash-Sutcliff Efficiency (NSE) test. An NSE value of 0.5 or greater is an indication that the model is producing reasonably acceptable results. The results of this NSE analysis for the HMS modeling of Brays Bayou watershed are shown in the following table:

Table 3.1 NSE Values for Harvey, Imelda, and Beta

| | 8075000 | 8074810 | 8074760 |
|---|---|---|---|
| **Harvey** | 0.94 | .75* | 0.71 |
| **Imelda** | 0.80 | 0.90 | 0.61 |
| **Beta** | 0.79 | 0.57 | -5.70 |

As shown in the table above, the NSE values are all above 0.5, except for the Beta storm at the downstream-most gage (8074760). Since this is the only one that had a poor comparison, it was determined that the model was acceptable at this time for the purposes of this project.

*HEC-RAS Modeling*

The hydraulic model used for this project for the Brays Bayou watershed was the HEC-RAS model from the HCFCD M3 Library. This modeling was based on the TSARP work back in the early 2000s and was adopted by Harris County in 2007. The RAS model for this watershed encompasses not only cross-sectional data for Brays Bayou, but also its major tributaries, being Keegans Bayou and Willow Waterhole Bayou, as shown in **Figure 3.11**.

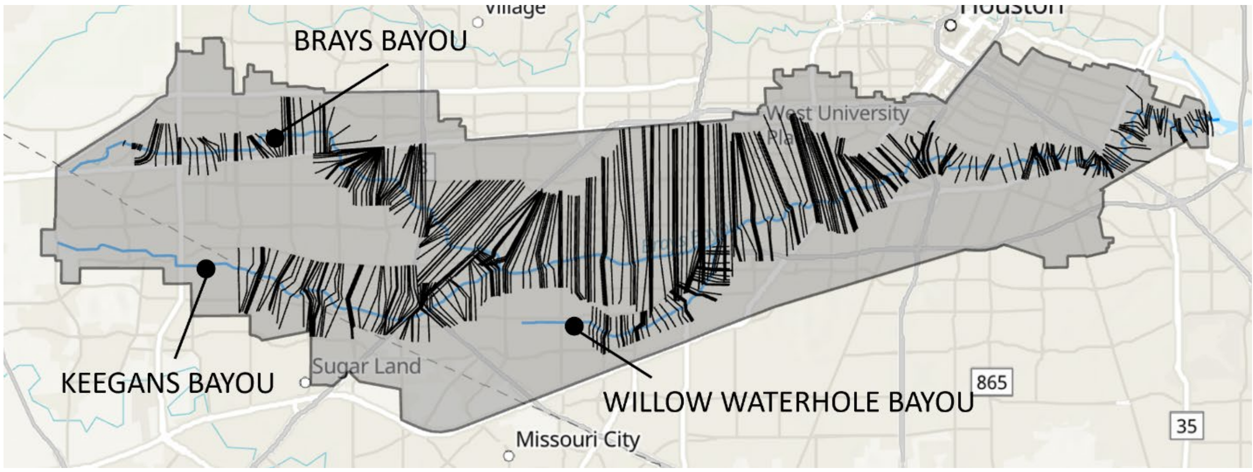



Figure 3.11 HEC-RAS Cross-section Locations for Brays Bayou and its Major Tributaries

Because this RAS model for Brays Bayou was developed in the early 2000s, it does not reflect the on-going channel improvements being constructed along Brays Bayou. This Brays Bayou Flood Damage Reduction Project, commonly known as "Project Brays", is a 480-million-dollar regional flood mitigation project in the Brays Bayou Watershed implemented by the U.S. Army Corps of Engineers (Corps) and the Harris County Flood Control District (HCFCD). In Project Brays, the bayou channel downstream of Fondren Road is being widened, and bridges are being expanded, to improve channel conveyance during a flood event. The effort started in the year 2006 and is expected to finish in 2021.

It is important that this project uses the most updated condition of the Brays Bayou channels, including changes from Project Brays. To apply these changes into the HEC-RAS model, we modified the cross-sections of the Brays Bayou where channels were widened. For channel work that was completed before 2018, we modified our HEC-RAS cross-sections based on the 2018 Lidar Data published by the Texas Natural Resources System. These cross-sections are recreated in HEC-RAS using the 2018 Lidar data, so that they represent the completion state of the channel widening in Project Brays. For channel work that was completed in and after 2018, we modified our HEC-RAS cross-sections based on construction drawings provided by HCFCD.

We have also added hydraulic models of Keegans Bayou and Willow Waterhole Bayou, two flood-prone tributaries of the Brays Bayou, to our main HEC-RAS model by using the stitching function of HEC-RAS geometry editor. The function allows users to add tributaries to the main reach by connecting the outlet of the tributaries to the main reach. Both models of the tributaries were obtained from HCFCD's M3 database with no other changes made.

The RAS model was run for the three historic storm events using the peak flow values obtained from the HMS modeling of those storms for this watershed. The resulting computed peak water surface elevations from this RAS model were compared to the observed peak levels reported at the various HCFCD gages along these bayous, as shown in the table below. The average difference is generally around 1 foot, but such differences may reflect inclusion of Project Brays features into HEC-RAS.

Table 3.2 HEC-RAS validation results comparison

| HCFCD | Imelda | | | Beta | | | Harvey | | |
|---|---|---|---|---|---|---|---|---|---|
| Gage | HCFCD | RAS | Difference | HCFCD | RAS | Difference | HCFCD | RAS | Difference |
| 400 | 34.67 | 33.55 | -1.12 | 36.2 | 34.86 | -1.34 | 41.5 | 40.06 | -1.44 |
| 410 | 14.72 | 14.04 | -0.68 | 12.7 | 15.81 | 3.11 | 20.7 | 21.32 | 0.62 |
| 420 | 39.17 | 38.15 | -1.02 | 39.8 | 40.7 | 0.9 | 45.7 | 44.75 | -0.95 |
| 435 | 46.52 | 45.98 | -0.54 | 46.7 | 48.89 | 2.19 | 53.6 | 53.55 | -0.05 |
| 440 | 47.49 | 47.8 | 0.31 | 48.1 | 50.42 | 2.32 | 54.1 | 54.54 | 0.44 |
| 445 | 54.14 | 53.54 | -0.6 | 54.1 | 54.65 | 0.55 | 58.3 | 56.86 | -1.44 |
| 460 | 56.86 | 55.38 | -1.48 | 55.8 | 57.7 | 1.9 | 63.3 | 62.51 | -0.79 |
| 465* | 60.16 | 61.47 | 1.31 | 57.9 | 63.31 | 5.41 | 67.5 | 69.25 | 1.75 |
| 480 | 72.8 | 69.9 | -2.9 | 72.6 | 71.34 | -1.26 | 74.2 | 73.96 | -0.24 |
| 485 | 75.57 | 77.92 | 2.35 | 75.8 | 78.58 | 2.78 | 79.4 | 81.4 | 2 |
| 490 | 76.85 | 78.88 | 2.03 | 77.61 | 78.1 | 0.49 | 80.27 | 80.2 | -0.07 |

Average Peak WSE Difference: 0.21 ft / *Gage affected by addition of detention basins in 2007

The average difference between the actual depth and the modeled depth is .21 ft (Omitting Gage 465), meaning that this RAS model can accurately predict river depth throughout the majority of Brays Bayou Watershed. The model was validated by comparing stream depth at 11 different HCFCD gages to the modeled depth during Hurricane Harvey, Tropical Storm Imelda, and Tropical Storm Beta.

Note: The 5.41 feet difference at gage 465 for TS Beta was caused by the three detention basins for Project Brays constructed in and after 2007, after the HEC-HMS model was published by HCFCD. Therefore, these basins are not modeled in HEC-HMS. Modeling shows that the impact of these detention basins is only significant at a local level, and therefore it did not affect the RAS model's ability to accurately predict depth further downstream in the majority of the floodplain of the Brays Bayou Watershed.

## WHITE OAK BAYOU

White Oak Bayou is another major tributary to Buffalo Bayou, running from the northwest side of the city to the southeast into downtown Houston. Its watershed is larger at the upstream end, and narrows as it approaches Buffalo Bayou, is heavily developed and covers about 111 square miles (see **Figure 3.12**). The main drainage channel in the watershed is White Oak Bayou, along with four major tributaries: Vogel Creek, Cole Creek, Brickhouse Gully, and Little White Oak Bayou.

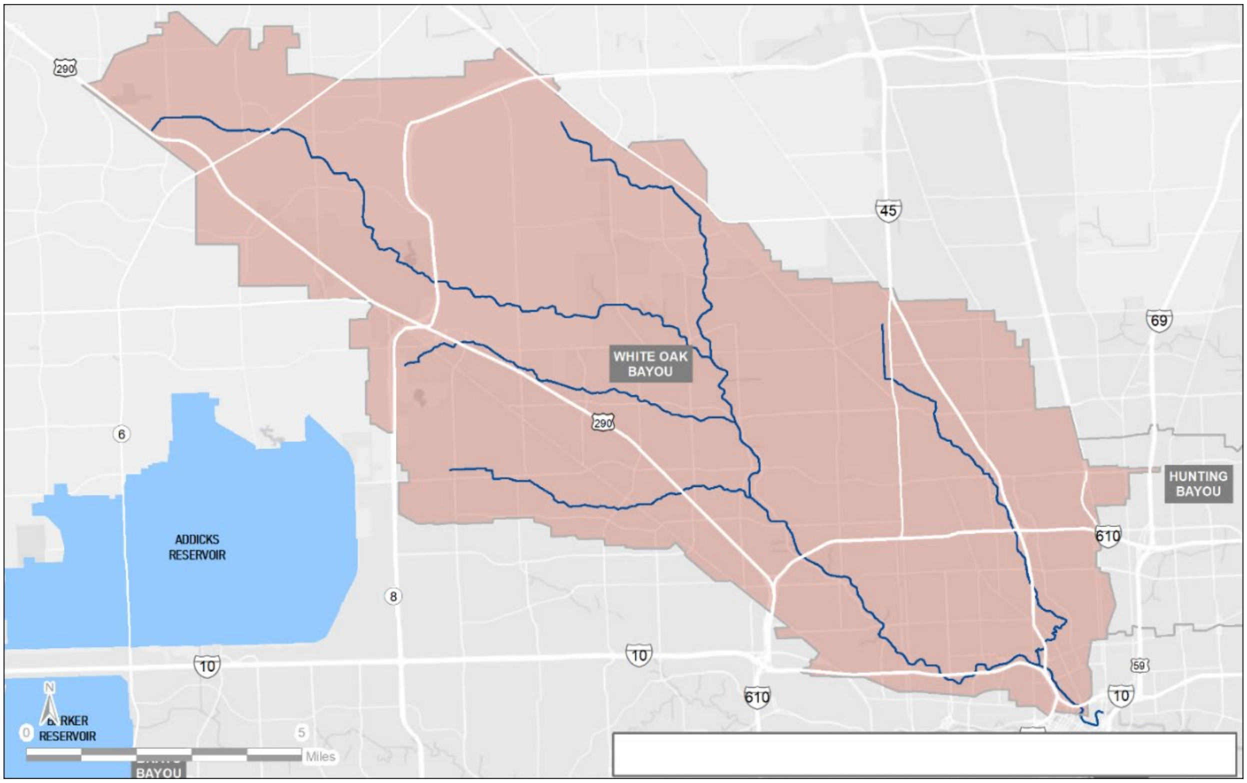



**Figure 3.12** Watershed Map of White Oak Bayou

### *HEC-HMS Modeling*

For this FIRST project, hydrologic and hydraulic analyses were accomplished using the HCFCD's updated 2016 Risk Map model for the watershed. The 2016 Risk Map model incorporated updates to the TSARP modeling due to the White Oak Bayou Federal Flood Damage Reduction Project. Beginning in 1998, that federal project has been a joint initiative between the USACE and HCFCD with the purpose of reducing flood hazard within the watershed and consists of multiple individual projects, including detention basins and channel conveyance improvements. The HMS model set-up for the White Oak Bayou watershed is shown in **Figure 3.13**.

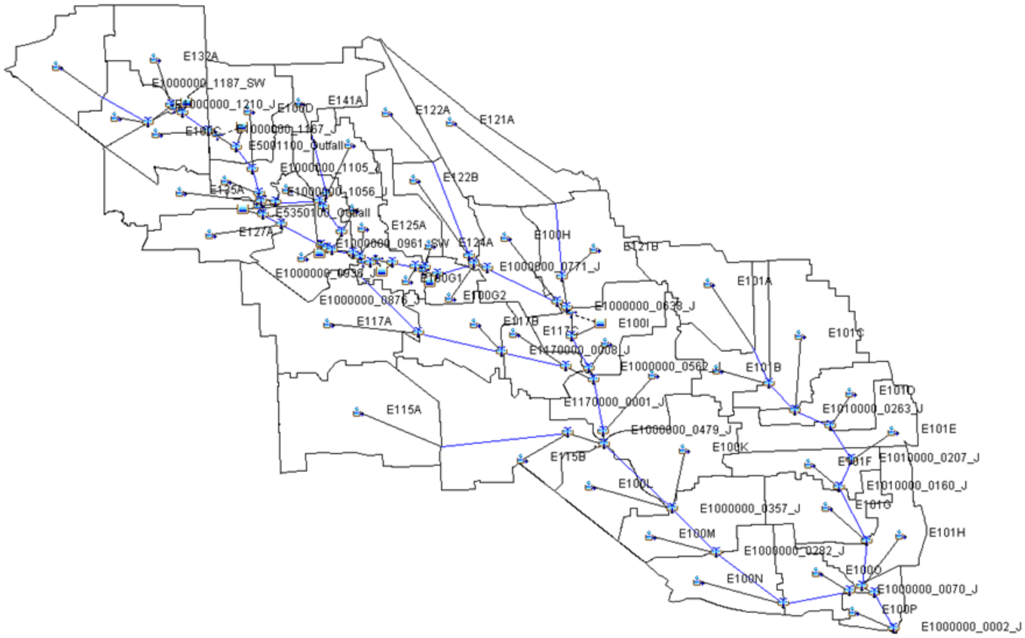


Figure 3.13 HMS Subarea Map of White Oak Bayou Watershed

The 2016 Risk Map hydrologic model was validated using three recent storms: Harvey (2017), Imelda (2019), and Beta (2020). The resulting computed flow hydrographs were compared to the observed hydrographs at the corresponding USGS stream gage in the watershed. **Figure 3.14** shows the location of the HCFCD and USGS gages in this watershed, and **Figure 3.15** show examples of the comparison of the computed flows to the observed flows (additional flow hydrograph comparisons are included in **Appendix B**).

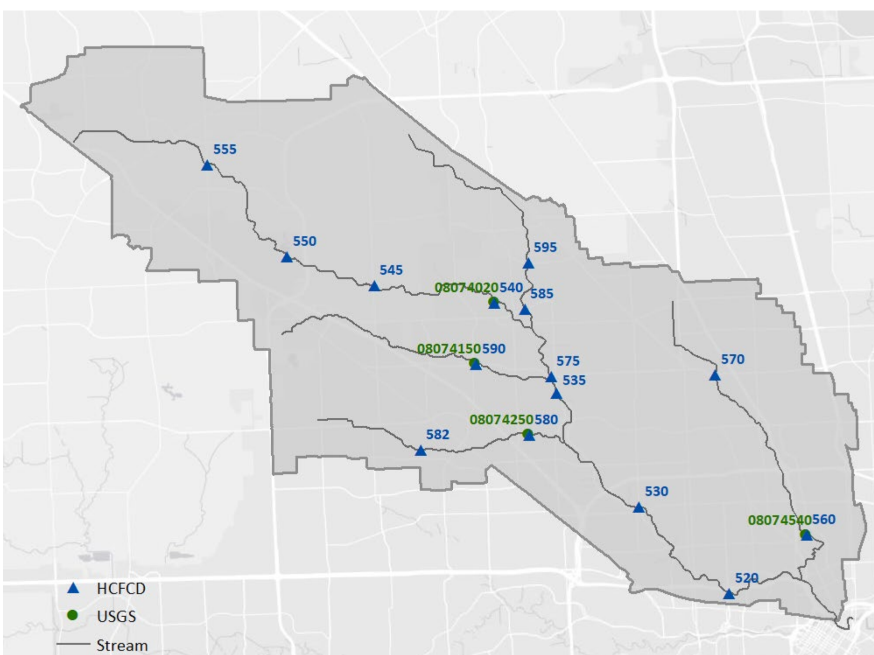
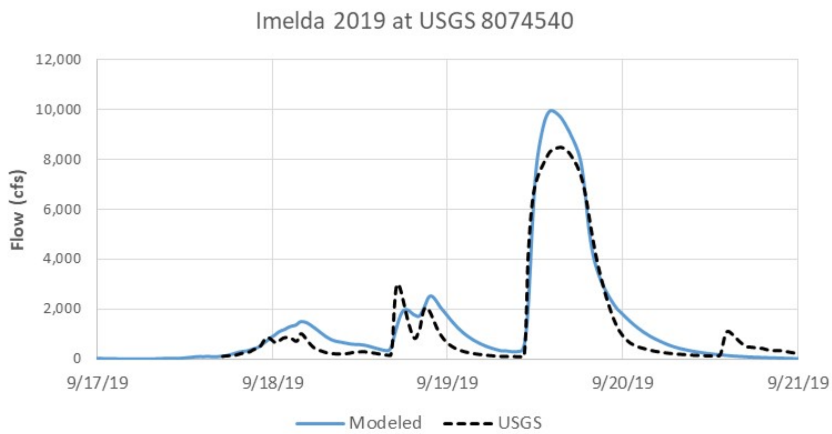



Figure 3.14 Location of the USGS and HCFCD gages in the White Oak Bayou Watershed



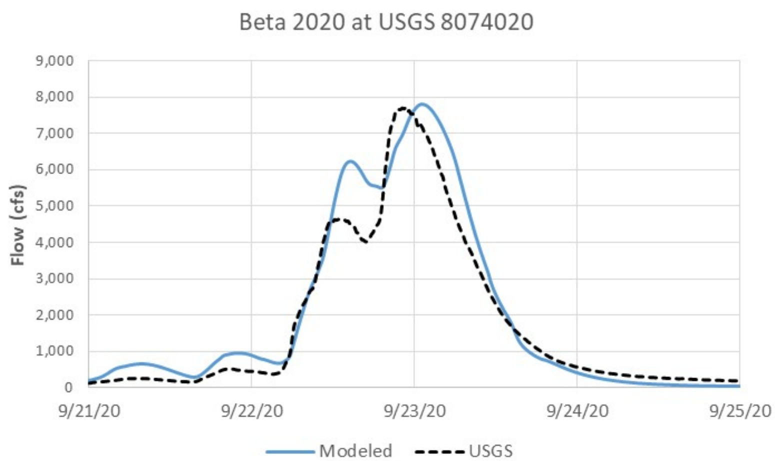




Figure 3.15 Comparison of Modeled and Observed Flow Hydrographs for White Oak Bayou

Modeled flow performance was evaluated using a standard performance metric, the Nash-Sutcliffe Efficiency (NSE), which measures how well simulated values match observed data. The time series data used to compute the NSE values vary depending on the availability of the corresponding USGS flow data. It is important to note that some gages had incomplete flow records for certain storms (the NSE values computed at these gages are marked with an asterisk as shown in the table below). The computed average NSE values is 0.72, which indicates good model performance (NSE values >0.5 are generally considered acceptable / good). Note: One Harvey value of 0.02 is an anomaly of the test.

