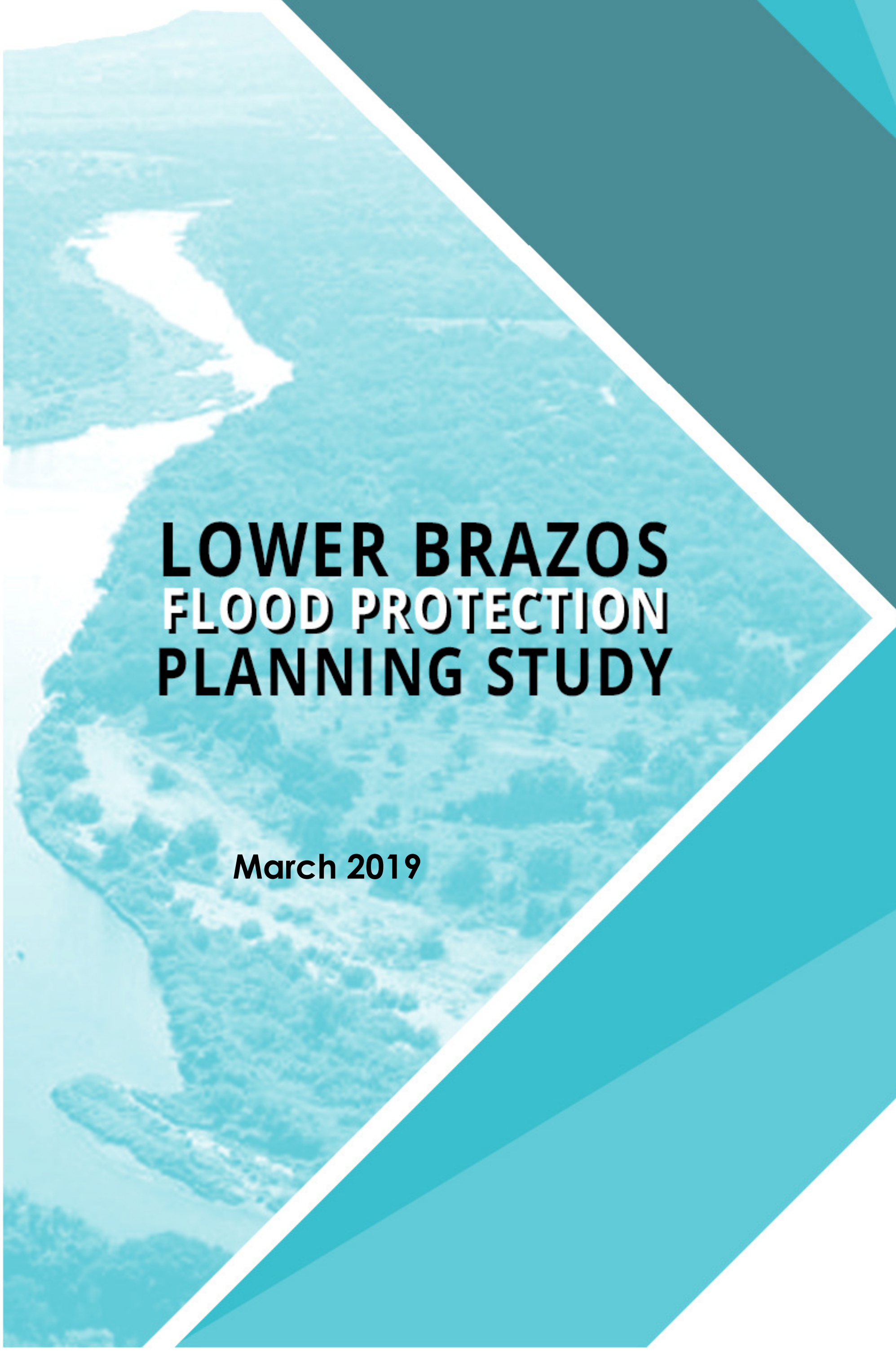
Brazos
RIVER AUTHORITY



LOWER BRAZOS FLOOD PROTECTION PLANNING STUDY

March 2019

HALFF

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Executive Summary

Communities along the Lower Brazos River are threatened by frequent flooding. Numerous cities, counties, districts, as well as a petrochemical industry and a thriving port on the coast are connected by the Brazos River. The basin has experienced major floods with 24 major flooding events (discharge greater than 70,000 cubic feet per second) at the Richmond U.S. Geological Survey (USGS) gauge. Record major floods have occurred as recently as 2016 and 2017. Approximately 140,000 people are estimated to reside within the Lower Brazos River current effective 1-percent annual chance exceedance (1% ACE) floodplain with approximately 51,000 insurable structures worth $19.4 billion. The hydrologic and hydraulic models for the majority of the Brazos River from Waller County to the Gulf of Mexico are based on outdated analysis and studies that cover political boundaries. Therefore, a comprehensive basin-based floodplain protection plan was necessary to more accurately determine the overall existing flood hazards and determine the feasibility of flood reduction alternatives.

The Brazos River Authority (BRA) was awarded a Texas Water Development Board (TWDB) Flood Protection Grant for the development of the Lower Brazos Floodplain Protection Planning Study. In addition to BRA, eight stakeholders participated financially in the study including: Brazoria County, Waller County, Washington County, Lake Jackson, Sandy Point, Sugar Land, Velasco Drainage District, and Pecan Grove MUD. Fort Bend County provided a recently developed hydraulic model of the Brazos River to incorporate into the study. Multiple public meetings, stakeholder meetings, and coordination meetings were held throughout the Lower Brazos Floodplain Protection Planning Study. Meetings where held at locations throughout the lower basin including Richmond, Rosharon, Hempstead, Rosenberg, Angleton, and Prairie View.

The total Brazos River Basin is approximately 44,620 square miles. According to the USGS, 9,600 square miles are classified as non-contributing. Approximately 10,000 square miles of the total Brazos River Basin is located below U.S. Army Corps of Engineers (USACE) reservoirs. Hydrologic and hydraulic analyses of the lower basin were conducted with the goal of calculating updated discharge rates and water surface elevations in the Brazos River for the 10%, 2%, 1% and 0.2% ACE storm events. The hydrologic analysis included both a historical gauge frequency analysis to establish frequency peak discharge conditions (both unregulated and regulated) at key locations within the basin and the development of a calibrated hydrologic model. The hydrologic model generated peak discharges for the 10%, 2%, 1% and 0.2% ACE storm events that were consistent with the gauge frequency analysis at the Hempstead and Richmond USGS streamflow gauges.

To calculate water surface elevations and final discharge rates in the Brazos River for the 10%, 2%, 1% and 0.2% ACE storm events, a 1-dimensional (1-D) unsteady hydraulic model was developed from the Waller/Grimes County line downstream to the Gulf of Mexico. Over 220 miles of the Brazos River were included in the hydraulic model along with multiple overflow streams (Bessies Creek, Jones Creek, Ditch H, and Oyster Creek). LiDAR and field survey data were utilized for the hydraulic model development upstream and downstream of Fort Bend County. The geometry of the existing Fort Bend County 2009 hydraulic model was incorporated into the overall Lower Brazos River hydraulic model. The incorporated hydraulic model included bridge structures, levees and overflow areas that were identified within the study area.

Discharges generated with the hydrologic model (HEC-HMS) were routed through the hydraulic (HEC-RAS) model to calculate water surface elevations and final discharges. Three historical storms (2007, 2016, 2017) were used to calibrate the hydraulic model to match the observed water surface elevations at USGS gauges and various high-water marks. Water surface elevations and discharge rates were computed with the Lower Brazos River hydraulic model for the 10%, 2%, 1% and 0.2% ACE events.

The combined hydrologic and hydraulic analyses determined that peak discharges in the Brazos River for the 1% ACE were generally lower than the discharges published in the current effective Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS). However, the resultant 1% ACE water surface elevations at the San Felipe and Richmond USGS gauges were higher than those published in the FIS. The 1% ACE water surface elevations and discharges from the hydrologic and hydraulic analyses are compared to the FIS in Table ES1. Higher water surface elevations for the 1% ACE showed an increased flood risk at various locations and less available freeboard for several levees along the Lower Brazos River, especially near Richmond. In general, the 1% ACE inundation extents were similar to the FEMA Flood Insurance Rate Maps (FIRM).