Table 3.3 NSE Values for Harvey, Imelda, and Beta

| | 8074020 | 8074150 | 8074250 | 8074540 |
|---|---|---|---|---|
| **Harvey** | 0.80 | 0.02 | 0.76 | 0.90 |
| **Imelda** | 0.47 | 0.62** | 0.96** | 0.93* |
| **Beta** | 0.87 | 0.86* | 0.82* | 0.67* |

*HEC-RAS Modeling*

After simulating the historical storms in HMS, the resulting peak flows from certain junctions were entered into the HEC-RAS (1D steady-state) model at corresponding cross-sections to compute peak flood levels along the channels. **Figure 3.16** shows the HEC-RAS model set-up for White Oak Bayou and its major tributaries.

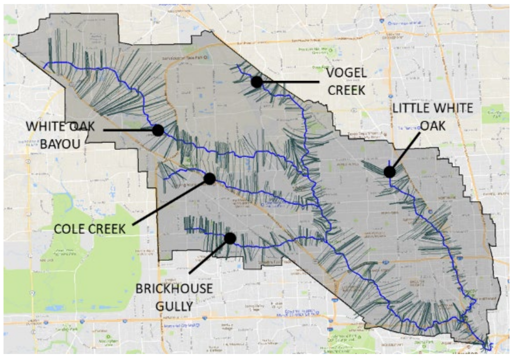



Figure 3.16 RAS Model Set-up for White Oak Bayou and its Tributaries

Downstream boundary conditions were set to normal depth. Since the 2016 Risk Map HEC-RAS models consist of separate hydraulic models for each channel or tributary, the models for the four major tributaries mentioned previously were linked (stitched) into the main channel model for this FIRST project.

For each of the historic storms, the modeled peak water surface elevation (HEC-RAS) was compared at 15 HCFCD gage locations, as shown in the table below (see figure showing HCFCD gage locations). The average difference is about one foot.

Table 3.4 HEC-RAS validation results comparison

| HCFCD | Imelda | | | Beta | | | Harvey | | |
|---|---|---|---|---|---|---|---|---|---|
| Gage | HCFCD | RAS | Diff | HCFCD | RAS | Diff | HCFCD | RAS | Diff |
| 555 | 108.9 | 109.15 | 0.25 | 112.08 | 111.21 | -0.87 | 113.1 | 113.48 | 0.38 |
| 550 | 91.13 | 92.17 | 1.04 | 96.14 | 95.06 | -1.08 | 98.2 | 98.05 | -0.15 |
| 545 | 80.27 | 81.15 | 0.88 | 86.19 | 85.24 | -0.95 | 90.7 | 89.35 | -1.35 |
| 540 | 70.31 | 70.53 | 0.22 | 73.43 | 73.18 | -0.25 | 77.6 | 77.83 | 0.23 |
| 575 | 62.37 | 64.32 | 1.95 | 60.07 | 61.39 | 1.32 | 68.8 | 68.67 | -0.13 |
| 535 | 60.85 | 62.46 | 1.61 | 57.58 | 59.02 | 1.44 | 66.6 | 66.91 | 0.31 |
| 530 | 49.91 | 51.99 | 2.08 | 42.15 | 45.04 | 2.89 | 56.9 | 56.2 | -0.7 |
| 520 | 38.07 | 37.07 | -1 | 30.15 | 30.34 | 0.19 | NA | 40.68 | NA |
| 595 | 75.28 | 74.85 | -0.43 | 75.12 | 74.02 | -1.1 | 77.8 | 78.17 | 0.37 |
| 585 | 68.91 | 67.19 | -1.72 | 68.6 | 66.46 | -2.14 | 75 | 72.78 | -2.22 |
| 590 | 74 | 75.03 | 1.03 | 72.33 | 73.34 | 1.01 | 74.6 | 78.16 | 3.56 |
| 582 | 77.15 | 77.47 | 0.32 | 73.16 | 73.93 | 0.77 | 77.4 | 77.72 | 0.32 |
| 580 | 64.1 | 64.15 | 0.05 | 60 | 59.51 | -0.49 | 66.7 | 66.43 | -0.27 |
| 570 | 65.46 | 65.52 | 0.06 | 59.35 | 60.32 | 0.97 | 65.4 | 65.72 | 0.32 |
| 560 | 42.42 | 39.98 | -2.44 | 32.49 | 31.07 | -1.42 | 44.1 | 40.74 | -3.36 |

## HUNTING BAYOU

Hunting Bayou is a tributary to Buffalo Bayou, running from the northeast side of the city to the east/southeast. Its watershed is also heavily developed and covers about 31 square miles (see **Figure 3.17**), and is very flood prone in the upper watershed area.

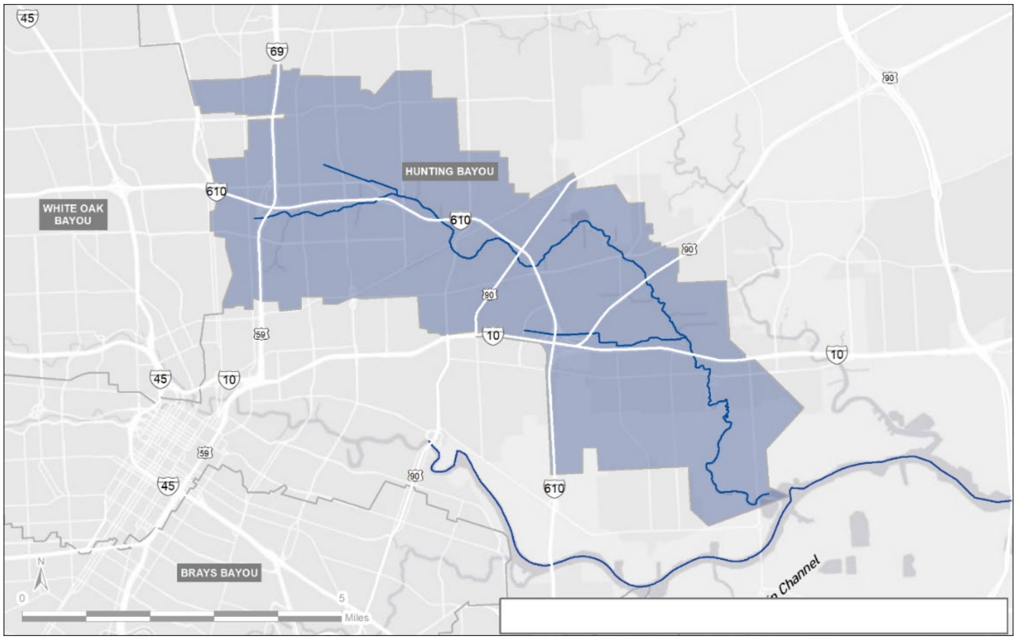



Figure 3.17 Watershed Map of Hunting Bayou

### *HEC-HMS Modeling*

The hydrologic model used for this project for the Hunting Bayou watershed was the HEC-HMS model from the HCFCD M3 Library. This modeling was based on the TSARP work back in the early 2000s and was adopted by Harris County in 2007. The HMS model for this watershed encompasses a number of subareas, as shown in **Figure 3.18**.

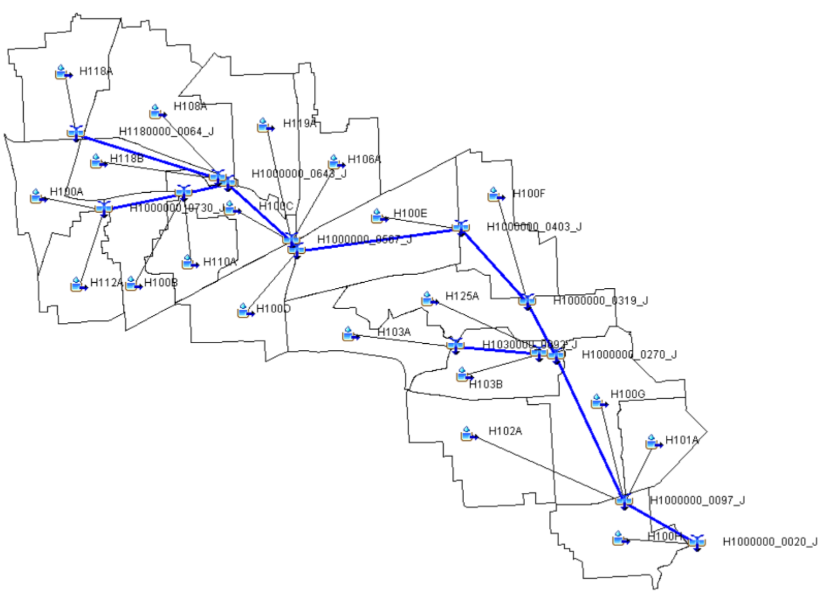



**Figure 3.18** HMS Subarea Map of the Hunting Bayou Watershed

The model was validated using radar rainfall for Tropical Storms Imelda and Beta, and rainfall from Harris County Flood Warning System (HCFWS)[1] rain gages incorporated with the Thiessen Polygon method for Hurricane Harvey. The results of the hydrologic modeling for these three storm events were compared to the flow hydrographs at the USGS stream gages in the watershed, the locations of which are shown in **Figure 3.19**. The red circles pictured in the figure are USGS streamgage locations. USGS Gage 08075763 is located at Hoffman St within Kashmere Gardens. Further downstream, USGS Gage 08075770 is located at Interstate Highway 610. These gages were used to validate results in both the HEC-HMS and HEC-RAS analyses.

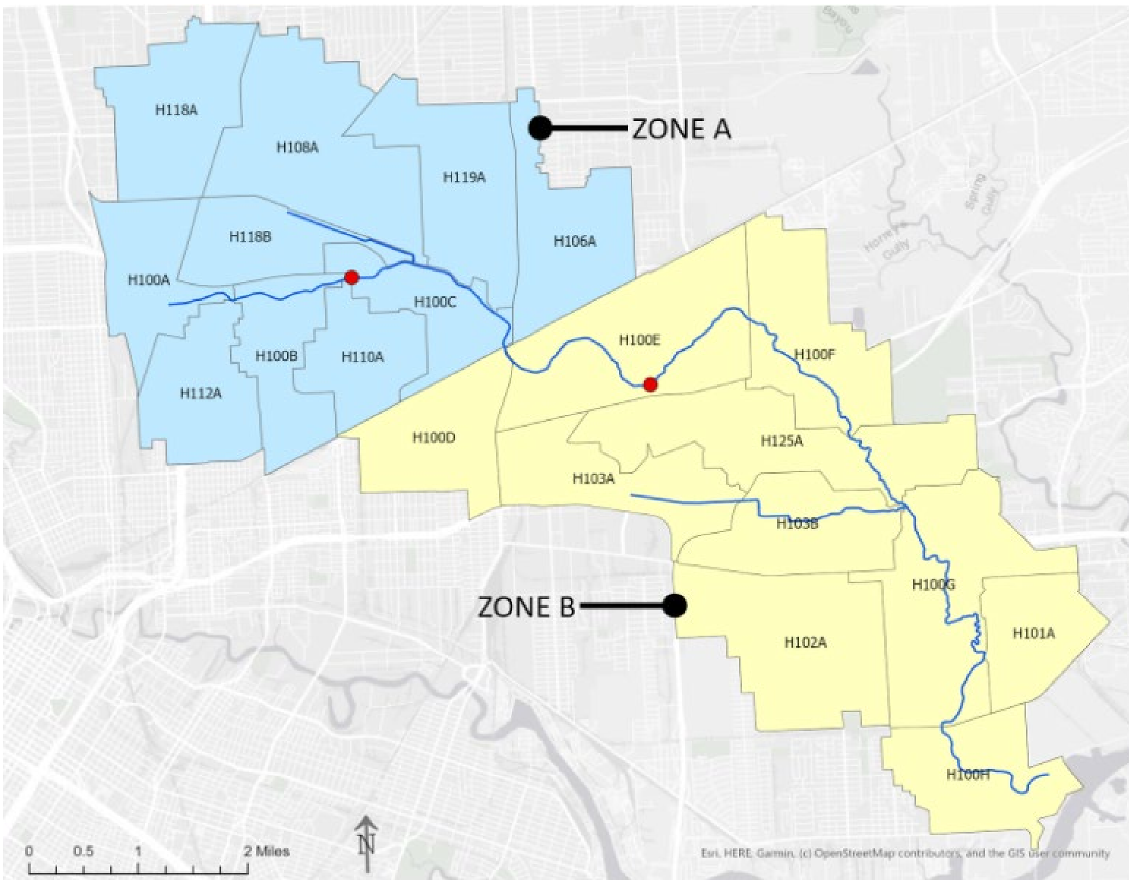
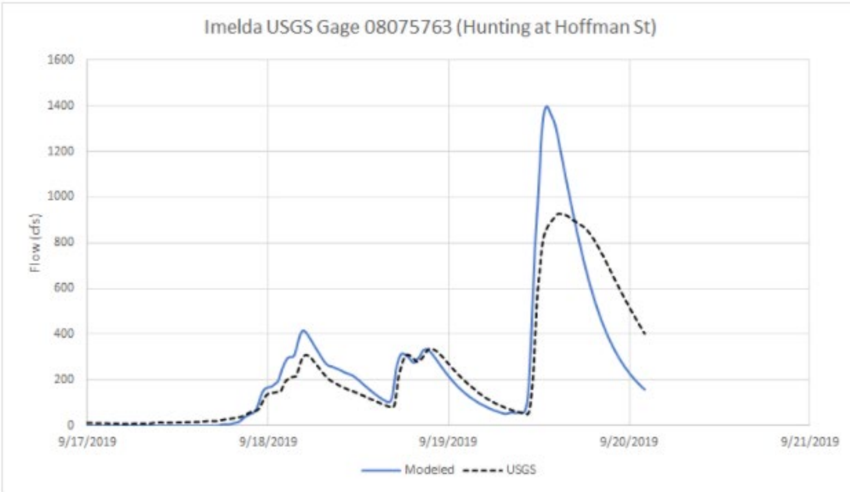



Figure 3.19 Location of the USGS and HCFCD Gages in the Hunting Bayou Watershed

Examples of the comparisons between the modeled and observed flow hydrographs are shown in **Figure 3.20** (see **Appendix B** for the flow hydrograph comparisons for all three storms).

[1] https://www.harriscountyfws.org/



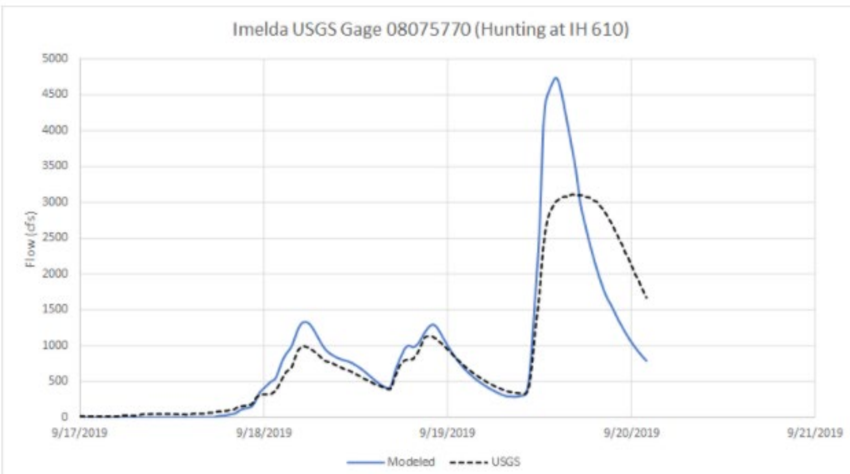




Figure 3.20 Comparison of Modeled and Observed Flow Hydrographs for Hunting Bayou

Modeled flow performance was evaluated using a standard performance metric, the Nash-Sutcliffe Efficiency (NSE), which measures how well simulated values match observed data. The time series data used to compute the NSE values vary depending on the availability of the corresponding USGS flow data. The computed average of the NSE values is 0.6, which indicates good model performance (NSE values >0.5 are generally considered acceptable / good).

Table 3.5 NSE results for all 6 validation scenarios for Hunting Bayou HEC-HMS

| | **08075763** | **08075770** |
|---|---|---|
| **Imelda** | 0.69 | 0.64 |
| **Beta** | 0.89 | 0.75 |
| **Harvey** | 0.41 | 0.24 |

*HEC-RAS Modeling*

For this RAS modeling analysis, the models for two tributaries were taken from Harris County's Model and Map Management (M3) System[2] and stitched in with the RAS model for the main channel of Hunting Bayou, including H118-00-00 (located in the upstream portion) and H103-00-00 (Wallisville Outfall - located in the downstream portion). A map of the RAS model set-up for the Hunting Bayou watershed is provided in **Figure 3.21** below, and it includes the labeled stitched-in tributaries. The dividing feature in between the upstream and downstream portions of the watershed is a rail corridor that impedes water flow.

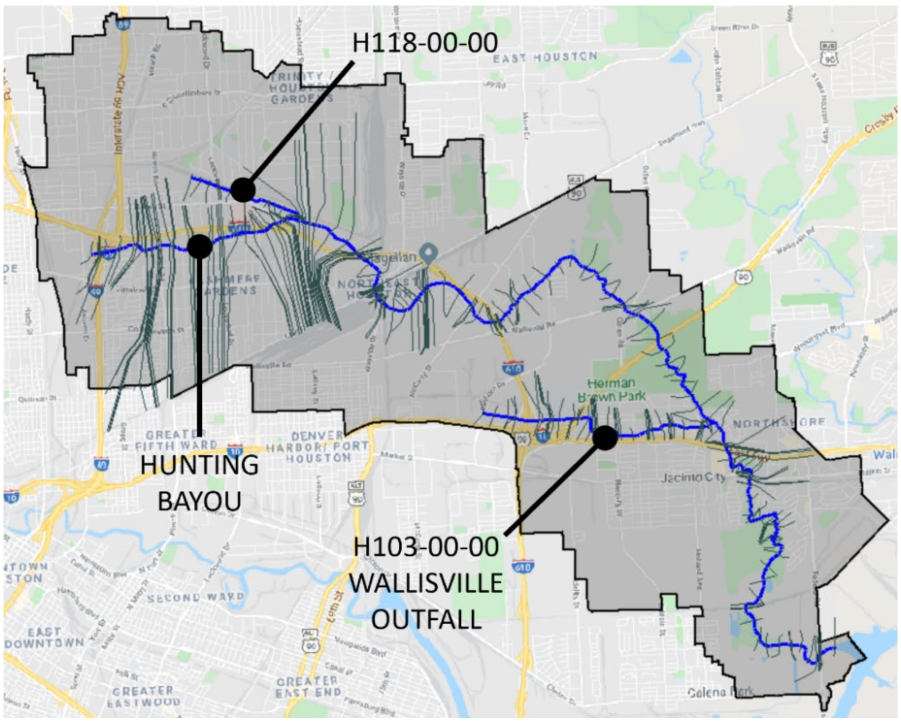



**Figure 3.21** RAS Model Set-up for Hunting Bayou and its Tributaries

For the purposes of this FIRST project, Hunting Bayou was evaluated under one-dimensional, steady-state flow conditions. The HEC-RAS model used cross section geometry data from Harris County Flood Control District (HCFCD) M3 system for Hunting Bayou's main channel (H100-00-00) and two stitched-in tributaries (H103-00-00 and H118-00-00). The hydraulic model was then validated based on three historical storms: Tropical Storm Imelda, Tropical Storm Beta, and Hurricane Harvey. The steady flow data input was from computed peak discharge flows of sixteen junctions from the HEC-HMS model that corresponded with HEC-RAS river stations. The downstream steady flow boundary condition type was normal depth which, based on the profile plot, was found to have a slope of 0.00067. The water surface elevations computed for the three storms were compared to the stream elevation of three HCFCD gages[3]. The table below shows a summary of the comparison for the validation storms. The average peak water surface elevation difference was about 0.5 feet.