Table ES1: Brazos River Discharges and Water Surface Elevations Comparisons

USGS Gauge	County	1% ACE FIS Discharge (cfs)	1% ACE Study Discharge (cfs)	1% ACE FIS Water Surface Elevation (NAVD 88 ft)	1% ACE Study Water Surface Elevation (NAVD 88 ft)
Hempstead	Washington/Waller	206,962	161,000	169.2	162.9
San Felipe	Austin/Waller	-	157,000	127.2	129.8
Richmond	Fort Bend	164,000	139,000	82.8	84.4
Rosharon	Brazoria	162,000	145,000	51.5	51.3

As a component of the Lower Brazos Floodplain Protection Planning Study, an evaluation of environmental resources and potential constraints along the Brazos River was conducted. The purpose of this evaluation was to provide BRA and stakeholders with a planning and scoping tool for prospective flood mitigation projects within the Lower Brazos River Basin. Through this GIS-based evaluation process, a geographic dataset was compiled for the study area representing environmental features with the potential to present regulatory constraints (i.e. potential permitting and/or mitigation constraints). The evaluation showed that flood mitigation projects may encounter environmental constraints including stream impoundments, wetlands, contaminated soils, impaired water surfaces, groundwater resources, water management entities, groundwater wells, endangered species, critical habitat, cultural resources, oil and gas, prime farmland and USACE Galveston District nationwide permit regional conditions.

A broad range of conceptual alternatives (comprehensive and localized) were evaluated to reduce the 1% ACE flood risk along the Brazos River. The evaluation included large scale alternatives (structural buyouts, detention, channelization, and a bypass channel) and local scale alternatives (construction of levees and raising existing levees to protect developed areas in the 1% ACE floodplain). The alternatives selected for the analysis were based on the ability to provide benefits to a large number of impacted structures.

Over 1,061 structures in Austin, Waller, Fort Bend, and Brazoria Counties were identified as potential structural buyouts. A buyout program generally offers the shortest time and lowest cost of implementation to reduce flood risk. Other large-scale alternatives such as the detention, channelization and a bypass channel were found to provide flood protection to some areas and little to no protection to other areas. These alternatives had an extremely high cost, long time of implementation, complex permitting, large property acquisition, and large environmental impact. Local levee alternatives could be used to offer flood protection to areas along the Brazos River. The local alternatives had a high project cost, long time of implementation, complex permitting, and environmental impacts. The project costs for the buyouts and local alternatives are listed in Table ES2. Moving forward, communities on the Lower Brazos River should consider these alternatives in planning for flood risk reduction.

Table ES2: Cost Estimates for Flood Mitigation Alternatives

Alternative	Estimated Total Project Cost
Structural Buyouts	$193,000,000
Simonton Ring Levee	$57,200,000
Weston Lakes Levee	$15,000,000
Columbia Lakes Levee	$9,800,000
Brazoria Reservoir -Oyster Creek Levee	$160,000,000
Pecan Grove Levee	$76,000,000

The Lower Brazos Floodplain Protection Planning Study has successfully developed a much-needed comprehensive basin-wide hydrologic and hydraulic analysis of the Lower Brazos River to establish water surface elevations and peak discharges. The study results showed that water surface elevations for the 1% ACE were on average 0.5 feet lower than the FEMA FIS elevations at the USGS gauges. However, the results did show higher elevations at the San Felipe and Richmond gauges. These higher water surface elevations showed an increased flood risk to communities on the Brazos near these locations. The information produced from the study is useful to communities to identify potential flood risks during significant storm events and to determine impacts to the flood risk for potential development along the river. The water surface elevations, discharges, flow timing, and inundation extents are also useful to floodplain administrators, emergency management operations personnel, levee operators, and others in helping to protect the public.

This study is considered a first step in developing a master plan for the Lower Brazos River basin. Several next steps beyond this study are recommended below to improve flood protection planning and response including:

- Levee Improvement Districts and communities adopt study results
- Update hydrology model with NOAA Atlas 14 rainfall
- Update the hydraulic model with post-Harvey topography
- Extend the detailed hydrologic and hydraulic modeling to College Station
- Develop a hydraulic model of the Navasota River
- Model inflows/outflows and operations at the USACE reservoirs
- Expand the stream gauge network along the Lower Brazos River and develop additional rating curves
- Incorporate modeling results into FEMA Flood Insurance Studies and Flood Insurance Rate Maps
- Develop a Lower Brazos River Coalition to maintain the model of the Lower Brazos River and adopt similar development criteria where applicable
- Engage the National Weather Service (NWS) to enhance flood warning capabilities using the hydrologic and hydraulic models developed with this study
- Engage the USACE to further develop the hydraulic model and flood warning capabilities
- Evaluate development impacts in the basin by considering projected growth and flow volumes
- Identify conservancy areas along the river
- Update Hazard Mitigation Plans in region

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Acronyms

1-D	One Dimensional
ACE	Annual Chance Exceedance
AHPA	Archaeological and Historical Preservation Act of 1974
ARPA	Archaeological Resources Protection Act of 1979
AU	Assessment Unit
BFE	Base Flood Elevation
BRA	Brazos River Authority
BCA	Benefit Cost Analysis
CDC	Corridor Development Certificate
CFS	Cubic Feet Per Second
CoCoRaHS	Community Collaborative Rain, Hail, and Snow Network
DFW	Dallas/Fort Worth
DFIRM	Digital Flood Insurance Rate Maps
ECOS	Environmental Conservation Online System
EHA	Espey, Huston, & Associates
EMST	Ecological Mapping System of Texas
EOR	Element Occurrence Record
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FAC	Facultative
FACU	Facultative Upland
FACW	Facultative Wetland
FDA	Flood Damage Reduction Analysis
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
FNI	Freese and Nichols, Inc.
FPPA	Federal Farmland Protection Policy Act
GIS	Geographic Information System
GMA	Groundwater Managment Area
GWCD	Groundwater Conservation
GPS	Global Positioning System
Halff	Halff Associates, Inc.
HEC	Hydrologic Engineering Center
H-GAC	Houston-Galveston Area Council
HMA	Hazard Mitigation Assistance
HMAC	Hot Mix Asphalt Concrete
HMS	Hydrologic Modeling System
HMGP	Hazard Mitigation Grant Program
HWP	High Wetland Potential

Acronyms, Continued

IPaC	Information for Planning and Consultation
LBRED	Lower Brazos River Environmental Database
LESA	Land Evaluation and Site Assessment
LID	Levee Improvement District
LiDAR	Light Detection and Ranging Data
LJA	LJA Engineering and Surveying, Inc.
LWP	Low Wetland Potential
MWP	Moderate Wetland Potential
NAD83	National American Datum of 1983
NAVD88	National American Vertical Datum of 1988
NED	National Elevation Datasets
NEPA	National Environmental Policy Act
NHD	National Hydrography Dataset
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NRHP	National Register of Historic Places
NWI	National Wetlands Inventory
NWS	National Weather Service
NWP	Nationwide Permit
OBL	Obligate
RA	River Authorities
RHA	Rivers and Harbors Act of 1899
RAS	River Analysis System
ROW	Right-Of-Way
RWPA	Regional Water Planning Areas
SDR	Submitted Drillers Report
SGCN	Species of Greatest Conservation Need
SHPO	State Historic Preservation Office
SLD	Special Law Districts
SWCD	Soil and Water Conservation District
TASA	Texas Archaeological Sites Atlas
TCEQ	Texas Commission on Environmental Quality
THC	Texas Historical Commission
TNRC	Texas Natural Resources Code
TNRIS	Texas Natural Resources Information System
TPWD	Texas Parks and Wildlife Department
TSSWCB	Texas State Soil and Water Conservation Board
TWDB	Texas Water Development Board
TxDOT	Texas Department of Transportation
TXNDD	Texas Natural Diversity Database
TXRRC	Texas Railroad Commission

Acronyms, Continued

UPL	Upland
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish & Wildlife Service
USGS	U.S. Geological Survey
WSEL	Water Surface Elevation