[2] https://www.hcfcd.org/Interactive-Mapping-Tools/Model-and-Map-Management-M3-System

[3] https://www.harriscountyfws.org/

Table 3.6 HEC-RAS validation results comparison

| HCFCD | Imelda | | | Beta | | | Harvey | | |
|---|---|---|---|---|---|---|---|---|---|
| Gage | HCFCD | RAS | Diff | HCFCD | RAS | Diff | HCFCD | RAS | Diff |
| 820 | 22.2 | 21.06 | -1.14 | 14.47 | 13.27 | -1.20 | 27 | 25.41 | -1.59 |
| 830 | 34.1 | 35.01 | 0.91 | 27.72 | 26.11 | -1.61 | 37 | 37.44 | 0.44 |
| 840 | 41.4 | 42.12 | 0.72 | 35.39 | 34.68 | -0.71 | 44.4 | 44.38 | -0.02 |

### SIMS BAYOU (SUNNYSIDE)

Sims Bayou is a tributary to Buffalo Bayou, running from the southwest side of the city to the east. Its watershed is fairly narrow, heavily developed and covers about 94 square miles (see **Figure 3.22**). A particularly vulnerable area in this watershed is known as Sunnyside, which is the area focused on in developing the FIRST project for this watershed. Sunnyside is located north of Sims Bayou and east of State Highway 288, covering about 6.35 square miles, as shown in **Figure 3.23**.

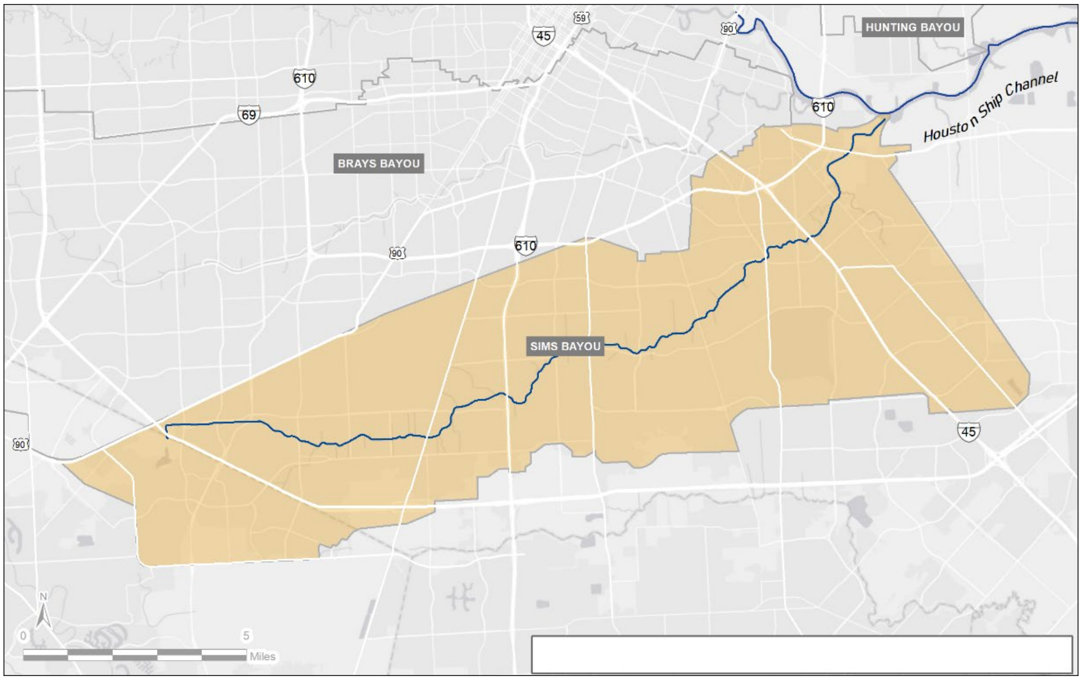



Figure 3.22 Watershed Map of Sims Bayou

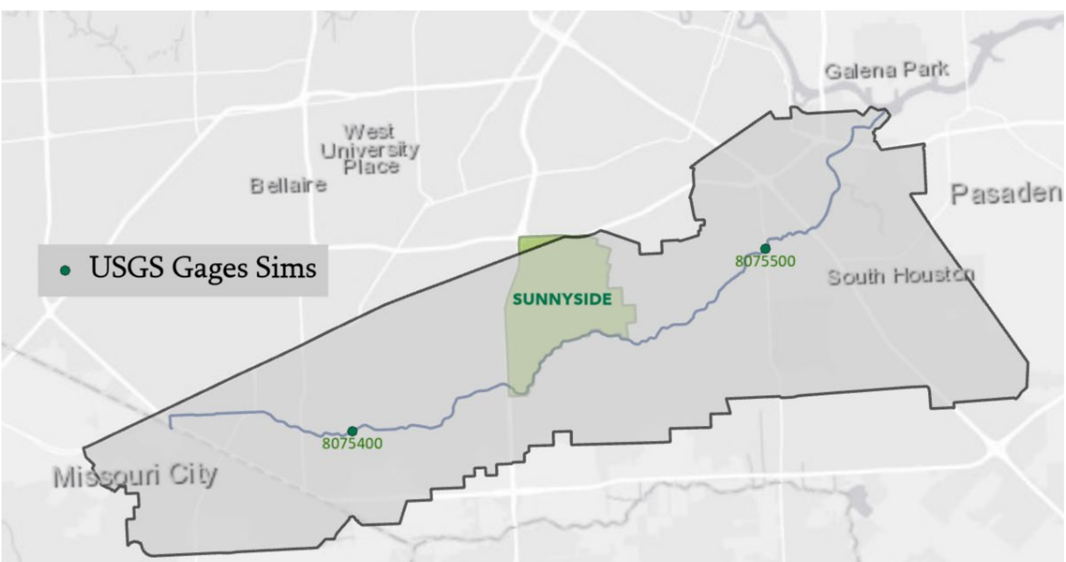



Figure 3.23 Map Showing Location of Sunnyside in the Sims Bayou Watershed

*HEC-HMS Modeling*

The hydrologic analysis for Sunnyside was completed using HEC-HMS 4.6.1. The model used was from the M3 model library for HCFCD. No alterations were made to the basin model. **Figure 3.24** shows the HMS model set-up for the Sims Bayou Watershed.

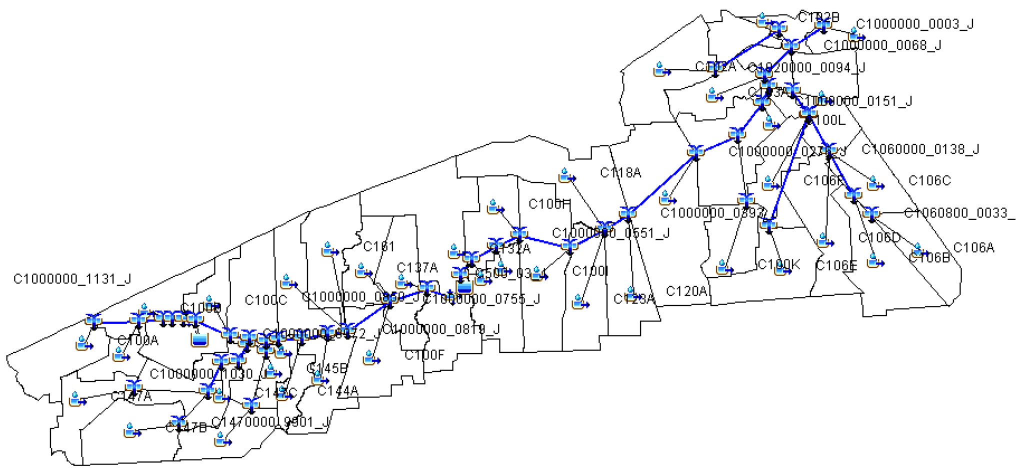



Figure 3.24 HMS Model Set-up for the Sims Bayou Watershed

Tropical storms Beta and Imelda were used to validate the HMS model. Radar rainfall was provided by VAI for both storms. Flow hydrographs at USGS gages 08075400 (Hiram Clarke Rd.) and 08075500 were used to validate the HMS model from HCFCD. Gage 08075400 is upstream of Sunnyside and gage 0807550 is downstream of Sunnyside. To compare HMS flow values to USGS recorded data from Tropical Storms Imelda and Beta, HMS junctions closest to USGS Gages 08075400 and 08075500 were used. Though the peak flow was often underestimated by the model, the hydrographs using radar rainfall were able to match the shape of the triple-peak storms well. An example of the comparison of modeled and observed flows is shown in **Figure 3.25**.

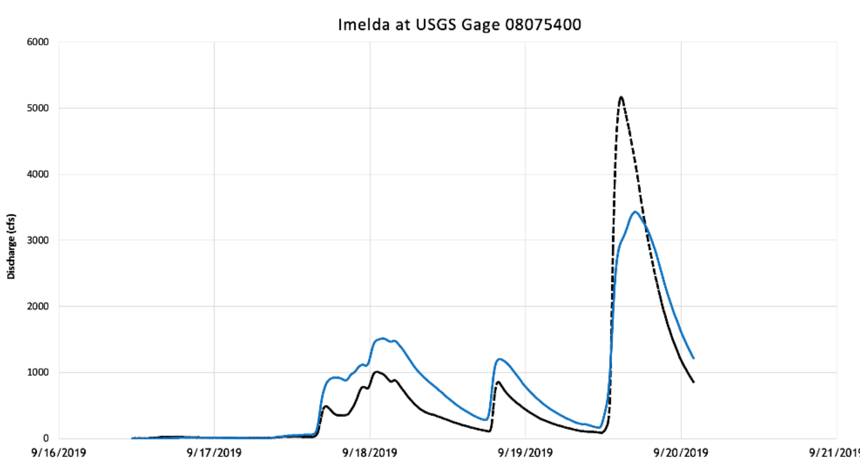


Figure 3.25 Comparison of Modeled and Observed Flow Hydrographs for Sims Bayou

Modeled flow performance was evaluated using a standard performance metric, the Nash-Sutcliffe Efficiency (NSE), which measures how well simulated values match observed data. The time series data used to compute the NSE values vary depending on the availability of the corresponding USGS flow data. The computed NSE values at the upstream gage of .84 and .79 and values at the downstream gage of .73 and .62 indicates good model performance (NSE values >0.5 are generally considered acceptable / good).

Table 3.7 NSE Values for Imelda and Beta

| | 08075400 | 08075500 |
|---|---|---|
| **Imelda** | 0.79 | 0.62* |
| **Beta** | 0.84 | 0.73 |

Average NSE: 0.75

* Incomplete gage records

** Missing substantial gage records during the bulk of the storm event

*HEC-RAS Modeling*

Because most of Sunnyside is outside of the floodplain of Sims Bayou, HEC-RAS 2D was chosen to model this neighborhood. This allows for pluvial (overland) flooding to be modeled rather than just riverine flooding.

The upstream boundary condition for Sunnyside was based on hydrographs determined at the gage just upstream (**Figure 3.26**).

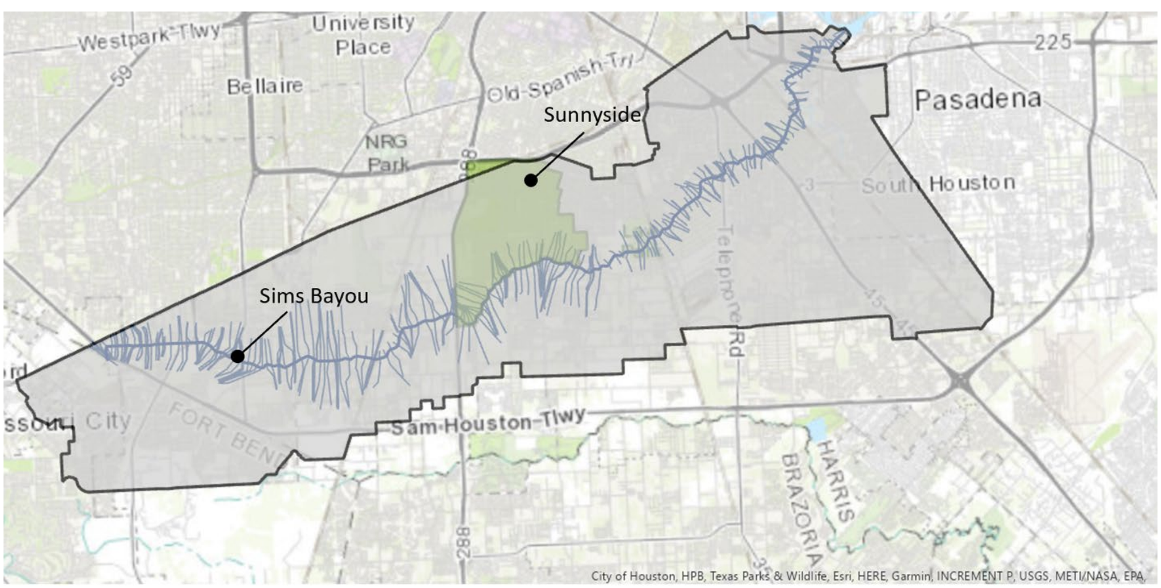


Figure 3.26 HEC-RAS 1D Model Set-up for Sims Bayou

A 2D, unsteady flow model was also created in HEC-RAS 5.0.7 for this FIRST project. To create the HEC-RAS 2D model for this project, 2018 LiDAR from the GIS center at Rice was utilized. GIS was used to merge all the LiDAR quartiles needed into a single raster. Land use data was from the 2016 NLCD (national land cover database). In HEC-RAS, the projection was set to the NAD_1983_StatePlane_Texas_South_Central. After the projection was selected, terrain (LiDAR) and land use data were loaded into the RAS model. Manning's n values were assigned to the various land cover types. In the geometry editor, a Sunnyside shapefile was displayed to aid in the drawing of the 2D domain. To increase the accuracy of the model in showing riverine flooding, the 2D domain was extended south of the bayou (Sunnyside is north of the bayou). The total size of the 2D model domain is 10.77 square miles. After the 2D domain was drawn, the computational mesh was created use a 100 foot x 100 foot cell size. See **Figures 3.27, 3.28** and **3.29** for the RAS 2D model layers of data.

To increase the accuracy of the 2D model, separate Manning's n values were delineated for the channel. In GIS, the buffer tool was used around the channel to create a 100-foot buffer (50 feet on each side) around the channel. This shapefile was imported into the geometry editor in RAS and breaklines were used to create separate cells for the channel. Cells of the channel were given a Manning's n value of .035 (this was based on the n value applied to the channel in the HCFCD M3 HEC-RAS 1D model).

Boundary conditions were applied at the upstream and downstream ends of the domain. The upstream boundary condition line was drawn across the channel, and the downstream boundary condition line was drawn along the entire east side of the domain to ensure that water would not pond.

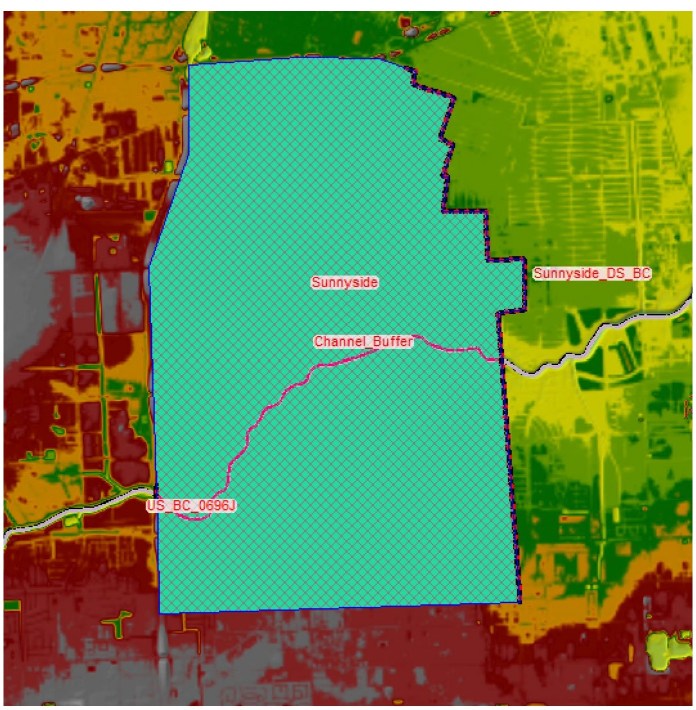


Figure 3.27 HEC-RAS 2D Domain for Sunnyside

Because the Sunnyside 2D model captures both pluvial and riverine flooding, it is not possible to validate the results of the pluvial flooding. However, the water surface elevation in the channel can be validated using the HCFCD gages (**Figure 3.30**). HCFCD gage 370 on state highway 288 is at the very upstream end of the channel. HCFCD gage 360 on Martin Luther King Road was used to validate the downstream end of the domain, although the gage is about a quarter mile downstream of the domain boundary (which means that the water surface elevation in the model should be a little higher than what was measured at gage 360).

The model was calibrated by adjusting the energy slope at the upstream and downstream boundary conditions. Energy slopes between .0001 and .05 were tested to find the best match with the known water level at the upstream and downstream ends. Ultimately, values of .002 at the upstream end and .00075 at the downstream end were found to have the best match. These values for the energy slope are consistent with the extremely flat nature of Houston. The upstream end overestimates the water surface elevation by a little over a foot, although this can be explained by the presence of a bridge at the gage which was not modeled in HEC-RAS 2D.

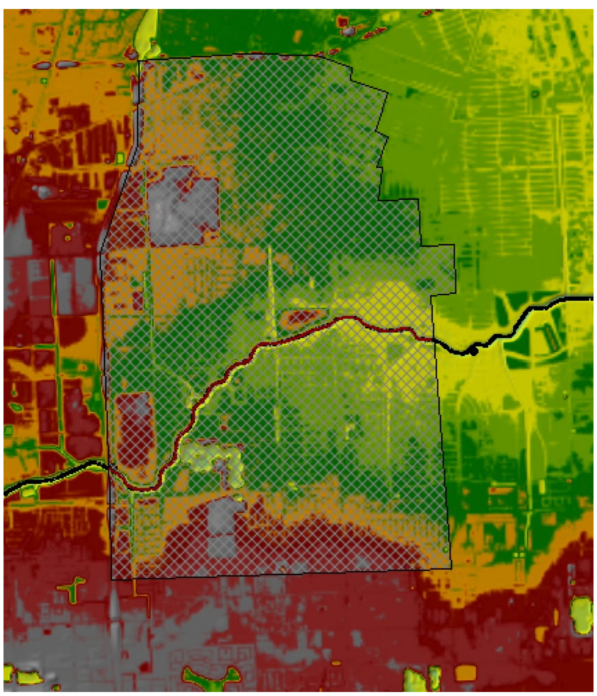


Figure 3.28 Terrain in RAS Mapper

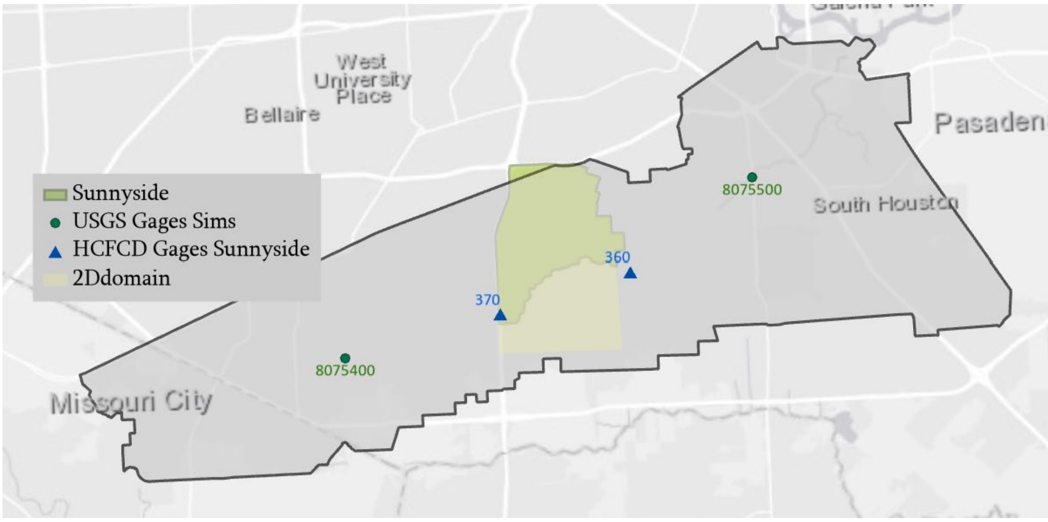



Figure 3.29 Location of USGS and HCFCD Gages in Sims Bayou Watershed

The results of the RAS 2D model for the historic storms compared to the flood levels reported at the HCFCD gages are shown in the table below. The average difference is less than one foot.

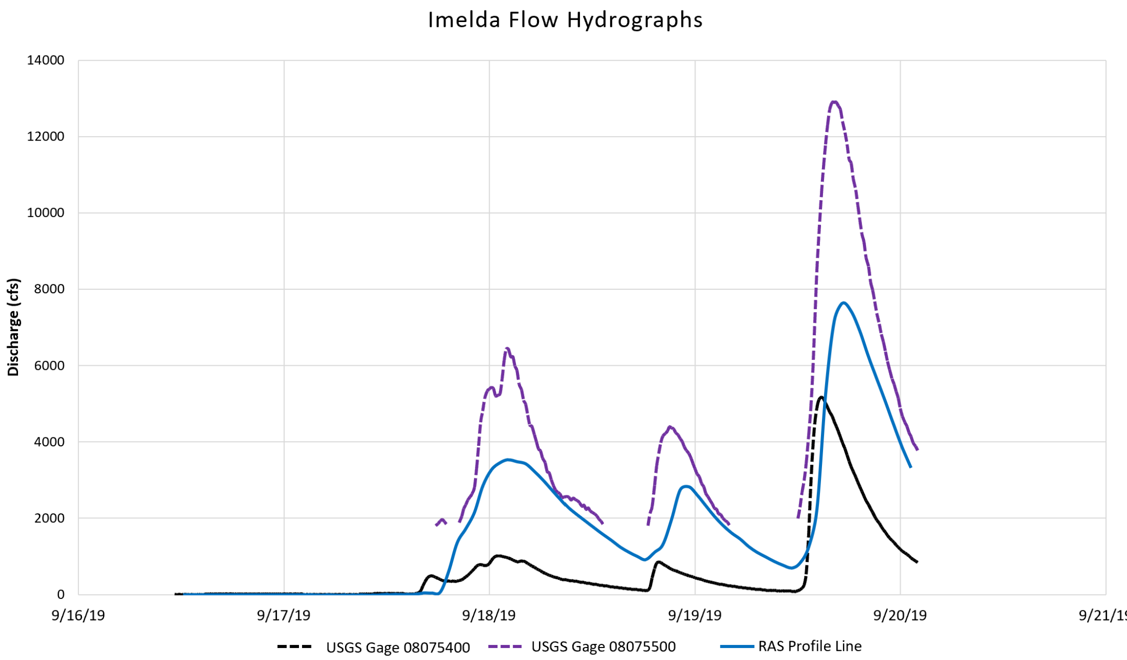
Table 3.8 HEC-RAS Validation Results Comparison

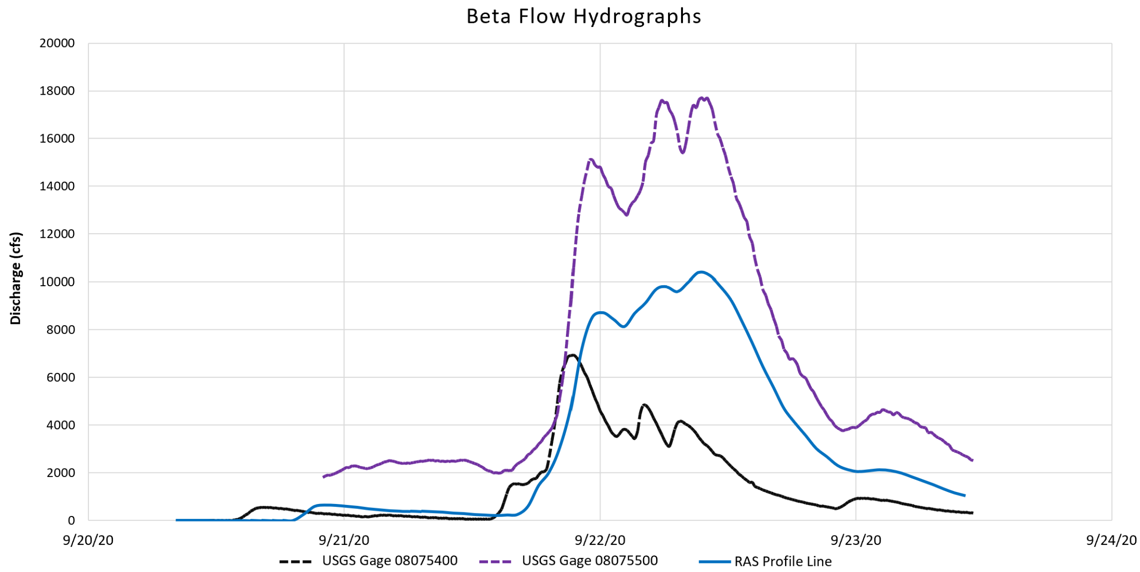
| **HCFCD** | **Imelda** | | | **Beta** | | |
|---|---|---|---|---|---|---|
| **Gage** | **HCFCD** | **RAS** | **Diff** | **HCFCD** | **RAS** | **Diff** |
| 370 | 29.65 | 30.98 | 1.33 | 31.07 | 32.44 | 1.33 |
| 360 | 23.33 | 22.88 | -.45 | 25.07 | 25.27 | .2 |

HEC-RAS 2D also has the ability to produce flow hydrographs using profile lines. A profile line was drawn at the downstream end of the model, capturing all riverine and pluvial flow that will flow into the channel. There are two USGS gages along Sims Bayou, with one upstream and one downstream of Sunnyside. The hydrograph from the RAS profile line is compared to these gages for both Beta and Imelda (**Figure 3.31**). It is logical that the flow coming out of Sunnyside should be somewhere in between the flow values of the upstream and downstream USGS gages. The hydrograph from RAS matches the shape of the USGS hydrographs well, which is a good indicator of accuracy. HEC-RAS 2D (because it is unsteady) also has the ability to produce stage hydrographs at any location in the domain. Stage hydrographs were created at the very upstream and very downstream ends of the model and compared to HCFCD gages 370 and 360, respectively (**Figure 3.32**). Again, gage 360 is about a quarter mile downstream of the model domain, so comparisons in stage should not be exact matches.

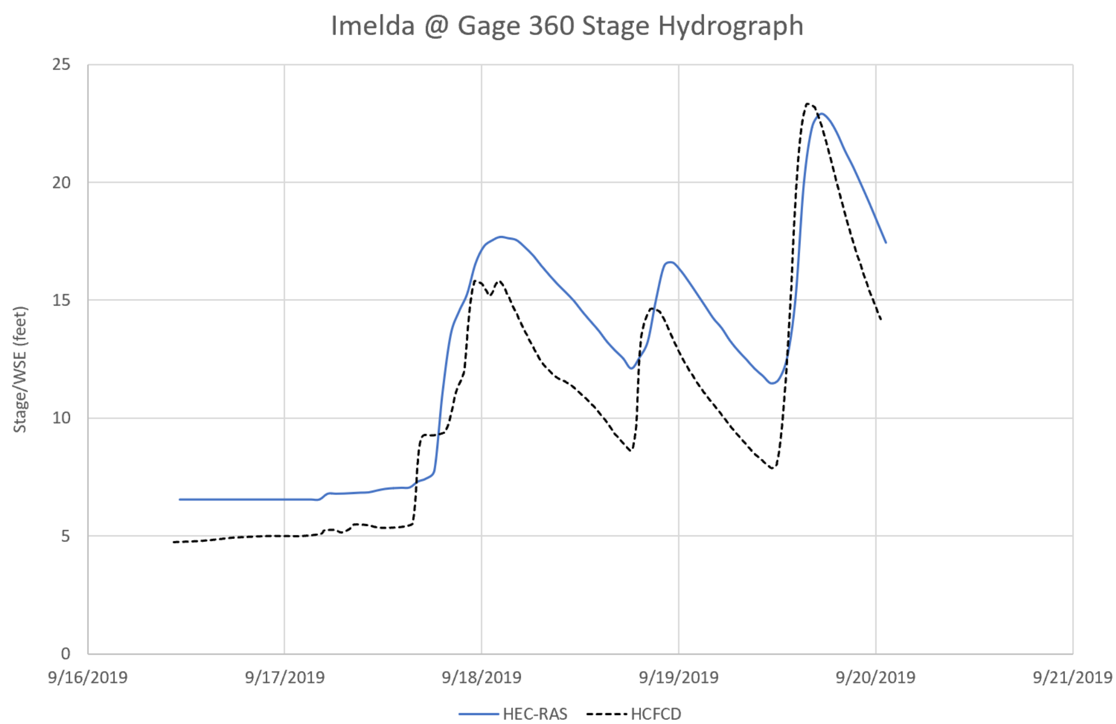
**Figure 3.30** shows a 2D HEC-RAS FPML for Sunnyside for 9 inches of rain in 12 hours.


**Figure 3.30** Floodplain Map Library for Sunnyside in Sims Bayou






Figures 3.31 Comparison of Modeled Flows in Sunnyside and Observed Flows on USGS Gages Downstream and Upstream of Sunnyside



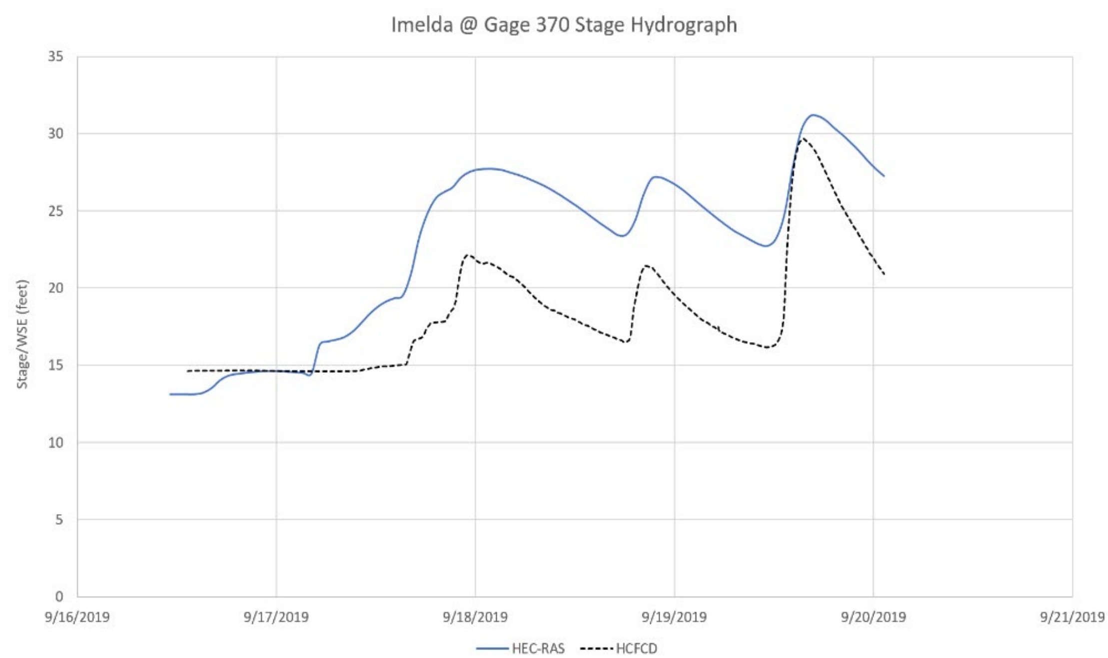
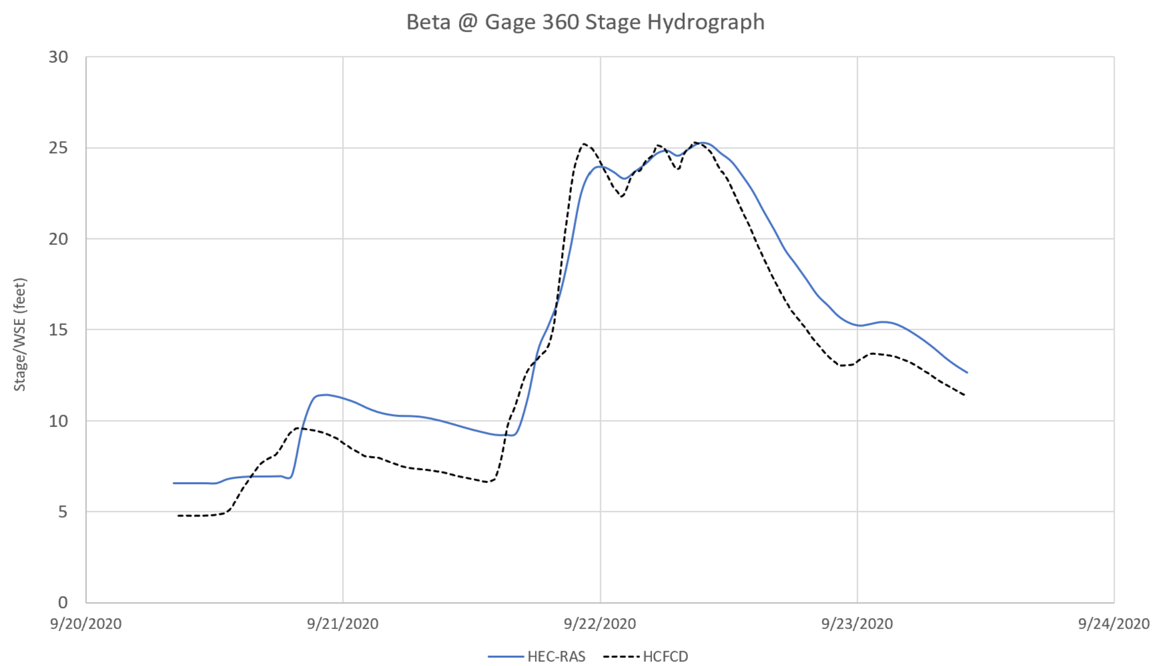




**Figure 3.32a** Comparison of Modeled and Observed Stage Hydrographs in Sunnyside



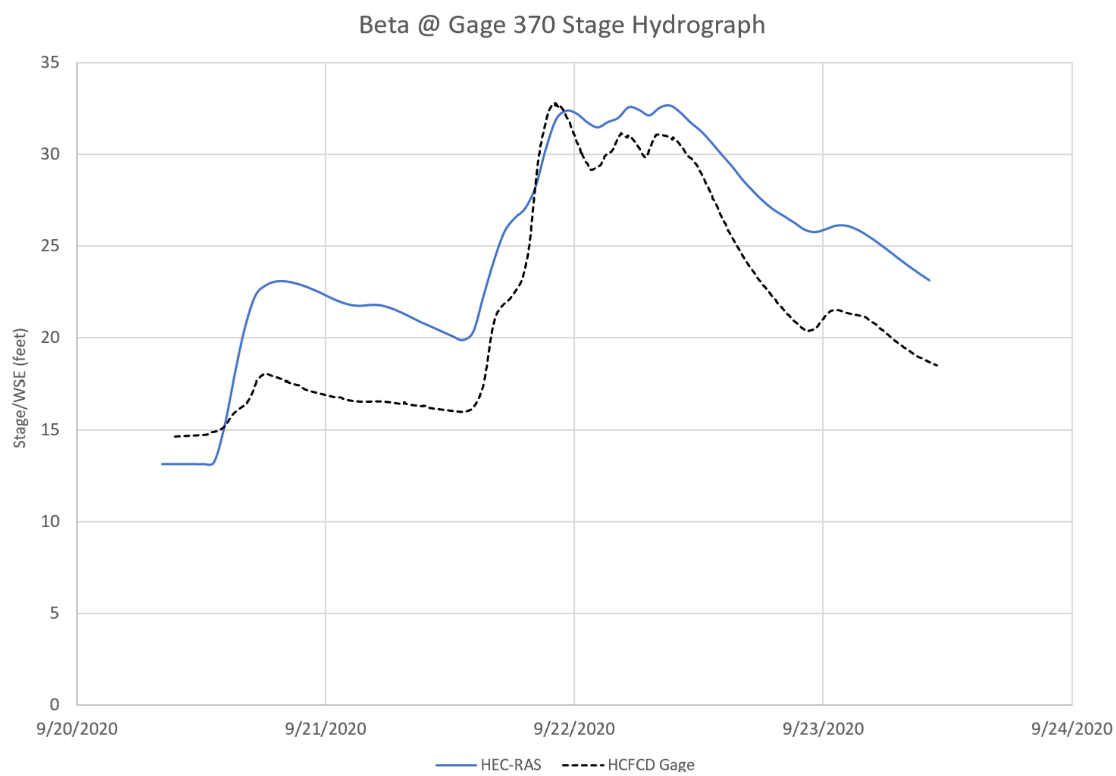




Figure 3.32b Comparison of Modeled and Observed Stage Hydrographs in Sunnyside

# IV. FLOODPLAIN MAP LIBRARY (FPML)

## OVERVIEW

Each watershed was in the study was divided into upstream and downstream areas to better represent spatially variable rainfalls during the application of the FPML, the floodplain map library. Approximately 75 maps were created for each watershed to represent combinations of rainfalls ranging from 5 inches to 17 inches spread over the upper and lower portions. These amounts were carefully selected to represent the range of large events for Houston, based on the 2018 NOAA Atlas 14 document. The following references relate to FAS development in Texas: Fang, N., et al., 2014; Fang, Z., et al., 2011; Fang, Z., et al., 2014; Fang, Z., et al., 2008; Fang, Z., et al., 2011; Fang, Z., et al., 2014.