1.0 Introduction and Background

Communities along the Lower Brazos River are threatened by frequent flooding. Numerous cities, counties, districts, as well as a petrochemical industry and a thriving port on the coast are connected by the Brazos River. Figure 1 shows the Lower Brazos River Basin project location map. From 1950 to 1982, significant flood protection was developed along the middle and upper Brazos River systems. However, 10,000 square miles of the lower basin remain uncontrolled. The basin has experienced major floods with 24 major flooding events (discharge greater than 70,000 cubic feet per second) at the Richmond U.S. Geological Survey (USGS) gauge. Record major floods occurred as recently as 2016 and 2017. Approximately 140,000 people are estimated to reside within the Lower Brazos River current effective FEMA 1-percent annual chance exceedance (1% ACE) floodplain with approximately 51,000 insurable structures worth $19.4 billion. Although a study of the portion of the Lower Brazos River Basin through Fort Bend County was completed in 2009, many areas have to rely on outdated hydrologic and hydraulic studies to address flood issues. The Lower Brazos River is an integrated system in which the entire basin must be considered including the interaction of reservoirs, levees, overflows, diversions, bridges, etc. to accurately assess flood impacts and the complex interaction of these elements. A basin-wide based floodplain protection planning study was necessary to more accurately determine the overall existing flood hazards and determine the feasibility of flood reduction alternatives.

The information from this study can be used as a basis for improving the Flood Early Warning System capabilities of the National Weather Service (NWS) and emergency management officials. There are levees along the Brazos River that protect large residential and industrial areas. The residents and businesses within the levee improvement districts (LIDs) can benefit from the updated information to determine level of protection of the levees as well as provide flood warning for the surrounding areas.

The flood hazards in the Lower Brazos River study area were addressed in this planning study by using current LiDAR topography to develop a continuous, basin-wide, calibrated hydrologic and hydraulic model of the Lower Brazos River Basin. These models along with socioeconomic and environmental data were used to analyze the feasibility of flood reduction alternatives. The results of the hydrologic and hydraulic analysis were used to develop flood inundation maps that can be used for development planning and regulation. This report presents the results of hydrologic, hydraulic, and alternative analyses of the Lower Brazos River from the Waller/Grimes county line to the Gulf of Mexico. Items discussed in this report include:

- Data Collection
- Terrain and Survey
- Hydrologic Analysis
- Hydraulic Analysis
- Environmental Analysis
- Flood Mitigation Alternatives Analysis