## SELECTED WATERSHEDS

### BRAYS BAYOU

The figure below shows the division of FPML zones for Brays Bayou watershed. The upstream portion, Zone A, covers approximately 50 $mi^2$, and includes the contributing drainage areas from Upper Brays and Keegans Bayou. The downstream portion, Zone B, covers approximately 70 $mi^2$, and includes the drainage areas from Lower Brays, near the TMC and University of Houston campus.

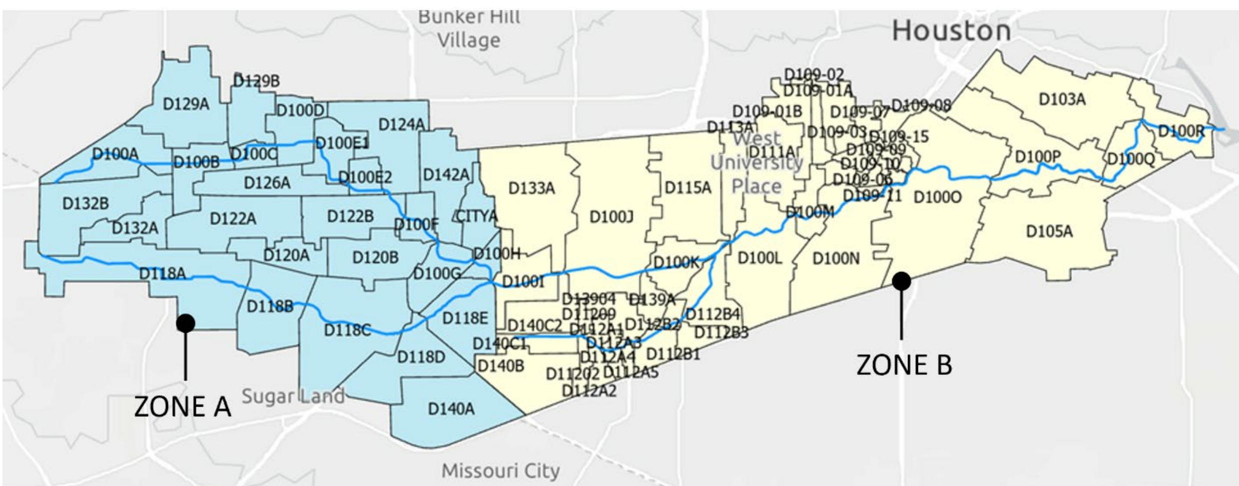


Figure 3.33 Brays Bayou upstream (A) and downstream (B) areas

## WHITE OAK BAYOU

The figure below shows the division of FPML zones for White Oak Bayou watershed. The upstream portion, Zone A, covers approximately 46 mi$^2$, and includes the contributing drainage areas from Upper White Oak Bayou and Vogel Creek. The downstream portion, Zone B, covers approximately 65 mi$^2$, and includes the drainage areas from Lower White Oak Bayou, Little White Oak Bayou, Cole Creek, and Brickhouse Gully.

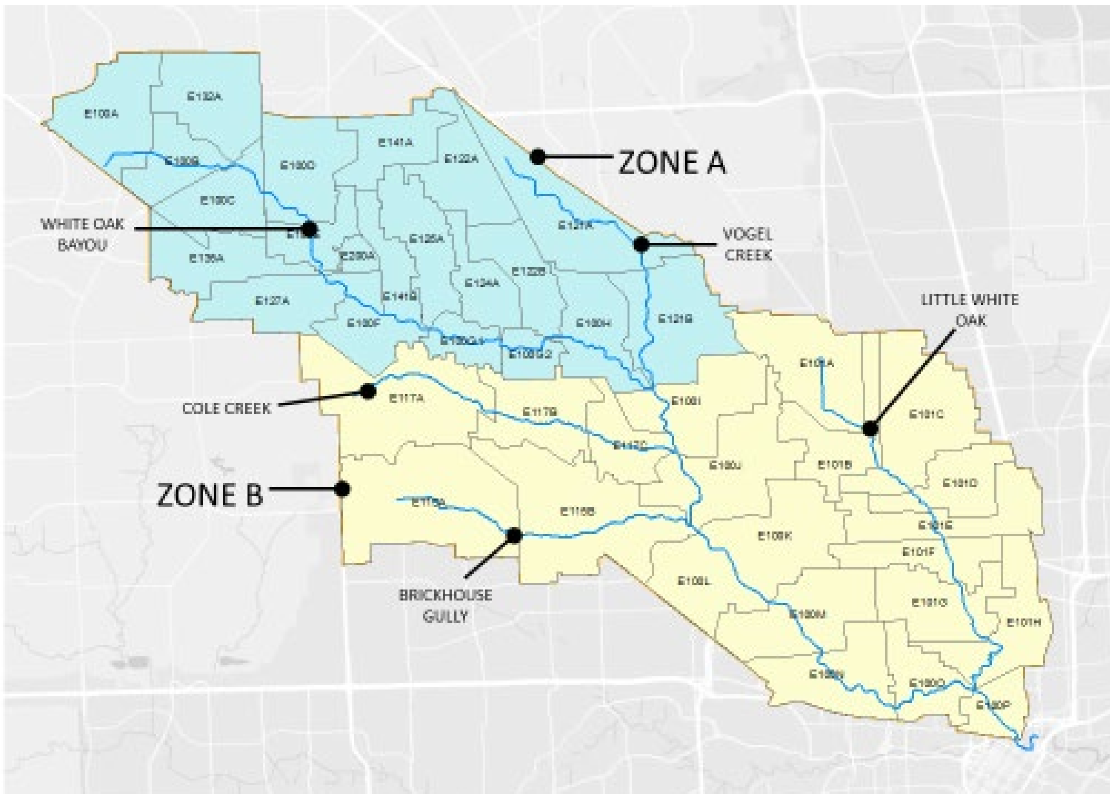



Figure 3.34 White Oak Bayou upstream (A) and downstream (B) areas

## HUNTING BAYOU

The figure below shows the division of FPML zones for Hunting Bayou watershed. The upstream portion, Zone A, covers approximately 13.7 $mi^2$, and includes the contributing drainage area shown in blue. The downstream portion, Zone B, covers approximately 17.3 $mi^2$, and includes the drainage areas from Lower Hunting Bayou in yellow.

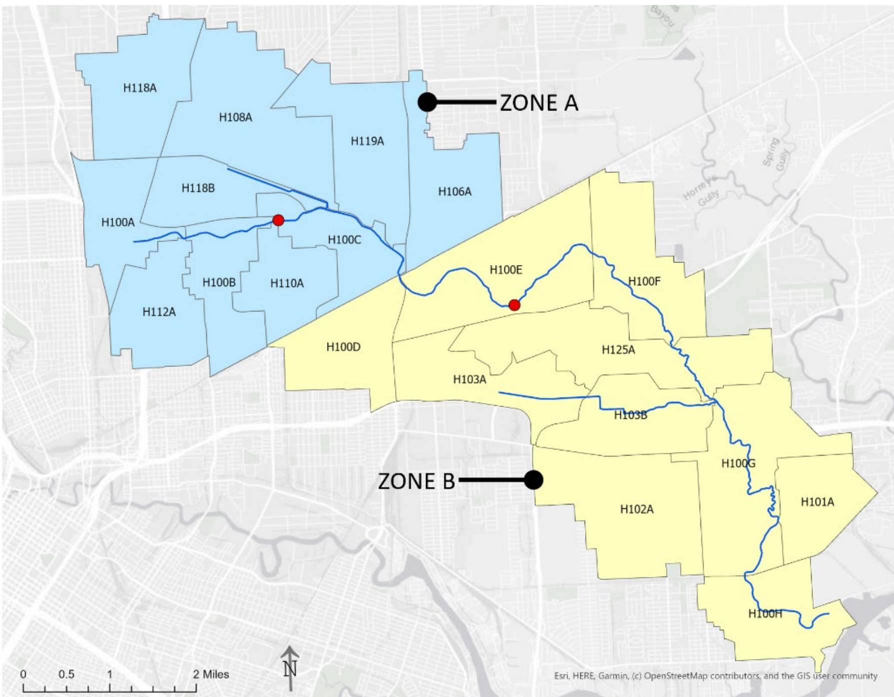



Figure 3.35 Hunting Bayou upstream (A) and downstream (B) areas

## SIMS BAYOU/SUNNYSIDE

Zone A for Sunnyside includes the upper portion of Sims Bayou watershed that drains into the Sunnyside neighborhood. Zone B is the Sunnyside region, which includes subbasins C100H, C100I, C118, and C132. FPMLs for this watershed are focused on the Sunnyside neighborhood. Unlike the FPMLS for the three other watersheds, the FPMLs for Sims / Sunnyside were generated using HEC-RAS 2D.

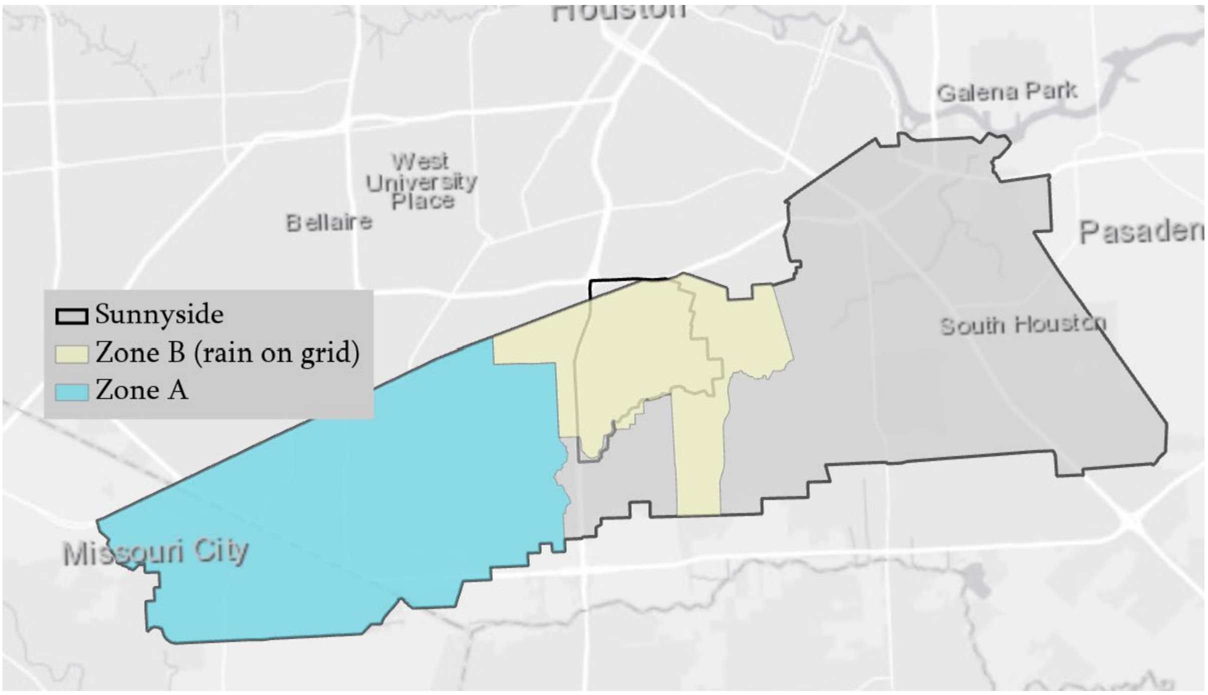



**Figure 3.36** Sims Bayou upstream (A) and downstream (B) areas

## RAINFALL SCENARIOS

The FPML rainfall scenarios were chosen to represent the approximate equivalent of a 10 to 100 year storm in Houston, based on the NOAA Atlas 14 rainfall frequencies, for durations of six hours, twelve hours, and 24 hours. As seen in Table 3.9, for a 6-hour duration storm this ranges from 6 to 11 inches, for a 12-hour duration storm this ranges from 7 to 14 inches, and for a 24-hour duration this ranges from around 9 to 17 inches. Correspondingly, the following rainfall scenarios for the FPML were chosen. For 6-hour design storms, 5, 7, 9, 11, and 13 inches of rain were used. For 12-hour design storms, 7, 9, 11, 13, and 15 inches of rain were used. For 24-hour design storms, 9, 11, 13, 15, and 18 inches of rain were used. Each rainfall duration had five different rainfall depths, which could be applied separately to Zone A and zone B, resulting in 25 rainfall scenarios per duration, or a total of 75 rainfall scenarios per watershed.

Table 3.9 NOAA Atlas 14 (2018) rainfalls frequencies for Houston

| **Atlas 14 Precipitation Frequency Estimates (inches)** | | | | | |
|---|---|---|---|---|---|
| | Return Period (years) | | | | |
| **Duration** | 5 | 10 | 25 | 50 | 100 |
| **6-hour** | 4.95 | 6.13 | 7.93 | 9.49 | 11.3 |
| **12-hour** | - | 7.35 | 9.64 | 11.6 | 14.0 |
| **24-hour** | - | 8.70 | 11.5 | 14.0 | 16.9 |

Each rainfall scenario was entered into HEC-HMS using one design gage to represent Zone A, and one design gage to represent Zone B, each having a hyetograph with a total cumulative rainfall equal to the chosen rainfall depth for that scenario. The SCS Type III distribution was used to create these synthetic hyetographs. The resulting hydrograph peaks for 75 combinations were then entered into HEC-RAS to create the floodplain map library for each watershed.

# V. CRITICAL FACILITIES BY WATERSHED

## BRAYS BAYOU

The critical facilities included in this analysis include five hospitals, three fire stations, three nursing homes, and three storm shelters for a total of 14 selected locations. The critical facilities were selected in order to be relatively evenly distributed throughout the FEMA 500 year floodplain, and their names and addresses are as follows:

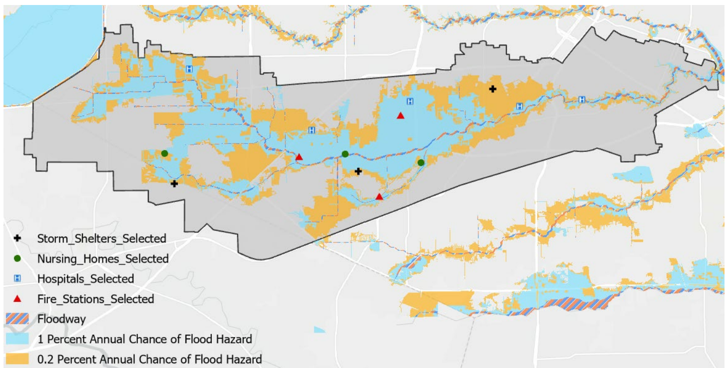



Figure 3.37 Critical Locations Within the 500-year Floodplain of Brays Bayou

### STORM SHELTERS

- Saint Thomas Aquinas Catholic Church (12627 West Bellfort Ave, Sugar Land, TX, 77478)
- Christ The King Lutheran Church (2353 Rice Blvd, Houston, TX, 77005)
- St. Thomas More Catholic Church (10330 Hillcroft St, Houston, TX, 77096)

### NURSING HOMES

- Royal Personal Care (12922 Becklin LN, Houston, TX, 77099)
- Seven Acres Jewish Senior Care Services Inc (6200 N Braeswood, Houston, TX, 77074)
- Autumn Leaves of Meyerland (4710 W Bellfort ST, Houston, TX, 77035)

### HOSPITALS

- Harris Health System Quentin Mease Hospital (3601 North Macgregor Way, Houton, TX, 77004)
- University of Texas M.D. Anderson Cancer Center (1515 Holcombe Blvd, Box 43, Houston, TX, 77030)
- Memorial Hermann Southwest Hospital (7600 Beechnut Street, Houston, TX, 77074)
- HCA Houston Healthcare West (12141 Richmond Avenue, Houston, TX, 77082)
- First Street Hospital (4801 Bissonet, Bellaire, TX, 77401)

### FIRE STATIONS

- Houston Fire Department Station 68 (8602 Bissonnet Street, Houston, TX, 77074)
- Bellaire Fire Department (5101 Jessamine Street, Bellaire, TX, 77401)
- Houston Fire Department / Emergency Medical Services Station 48 (11616 Chimney Rock Road, Houston, TX, 77035)

## WHITE OAK BAYOU

The critical facilities included in this analysis include five hospitals, two fire stations, four nursing homes, and four storm shelters for a total of 15 selected locations. The critical facilities were selected in order to be relatively evenly distributed throughout the FEMA 500 year floodplain, and their names and addresses are as follows:

### NURSING HOMES

- Winterhaven Healthcare Center (6531 Stuebner Airline Rd., Houston, TX 77091)
- Elmcroft of Cy-Fair (11246 Fallbrook, Houston, TX 77065)
- Woodwind Lakes Health and Rehabilitation Center (7215 Windfern Rd., Houston, TX 77040
- Brookdale the Heights (2121 Pinegate Dr., Houston, TX 77008)

### STORM SHELTERS

- Deliverance Temple Church of the Living God (451 Victoria Dr., Houston, TX 77022)
- All Nations Family Worship Center (3511 Pinemont, Houston, TX 77018)
- Edgewood Elementary School - Spring Branch ISD (8757 Kempwood Dr., Houston, TX 77080)
- St. Maximillian Kolbe Catholic Church (10135 West Rd., Houston, TX 77095)

### HOSPITALS

- Kindred Hospital Houston Northwest (11297 Fallbrook Dr., Houston, TX 77065)
- United Memorial Medical Center (510 West Tidwell Rd., Houston, TX 77070)
- Kindred Hospital the Heights (1800 West 26th St., Houston, TX 77008)
- Memorial Hermann Greater Heights Hospital (1635 North Loop West, Houston, TX, 77008)
- Cypress Fairbanks Medical Center (10655 Steepletop Dr., Houston, TX 77065

### FIRE STATIONS

- Houston Fire Department Station 4 (6530 West Little York Rd., Houston, Tx 77088)
- Houston Fire Department / Emergency Medical Services Station 13 (2215 West 43rd St., Houston, TX 77018)

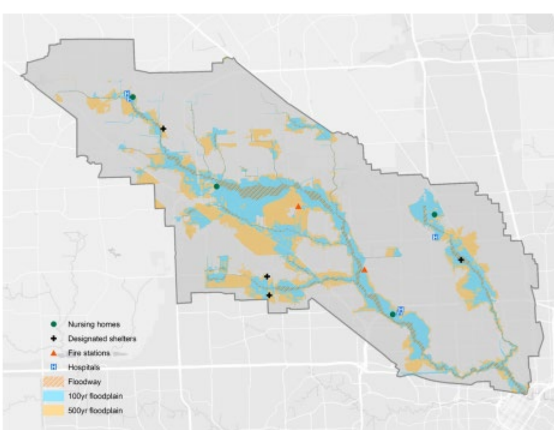



Figure 3.38 Critical Locations Within the 500-year Floodplain of White Oak Bayou

## HUNTING BAYOU

The critical facilities included in this analysis include one hospital, one fire station, two nursing homes, three shelters, three urgent care facilities, and six public schools for a total of 16 selected locations.

The majority of the critical facilities selected are located in the upstream portion of the watershed, within the Kashmere Gardens neighborhood, and their names and addresses are as follows:

- Lyndon B. Johnson Hospital (5656 Kelley St, Houston, TX 77026)
- Houston Fire Station 39 (5810 Pickfair St, Houston, TX 77026)
- Rainbow Gardens Care Home (3110 Lebadie St, Houston, TX 77026)
- Pinnacle Living Center Inc. (3127 Collingsworth St, Houston, TX 77026)
- Francis Scott Key Middle School (4000 Kelley St, Houston, TX 77026)
- McCrane-Kashmere Gardens Neighborhood Library (4802 Lockwood Dr, TX 77026)
- Betsy Ross Elementary School (2819 Bay St, Houston, TX 77026)
- Barbara Jordan Career Center (5800 Eastex Fwy, Houston, TX 77026)
- Kashmere Gardens Elementary (4901 Lockwood Dr, Houston, TX 77026)
- Fleming Middle School (4910 Collingsworth St, Houston, TX 77026)
- McGowen Elementary School (6820 Homestead Rd, Houston, TX 77028)

The remaining critical facilities are located in the downstream portion of the watershed and include one shelter, three urgent care facilities, and one public school:

- North Shore Community Fellowship of Faith Church (444 Maxey Rd, Houston, TX 77013)
- Concentra Urgent Care (8799 N Loop E Fwy Ste. 110, Houston, TX 77029)
- Concentra Urgent Care (10909 East Fwy, Houston, TX 77029)
- East Houston Urgent Care (11410 East Fwy #168, Houston, TX 77029)
- The Varnett School - East (804 Maxey Rd, Houston, TX 77013)

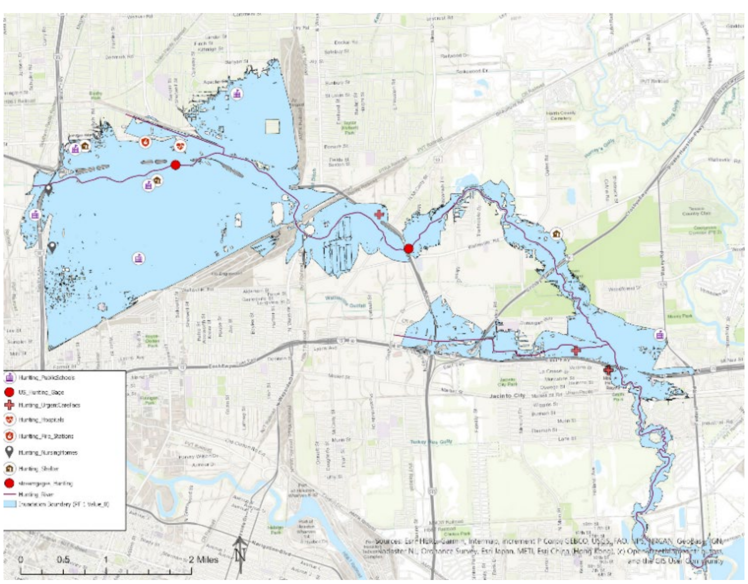


Figure 3.39 Critical Locations Within the 500-year Floodplain of Hunting Bayou.

## SUNNYSIDE

15 critical infrastructures were selected within and nearby Sunnyside as points of interest. No hospitals were selected as there are no hospitals in or nearby Sunnyside. The list is as follows:

### SHELTERS

- HCC (Houston Community College Warehouse)
- St. Paul Missionary Baptist Church
- Sunnyside Multi-Service Center
- St. Francis Xavier Catholic Church – Parish Hall
- Greater St. Matthew Church – Booker Family Life Center

### NURSING HOMES

- Mentis Neuro Health
- Terra Bella Health and Wellness Suites
- Mallow Place
- Treasure Tower Assisted Living
- The Brinkley House
- Cottage Grove Living LLC
- Outreach Assisted Living Facility II
- EFE Assisted Living Center Inc

### FIRE STATIONS

- Houston Fire Department Station 24
- Houston Fire Department/Emergency Medical Services Station 35

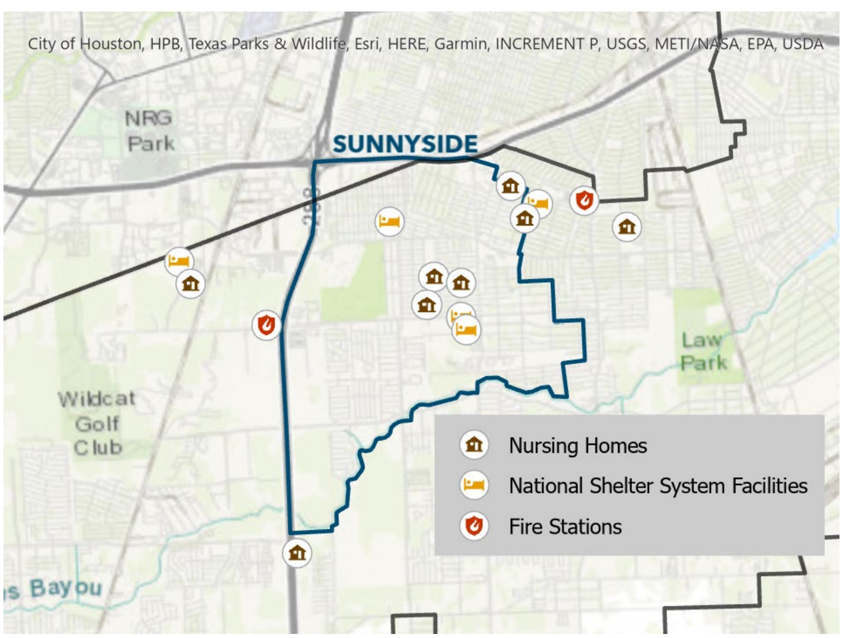
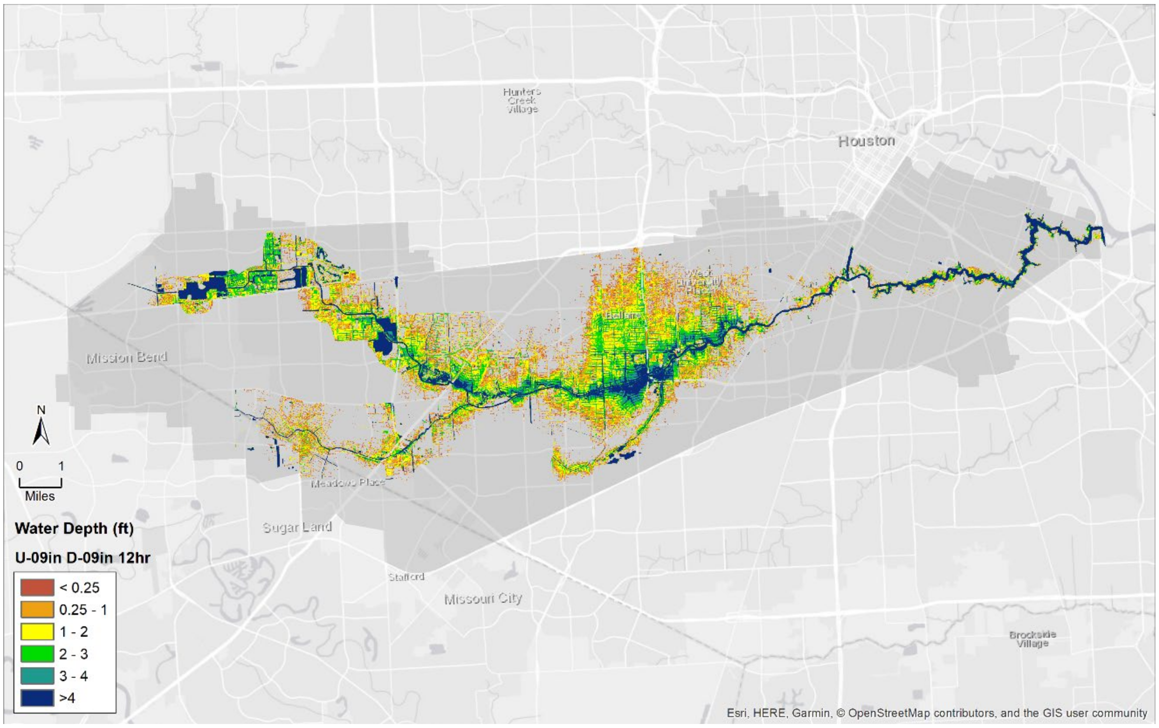
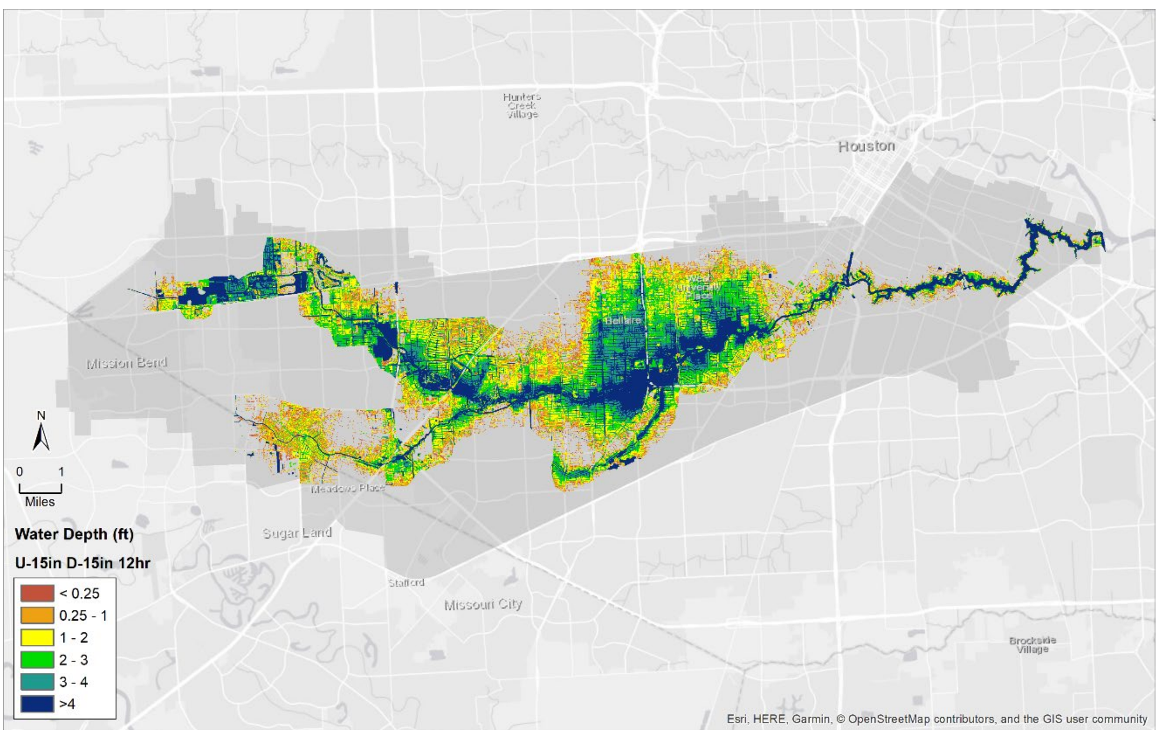



Figure 3.40 Critical Locations within Sunnyside

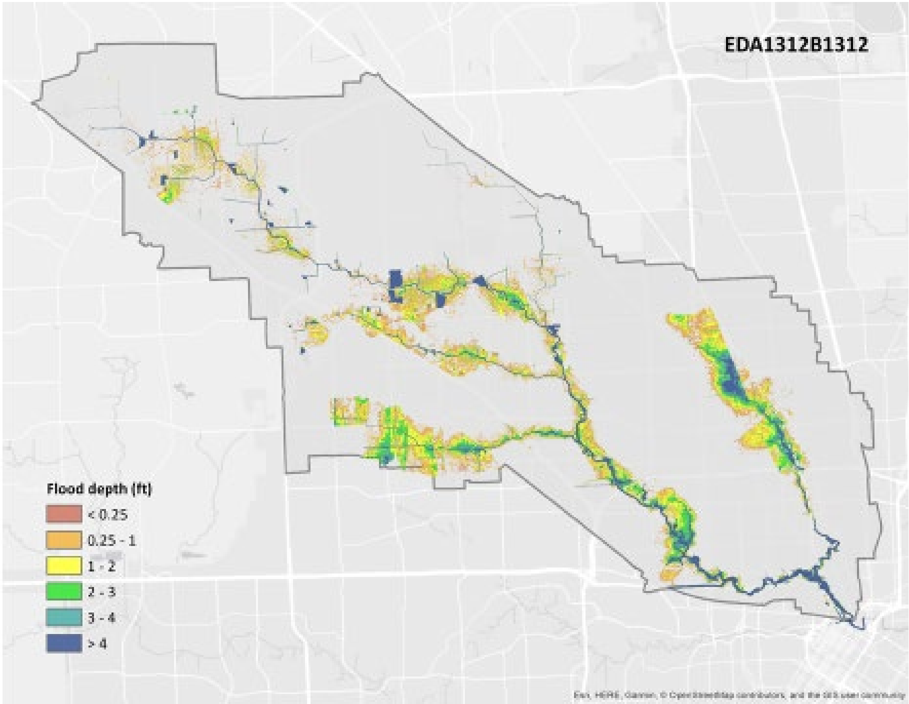
# VI. EXAMPLE FPMLS FOR SELECT WATERSHEDS