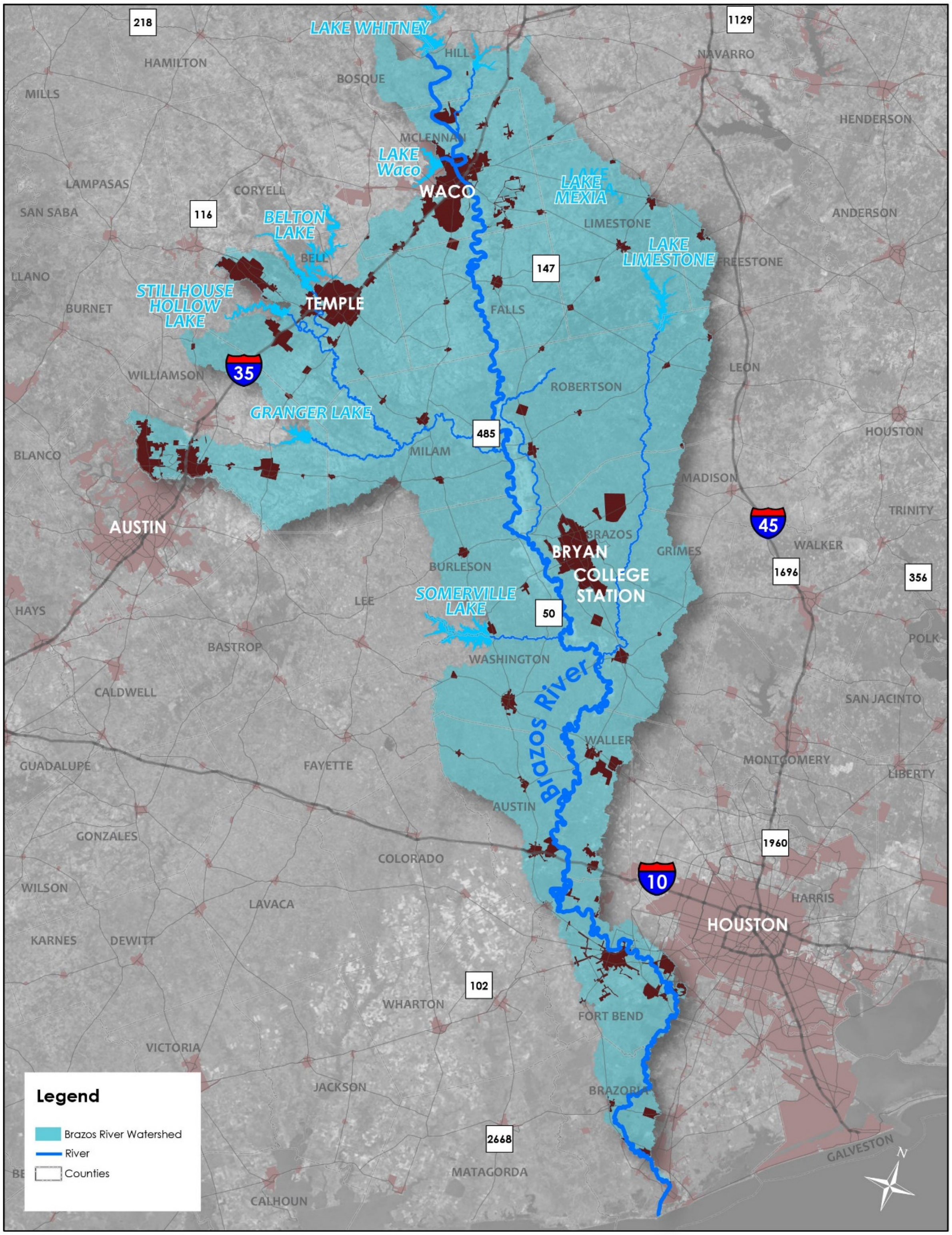


Figure 1: Project Location Map

The Brazos River Authority (BRA) was granted a Texas Water Development Board (TWDB) Flood Protection Planning Grant for the development of the Lower Brazos Floodplain Protection Planning Study. Phase 1 of the study was approved in October 2014 to develop the hydrologic model for the lower basin, detailed unsteady hydraulic model from Richmond to the Gulf of Mexico, environmental analysis, and flood reduction alternatives. Phase 2 was approved in May 2016 and extended the limits of the detailed unsteady hydraulics to the northern edge of Waller County near the Grimes county line. Additional funding was added to the project in March 2018 to include Hurricane Harvey in the frequency analysis, hydrologic calibration, and hydraulic calibration. Additional funding was also used to model areas of overflows for large flood events along Bessies Creek, Jones Creek, Ditch H, and Oyster Creek.

In addition to BRA, eight stakeholders participated financially in the study. Stakeholders are listed in Table 1. Fort Bend County also provided digital data including high water marks and a 2009 hydraulic model of the Brazos River through the county to be incorporated into the study. Multiple public meetings, stakeholder meetings, and coordination meetings were held throughout the Lower Brazos Floodplain Protection Planning Study area including Richmond, Rosharon, Hempstead, Rosenberg, Angleton, and Prairie View. See Appendix A for public meeting sign-in sheets.

Table 1: Study Stakeholders

Stakeholders
Brazoria County
Waller County
Lake Jackson
Sandy Point
Sugar Land
Washington County
Velasco Drainage District
Pecan Grove MUD
Data Providers
Fort Bend County

2.0 Data Collection

Numerous previous studies, reports, and high-water mark surveys have been completed throughout the years related to the Lower Brazos River. Documents obtained and reviewed were provided by BRA, USACE, TWDB, FEMA, Texas Department of Transportation (TxDOT), Fort Bend County and other agencies. The Brazos River within the detailed study area includes portions of four separate FEMA Flood Insurance Studies (FIS) including Brazoria, Fort Bend, Austin, and Waller counties.

The vertical datum utilized for this study is the North American Vertical Datum of 1988 (NAVD). Several previous studies were completed using the National Geodetic Vertical Datum of 1929 (NGVD). Conversion factors between NGVD to NAVD are included in Table 2 below.

Table 2: Vertical Datum Adjustments by County

County	Conversion Factor from NAVD29 to NGVD88
Austin	0.07 feet
Brazoria	0.1 feet
Fort Bend	-0.014 feet
Waller	0.045 feet
Washington	0.11 feet

There are 17 U.S. Geological Survey (USGS) stream flow gauges located in the Lower Brazos River Basin that were used for calibration. There are also numerous USGS gauges on tributaries and reservoirs throughout the basin. In total, over 42 USGS streamflow gauges have been or are currently in service within the Lower Brazos River Basin. Numerous historical storm events occurring at the stream gauges were researched for comparison and calibration purposes. Twenty-four historical large flood events (greater than 70,000 cfs) have been recorded on the Brazos River at the Richmond USGS gauge. The peak flood event measured since the gauge was established in 1922 occurred in September 2017 with a measured discharge of 122,000 cubic feet per second (cfs).