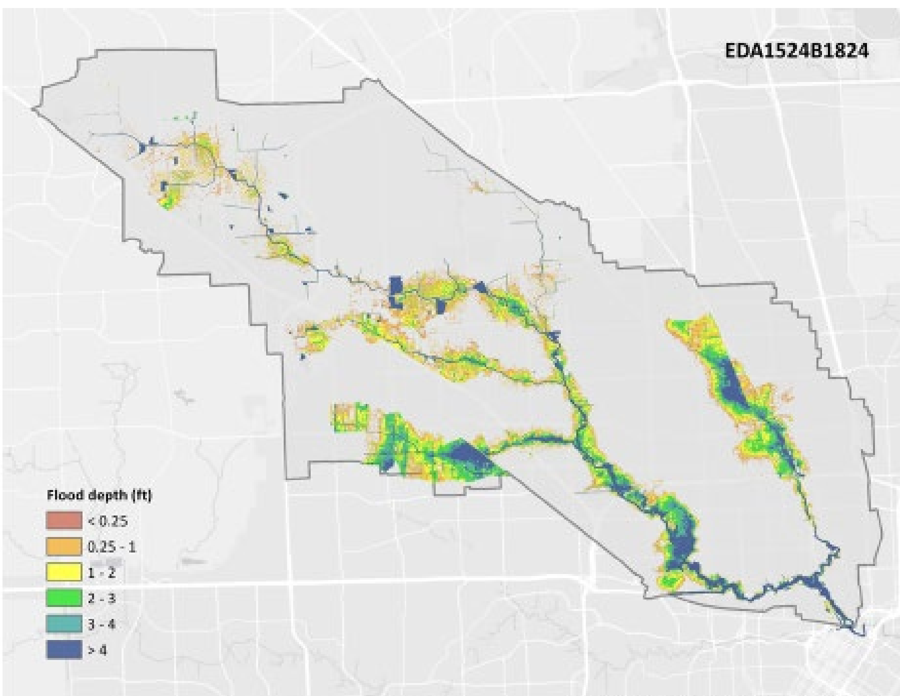
## BRAYS BAYOU



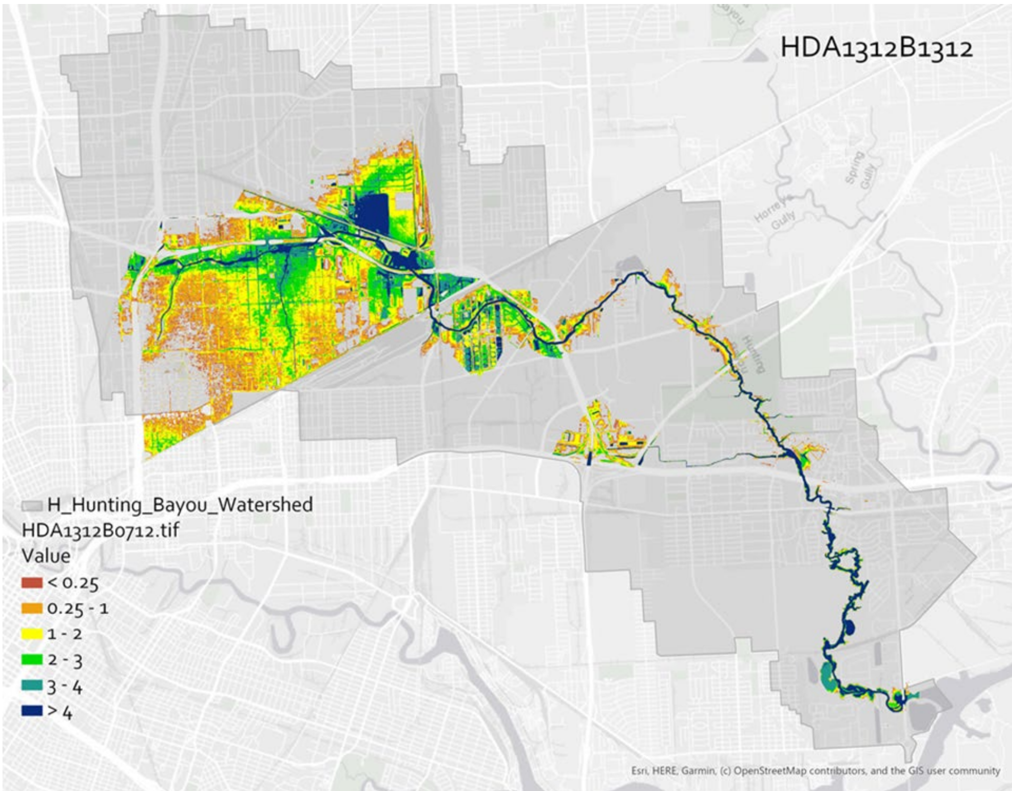



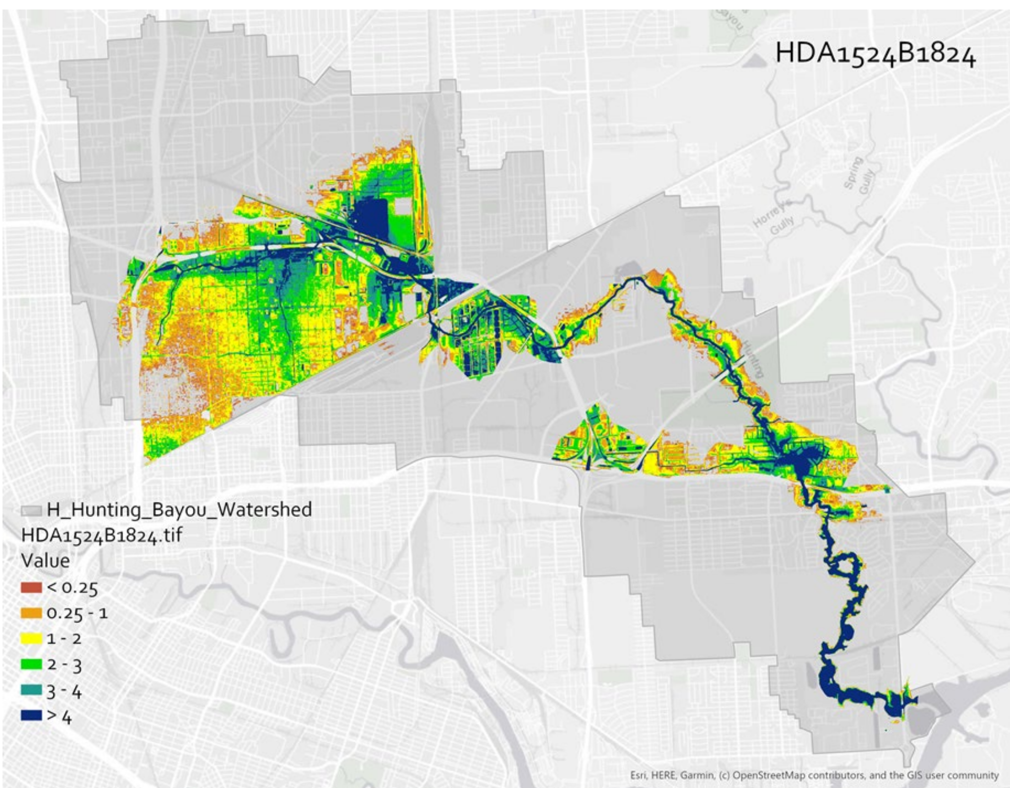
## WHITE OAK BAYOU



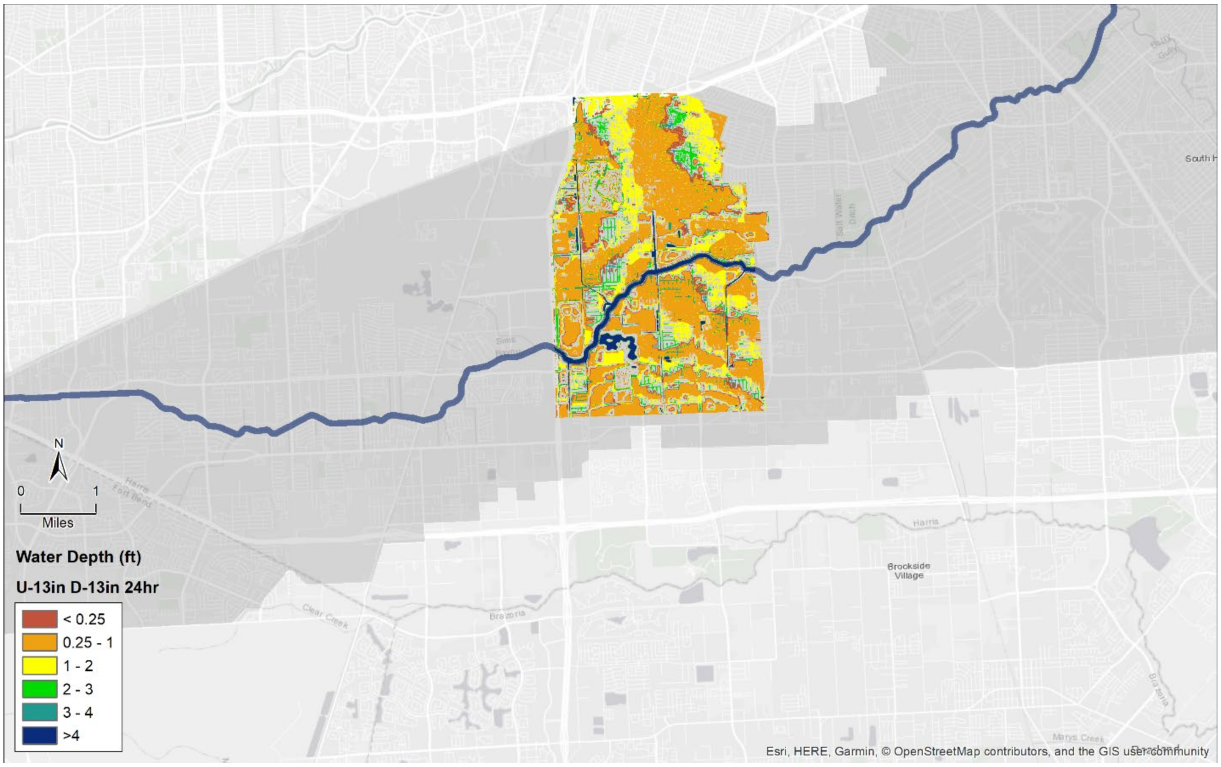



## HUNTING BAYOU



## SUNNYSIDE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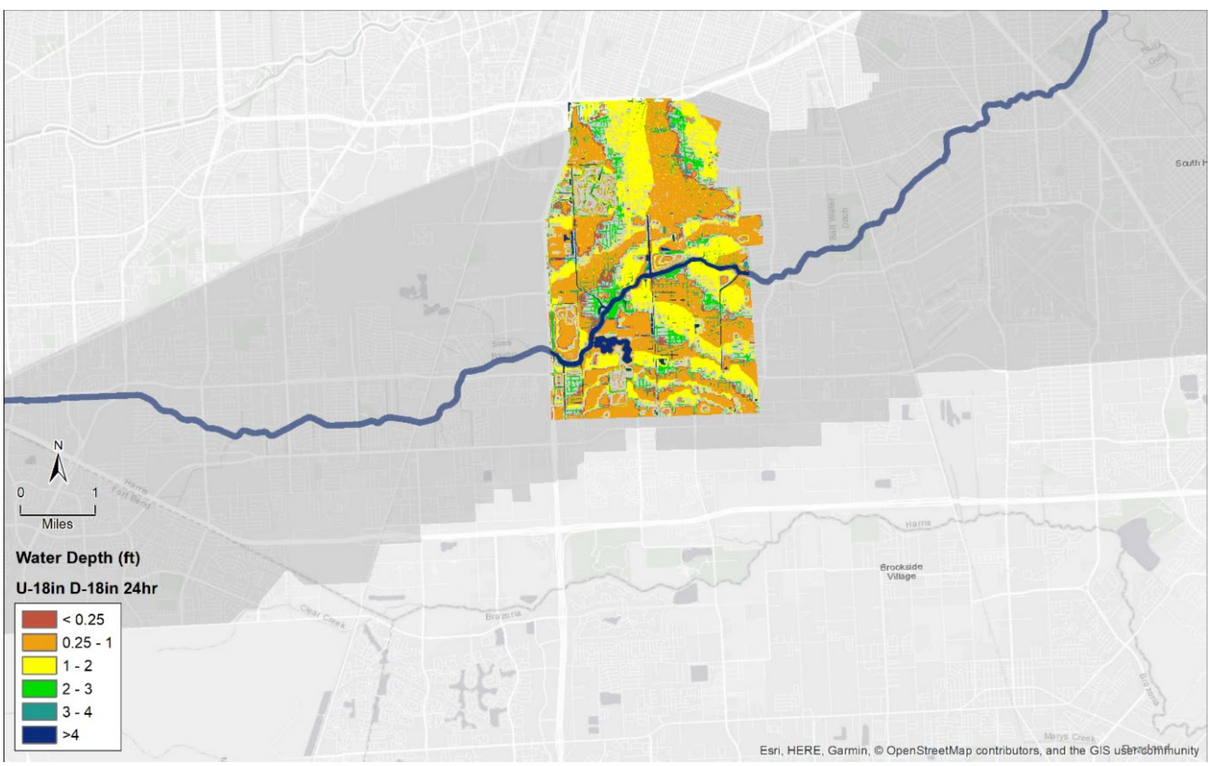
Brookside Village
Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community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Brookside Village
Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community

# VII. REAL-TIME WEB-BASED FLOOD INFORMATION SYSTEM

## METHODOLOGY OF COH FIRST SYSTEM

The Flood Information & Response System (FIRST) for the City of Houston (COH) is developed by a joint research team from the SSPEED Center at Rice University and the Fang Research Group (FRG) at the University of Texas at Arlington (UTA). The FIRST system currently covers four major watersheds in COH: Brays Bayou, Hunting Bayou, Sims Bayou Sunnyside, and White Oak Bayou. The FIRST is currently hosted at Amazon Web Services with an IP address of: http://ip/map. The state-of-the art of the FIRST system can (**A**) display rainfall intensity for all the sub-catchments of the four major watersheds in real time, and (**B**) forecast the flood inundation maps over the watersheds using NEXRAD radar rainfall data provided by Vieux & Associates, Inc. – one of the best radar rainfall data providers in the nation.

## FIRST ENABLED BY ESRI ARCMAP ONLINE

With the popularity of ArcMap Online – a web-based mapping application provided by Esri, the FIRST system is able to display the floodplain inundation maps within the ArcMap online map frame, serving as the main platform to provide real-time rainfall visualization, flood warnings, and monitor flood risks. **Figure 7.1** illustrates a map depicting the four major watersheds within ArcMap Online Platform on the FIRST website. This map shows outlines of watersheds (grey) and their sub-basins (black).

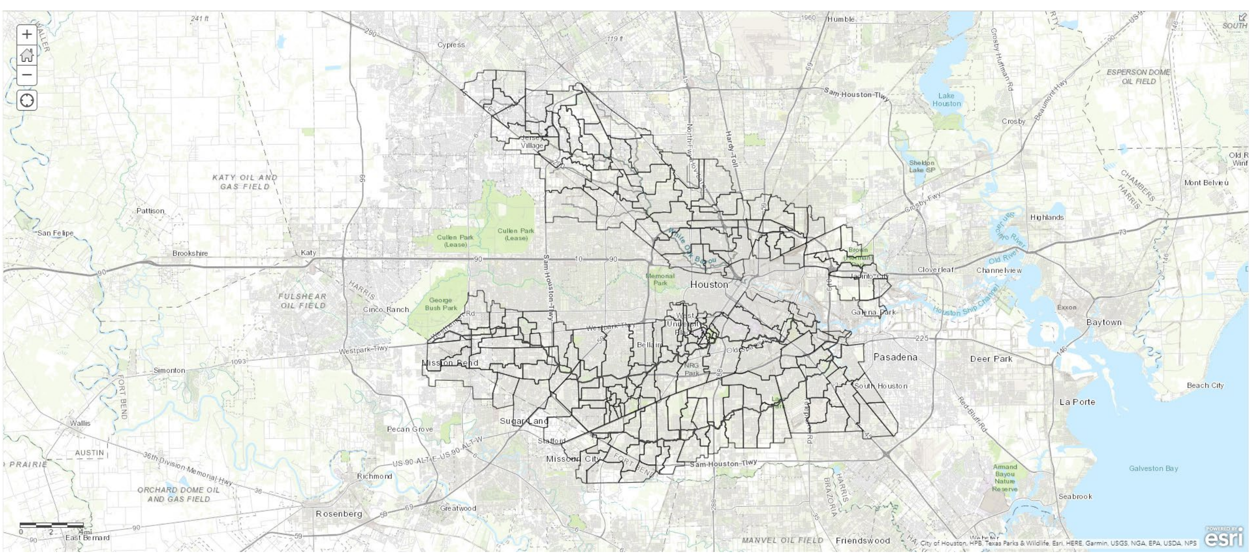


Figure 7.1 FIRST Layout

## REAL-TIME RADAR RAINFALL

The FIRST receives real-time radar rainfall data from Vieux & Associates Inc. (VAI), one of the premier data vendors in the nation Vieux Inc. VAI provides the near real-time (NRT) Gauge Adjusted Radar Rainfall

(GARR) data for this project based on their radar rainfall processing system using the local NWS NEXRAD, KHGX, an S-band weather radars. This radar rainfall data will also be provided by VAI directly to the COH for its use in real-time. The following references relate to radar rainfall conversion to runoff: Bedient, Philip B., et al., 2000; Bedient, Philip B., et al., 2003; Vieux, B. E., et al., 2005; Vieux, Baxter E., 2006.

The U.S. National Weather Service (NWS) along with other agencies deployed a network of weather surveillance radars for nationwide coverage. These radars are known as the WSR-88D, and more commonly as NEXt generation RADar, or NEXRAD. Crum and Alberty (1993) describe the WSR-88D system design and radar products. This radar is a Doppler radar with 10-cm wavelength (S-band) transmitter that records reflectivity, radial velocity, and spectrum width. S-band radars have a 10-cm wavelength which easily penetrates heavy rainfall making it useful for hydrologic applications. The WSR-88D is a volume-scanning radar, meaning that successive tilt angles are employed to cover large volumes of atmosphere out to 460 km for reflectivity and 230 km for precipitation, velocity and spectrum width. Each volume scan starts at a tilt angle of 0.5 degrees. Sensitivity of the NEXRAD system was examined by Vieux and Bedient (1998) for a historical extreme event in October of 1994 that caused widespread flooding in Houston and more than 100 Texas counties.

Depending on the volume coverage pattern (VCP) used to identify different types of meteorological phenomena, the time taken to complete the volume scan varies, affecting the time step of rainfall inputs derived from radar. Scanning strategies and development of new VCPs are continuing to change as the NWS makes operational changes to the system. Three weather conditions determine the number of sweeps/volume scan (one complete revolution at a particular tilt): 14 tilts during severe precipitation events, 9 tilts during non-severe precipitation events, and 5 during clear air conditions. Correspondingly, the rates of data acquisition are one volume scan per 5, 6, and 10 minutes for VCP 11, VCP21, and VCP31/32, respectively. If the radar is operating with VCP 11, the temporal update of reflectivity is every five minutes, which means that the smallest time increment for input to a hydrologic model is 5 minutes. Radar scanning characteristics of the recorded reflectivity affect the intervals at which rainfall rates are updated. When used in hydrologic applications, the time intervals between recorded reflectivity have important consequences on model results, depending on scale and application of the radar rainfall estimates. The NWS added two new VCPs in 2004 that the radar operator may use. A consequence of the VCP used in operations is that derived rainfall rate estimates will have variable temporal update frequencies ranging from more or less 5 minutes. Details on the NEXRAD system and its use in hydraulic and hydrologic modeling are found in Vieux (2016).

NRT GARR system redundancy is provided by Vieux consisting of backup radar products and data processing failover. Vieux provides a spatially distributed rain gauge only product in the case of radar system outages. Several dozen quality control algorithms are automatically applied to limit both radar and rain gauge errors. Automated system monitoring and support team notification supports system reliability. The Vieux hydrometeorology (Hydromet) team monitors the system and adjusts the radar Z-R relationship as appropriate to support a high level of accuracy. These bias-correction procedures have been implemented similarly to the US National Weather Service, but with key differences: 1) more rigorous gauge analysis and exclusion, 2) more representative conversion of radar reflectivity to rainfall using derived seasonal Z-R relationships for individual radars, and 3) higher quality control of radar (and gauge) anomalies. Local bias and mean field bias adjustment schemes are presented in Vieux and Vieux (2005). For hydrologic applications, the local bias technique has proven useful as described in Vieux (2016) for analysis of improved hydrologic prediction using locally biased radar versus gauge-only used as real-time flood forecasting input.

The Vieux system ingests NEXRAD Level III data including multiple elevation angles and dual polarization to reduce anomalies and partial beam blockages over the target basins. The system leverages a range of dual polarization filters that minimize ground clutter and performs vertical continuity checks. Bias correction is applied every 5-minutes and processing for the past hour and a half is repeated every 5-minutes. This improves the GARR by including rain gauge data that might not have reported in the most recent increment. Harris County Flood Control District (HCFCD) rain gauge data is ingested. A maximum bias is established, and a memory bias persists for an hour after the last adjustment is applied.

As with any measurement, both systematic and random errors are inherent in the process. Removing systematic error (bias) is achieved by applying a correction factor. This correction is often termed calibration or adjustment, or bias correction. The benefit of combining radar and gauges is reduced systematic error in the radar-derived precipitation measurement. Removing the bias has a major influence on hydrologic predictions. When bias corrected radar data was input into a hydrologic model, the hydrograph rising limb and peak flow proved more accurate than the hydrographs produced from the rain gauge data alone. Another advantage of radar over rain gauge networks for rainfall estimation is the density of measurement. Looper and Vieux (2012) demonstrated that hydrologic prediction accuracy improves when using bias-corrected radar in a distributed flood forecasting system.

## REAL-TIME GARR PROCESSING

1. Ingest Level II and III reflectivity data from NEXRAD
    - 1.1. Apply QC algorithms to mitigate ground clutter and anomalous propagation
    - 1.2. Convert reflectivity to rainfall rates using selected Z-R relationships
    - 1.3. Filter radar data into temporal aggregations
2. Ingest available rain gauge network data
    - 2.1. Filter gauge data into temporal aggregations
    - 2.2. Select available gauges for statistical tests
3. Combine radar/gauge pairs to compute bias correction
    - 3.1. Remove radar/gauge pairs that do not meet statistical criteria
    - 3.2. Process gauge-adjusted radar rainfall using local bias corrections
    - 3.3. Generate accuracy statistics, calibrated average difference, and number of gauges used
4. Populate database and generate output at 15-minute intervals.
5. Produce final output formats for 1x1 km pixels and basin aggregations

In support of this project, the GARR NRT processing provided by Vieux consists of GARR output formats for the target basin delineations as weighted basin averages for each 15-minute increment, placed on the project FTP site, and updated every 15-minutes. The data will be collected and stored in the FIRST data sever on a corresponding frequency.

## RAINFALL VISUALIZATION FOR FIRST

When rainfall occurs in one watershed, the FIRST algorithm determines corresponding colors for its sub-basins according to a rainfall estimate in every 15 minutes. Rainfall estimates are updated whenever the FIRST server receives new data. Showing colored rainfall information in ArcMap Online enables emergency personnel to better understand weather conditions during any events. The FIRST system (the website) uses the same algorithm to display rainfall intensity for each sub-catchment as the one used in Flood Alert System 5 for Brays Bayou as shown in **Figure 7.2**. The rainfall information is updated every 15 minutes.

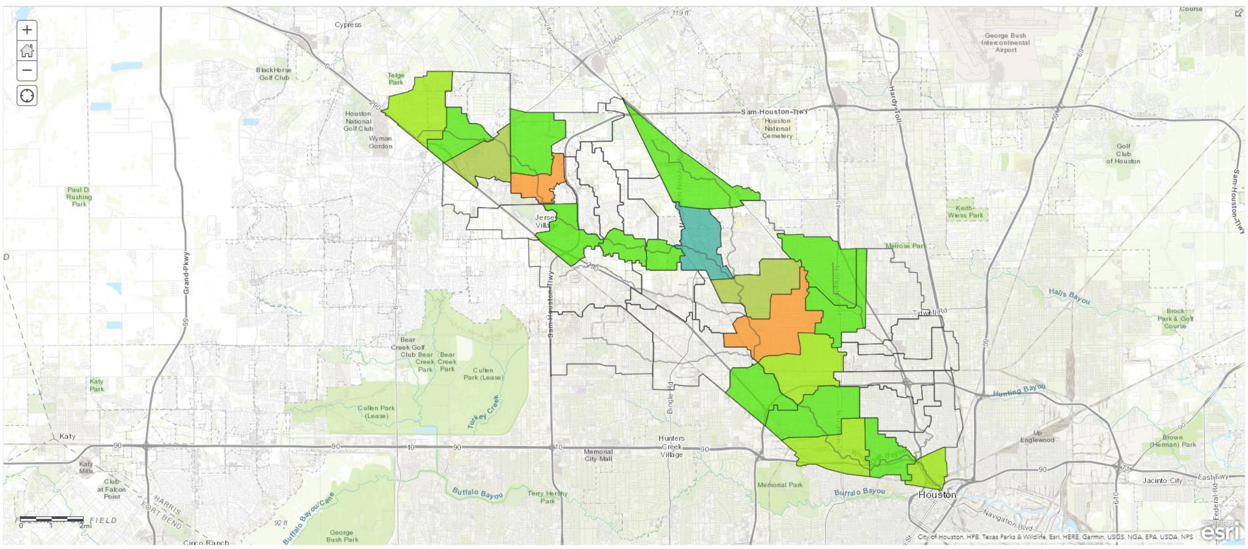

Figure 7.2 Rainfall Information Displayed on White Oak Bayou on FIRST

## FLOODPLAIN MAP LIBRARY (FPML) FOR FIRST

Due to the demand for mapped inundation information by emergency personnel, Fang et al. (2008) introduces a hydraulic prediction tool – Floodplain Map Library (FPML) that provides visual images of flooding conditions as storms progress. The FPML system consists of the maps that were pre-delineated based on various rainfall totals incorporating frequencies, durations, and spatial variations (**Figure 7.3**). Each possible scenario has a unique total rainfall value. The rainfall totals of floodplain maps range from 5 inches to 18 inches, representing an envelope of flooding probabilities between 10-year and 100-year frequencies. These maps allow emergency personnel to know at a glance where flooding will be most severe and which roads are most likely to be inundated. This prediction feature is useful to critical transportation infrastructure because it enables them to understand inundation conditions and initiate appropriate evacuation strategies at many levels to deal with emerging issues.

FIRST is equipped with a newly developed FPML dataset for all four major watersheds. Corresponding flood inundation maps can be called out based on 15-minute rainfall estimates. A robust selection algorithm was scripted in C# and works in the following logic using White Oak Bayou as an example:

1. The 15-minute radar rainfall information is consolidated into two mean areal precipitation (MAP) values in real time for the upstream and downstream sections of White Oak Bayou (U for upstream and D for downstream);
2. The consolidated rainfall information (MAP) is accumulated into three past durations: 6, 12, and 24 hours;
3. The algorithm compares the cumulative MAP values for the upstream and downstream sections against three threshold values: 5, 7, 9, 11, 13, 15, and 18 inches;
4. Once any threshold value is reached for the upstream and downstream sections, an appropriate flood plain map is called up from the pre-delineated Floodplain Map Library (FPML) and displayed on the ArcMap Online platform;
5. The FPML contains 75 floodplain maps that were generated from hydrologic and hydraulic simulations using the Tropical Storm Allison Recovery Project (TSARP) models in advance.

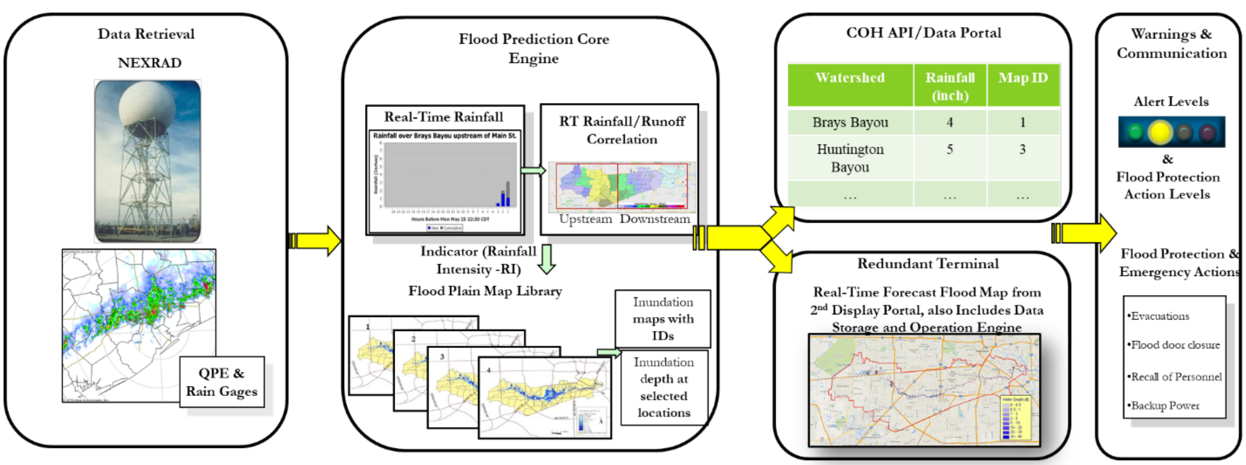


Figure 7.3 Flowchart and Data Operations of FPML

**Figure 7.4** shows one floodplain map in White Oak Bayou watershed of the FIRST's FPML system under a scenario of 8 inches of rainfall over 6 hours and 14 inches rainfall over 12 hours for the upstream and downstream, respectively.

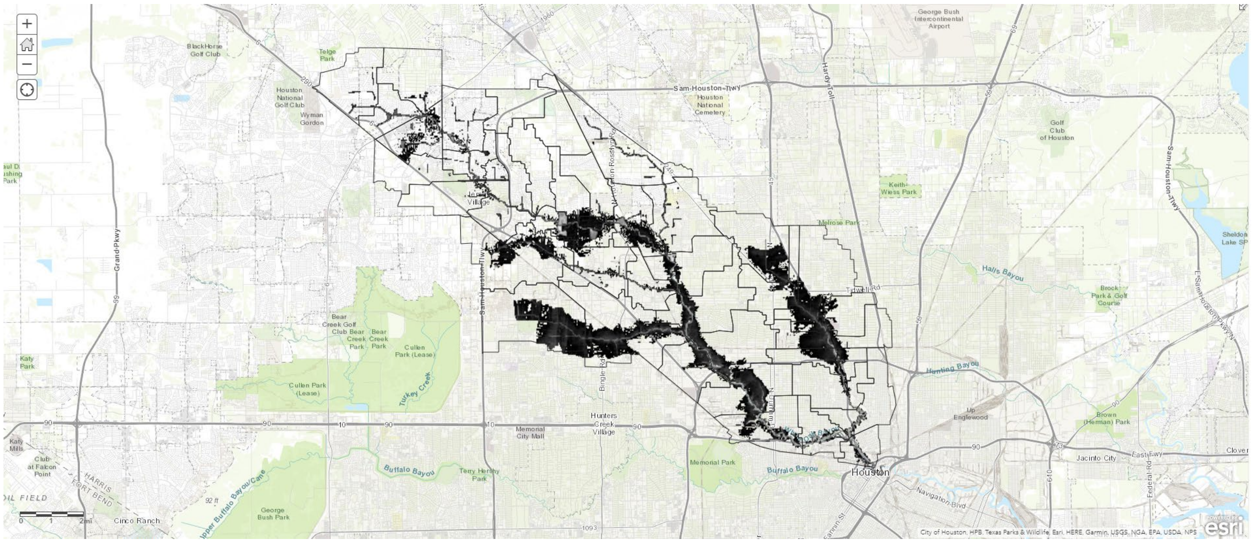

Figure 7.4 Floodplain Displayed on the FIRST

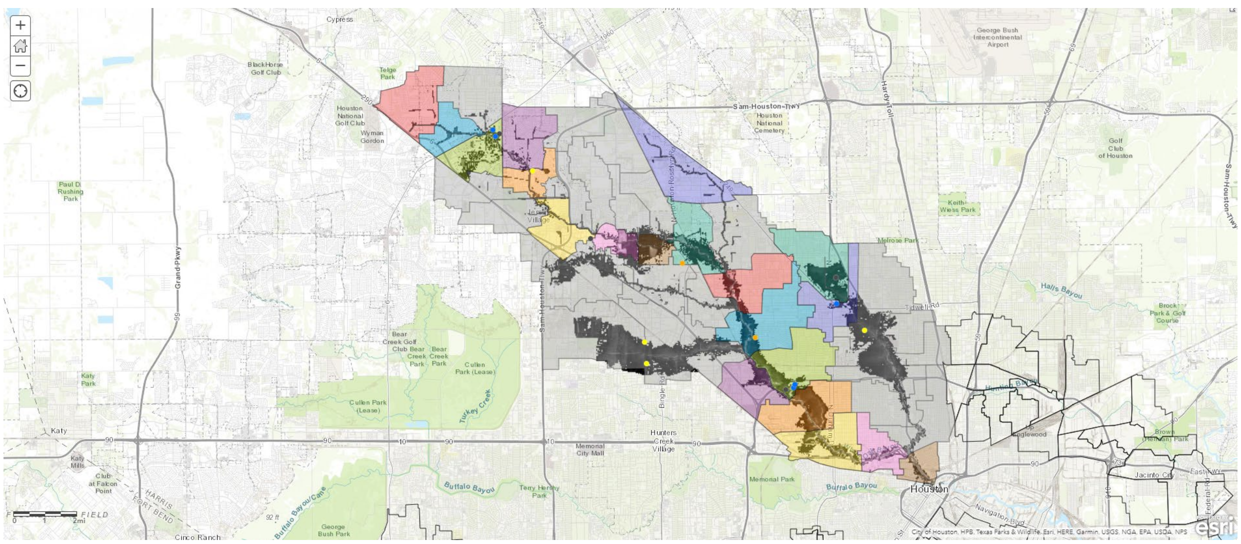

Figure 7.5 Critical Strucure Flood Risk Warning on FIRST

The algorithm was designed to dynamically link the most appropriate floodplain map to the rainfall pattern as a storm progresses based on actual rainfall measurements. **Figure 7.5** demonstrates that the appropriate floodplain map is selected by the algorithm based on the aforementioned logic during a hypothetical event. The system rounds up to the next higher level of floodplain maps based on the real-time rainfall. Not only does the floodplain map library system have the capability of zooming in certain hotspots and major transportation routes that repeatedly suffer flooding in the past but also it demonstrates the flood risks at the selected critical facilities with the symbol color changing from blue to yellow indicating the potential flooding risk. FPML with a hydrologic prediction feature on the interactive web site will provide the end users with comprehensive understanding of dynamic flood response allowing emergency personnel to promptly determine likelihood of road inundations and begin flood preparations with as much lead time as possible.

## FLOOD RISKS FOR CRITICAL FACILITIES

FIRST is designed to visualize the flood inundation maps in relative to the selected critical facilities located within the watersheds, including: hospitals, storm shelters, fire stations, and nursing homes. The flood inundation in terms of water depth and water surface elevation will appear on the map along with the selected critical facilities.

## FIRST DATA MANAGEMENT

The FIRST system interfaces with the data vendor and partners to pull or push data upon their preferences/requirements. The requested data are delivered to the COH's FTP site at a 15 minute frequency. The database/data are stored in the Amazon Web Service (AWS) cloud with the AWS cloud services. The important components of the system including database, running code, etc., are backed up daily in the cloud in case for any emergency and/or interruption. All stored data and inbound data files are periodically archived up to a certain time. The length of the historical data is kept is tentatively set up to two years but can be adjusted upon future budget and the requirements by the COH.

# VIII. LIMITATIONS

The performance and reliability of urban flood warning and mapping systems have improved substantially over the last decade, owing to the availability of NEXRAD radar precipitation and significant advancements in LiDAR and GIS software systems. As a result, real-time, spatially-distributed rainfall that is rapidly updated can be used by hydrologic/hydraulic models to estimate surface runoff, peak discharge, and inundation levels more accurately for specific areas of interest. One particular system, the Rice/Texas Medical Center FAS (see **Figure 8.1**), has been providing reliable hydrologic and flood warning information for the Texas Medical Center since 1997 for over 60 storm events with a forecast $R^2$ value of 90%. The system utilizes the NEXRAD Level II radar/rainfall data coupled with hydrologic/hydraulic models, and a floodplain map library that delivers vital flood information with up to 2-3 hours in advance. It has a user-friendly dashboard that allows users to visualize rainfall progression, Google Maps-based inundation extents, flood alert levels, hydrologic predictions, and real-time monitoring via cameras at the bayou.

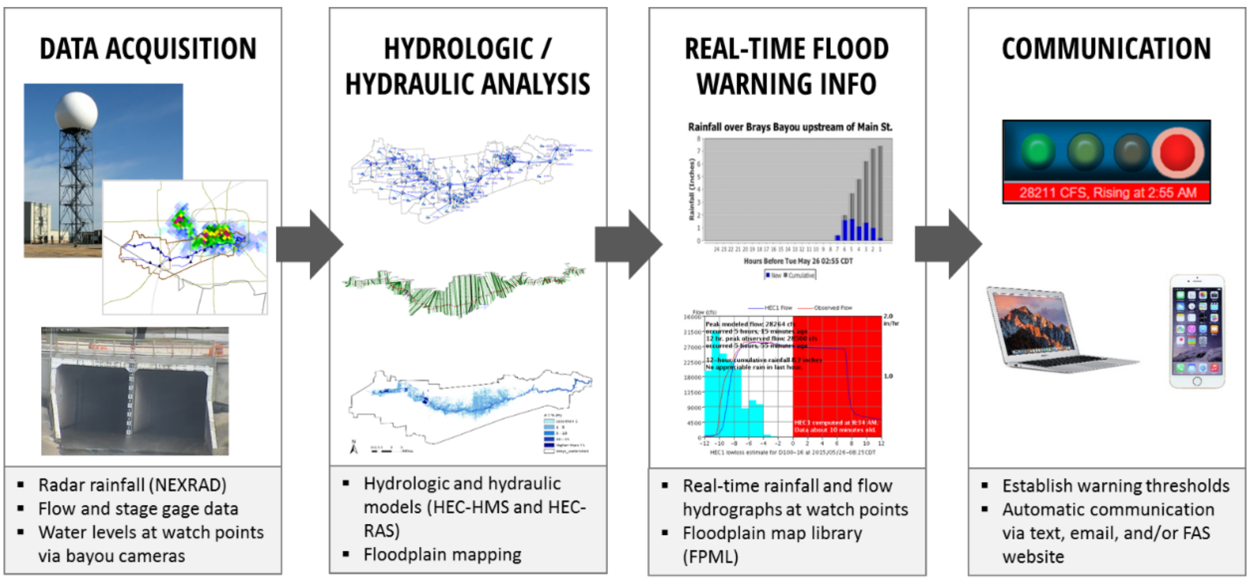


Figure 8.1 The Rice-Texas Medical Center Flood Alert System flowchart

There are limitations with any software and computer based system and field sampling of hydrologic data, and these are discussed briefly below.

## HYDROLOGIC AND HYDRAULIC MODELS FOR THE 4 WATERSHEDS

Hydrologic and hydraulic models were needed for this FIRST project and were obtained from the Harris County Flood Control District (HCFCD). The District developed and calibrated/validated these models as part of its Tropical Storm Allison Recovery Project (TSARP) in the early 2000s and used them to prepare the FEMA floodplain maps for Harris County. The District maintains these models in its M3 library and that is the source from which the hydrologic and hydraulic models used for this project were obtained. While the models are generally reliable for 1D modeling, there may be inherent errors in some of the models, and we actually improved on several of them based on Project Brays, and newer detention information on White Oak Bayou.

## RADAR RAINFALL DATA

Radar rainfall data is being provided from Vieux and Associates, Inc. (VAI), a firm that specializes in obtaining, calibrating and disseminating radar rainfall data for various agencies, including the HCFCD. This radar rainfall data was collected from VAI for the storm events used for calibration/verification of the hydrologic and hydraulic models for the 4 watersheds analyzed for this project. Radar rainfall data is considered the standard today, and VAI is a very reliable source for gage- adjusted radar rainfall (GARR).

## SPATIAL DATASETS (TERRAIN / LIDAR, LAND USE, STREAM GAGES)

Additional datasets were obtained as needed for this project. For example, ground elevation data (terrain data) for these 4 watersheds were obtained from the 2018 LIDAR dataset available for Harris County from TNRIS. In addition, 2016 land use data for the Sunnyside 2D model were obtained from the USGS National Land Cover Database (NLCD). Finally, stream gage data for the historic storms analyzed were obtained both from the HCFCD Flood Warning System (FWS) and from the USGS for their respective gages in the 4 watersheds. All of this type of GIS data can have errors associated with the application of the software analysis system and post processing, but current 2018 LiDAR is the standard in the field and is being used by HCFCD to remap all of Harris County. USGS and HCFCD gage data is generally very reliable and only in a very few cases did we find gages not working. These systems have been in place for decades and are considered very reliable.

## CRITICAL FACILITIES IN THE COH

Various critical facilities located in the City of Houston were identified using a national database known as Homeland Infrastructure Foundation Level Data (HIFLD). Such facilities include WWTPs, hospitals, fire stations, nursing homes, and storm shelters. From this list, a handful of critical facilities were selected for use as “watch points” at which pertinent flood information will be provided as part of the FIRST project. This data is very accurate and should provide a very useful list for the FIRST project as we provide real time inundation levels for selected facilities. This accuracy can only be +/- 1.0 ft due to limitations in the use of an FPML library of maps.

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