Several BRA and USACE reservoirs are located upstream of the detailed hydraulic study area. These major reservoirs include: Lake Aquilla (USACE), Lake Whitney (USACE), Lake Waco (USACE), Lake Limestone (BRA), Lake Belton (USACE), Stillhouse Hollow Lake (USACE), Lake Granger (USACE), and Lake Sommerville (USACE). The USACE projects have designated flood control storage pools that regulate flows through the detailed study area. There are numerous other smaller reservoirs owned by cities, power generation companies, mining companies, Texas Parks and Wildlife Department (TPWD), and private landowners within the Lower Brazos River Basin. These smaller reservoirs do not offer any designated flood control storage capacity, are small in size relative to the Lower Brazos River Basin and were not included in the hydrologic analysis as they would have negligible impacts on mainstem Brazos River flood flows.

Flood data were collected for the recent flood events along the Brazos river for the 2015, 2016, and 2017 storm events. Flood data collected included historical and recent high-water mark points, georeferenced flood photos, Facebook and Twitter posts by Fort Bend County Sherriff's Office, Fort Bend County Emergency Management, Velasco Drainage District, City of Sugar Land, and Halff Associates field visits. Figure 2 shows a photo posted on Twitter on May 28, 2016 by the NASA Space Station presenting the impacts of the flooding along the Brazos River just west of Monaville, Texas. Flood data collected were used for calibration of the hydrologic and hydraulic models. Appendix A includes additional information about the data collection.

Figure 2: NASA Photo Flooding on the Brazos River Just West of Monaville on May 28, 2016

3.0 Terrain and Survey

Light detection and ranging (LiDAR) data were collected from various sources and processed by URS (now AECOM) for the Lower Brazos River Basin. URS acquired LiDAR data sets for portions of Austin, Bell, Bosque, Brazos, Brazoria, Burleson, Falls, Fort Bend, Grimes, Leon, Limestone, Madison, McLennan, Milam, Robertson, Waller, Washington, and Williamson counties. Terrain data was collected from eight data sources including:

- Brazoria County 2006 LiDAR data
- Fort Bend County 2014 LiDAR data
- Houston-Galveston Area Council (HGAC) 2008 LiDAR data
- 2010 Texas Natural Resources Information System (TNRIS) LiDAR data
- 2011 TNRIS LiDAR Data
- 2013 TNRIS LiDAR Data
- 2007 Capital Area Council of Governments (CAPCOG) LiDAR Data
- USGS National Elevation Datasets (NED) at 10-meter resolution

Figure 3 presents the Lower Brazos River Basin terrain data available for this project. Appendix B contains additional information on the terrain development.

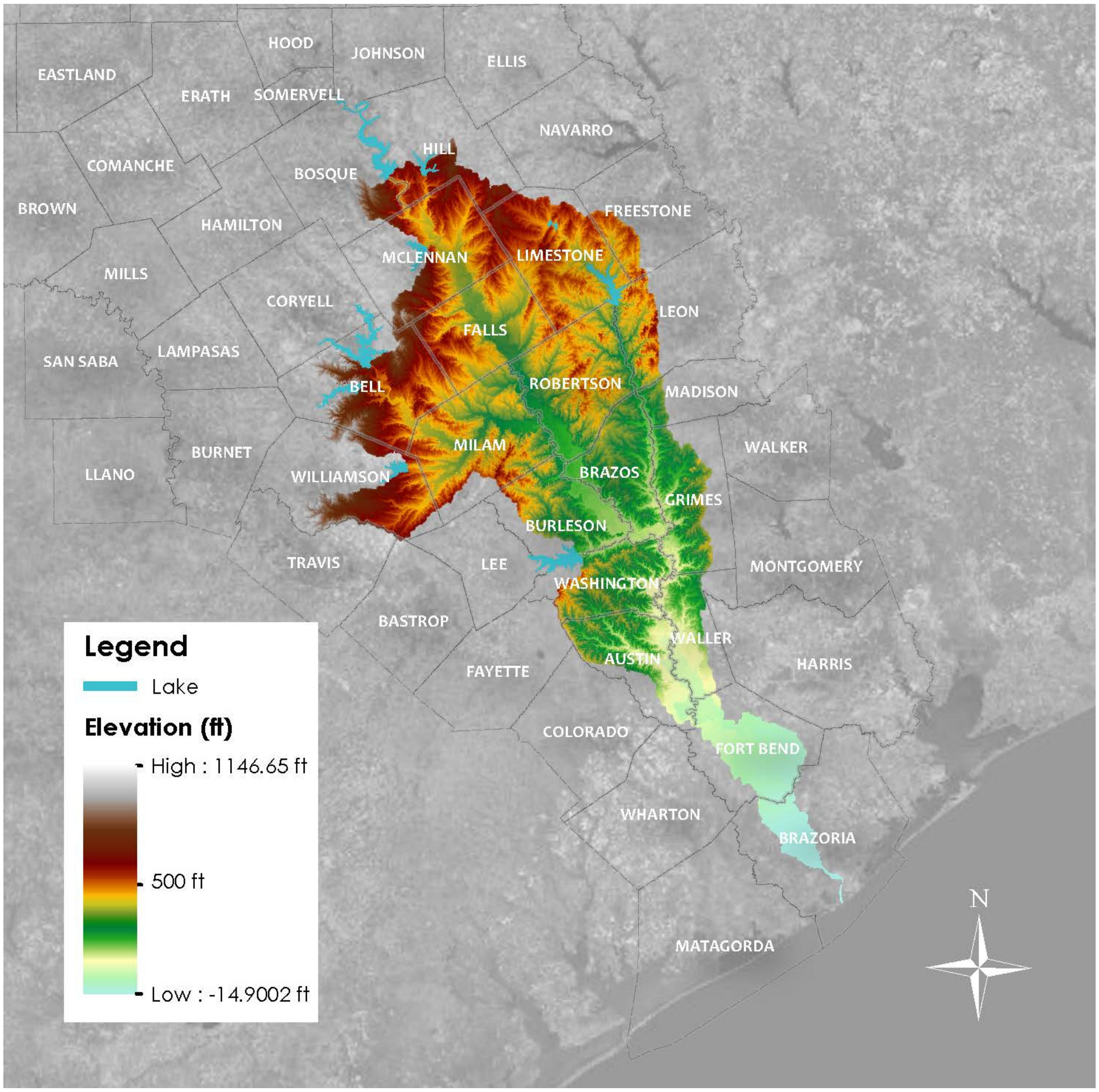


Figure 3: Lower Brazos Basin Terrain

The survey and topographic data used were referenced to the North American Horizontal Datum of 1983 (NAD83) with State Plane Texas South Central Projection (4204). The elevations were referenced to the 1988 North American Vertical Datum (NAVD88). The linear unit used for both horizontal and vertical measurements is U.S. Feet.

Halff obtained field survey of stream crossings and cross-sections on the Lower Brazos River upstream and downstream of Fort Bend County. The purpose of the field survey was to gather existing terrain data to be used in the development and calibration of the hydraulic model. Field survey for crossings and cross sections were not collected in Fort Bend County as the 2009 hydraulic model cross sections were surveyed by Fort Bend County and the existing data was leveraged for this study.

Field survey for crossings were primarily collected with Leica Global Positioning System (GPS) GS-14 equipment connected to Leica SmartNet and processed with Leica Infinity Software Version 2.3.2.2825. Bathymetric data were also collected at various locations along the Lower Brazos River. These data were collected by boat which traversed the channel multiple times to obtain depths using sonar. Field survey was collected along the river banks at these same locations where bathymetric data were collected. At each field survey location of crossings and cross sections, photos and field sketches were obtained. A total of 11 bridges and 36 cross sections were surveyed. Survey data were incorporated into the terrain for the development of the detailed hydraulic models.

Several site visits were conducted during the 2016 flood event to establish high-water marks and observe the impacts of the storm event. Site visits were conducted on May 31, June 3 and June 6, 2016 for Waller, Fort Bend and Brazoria counties, respectively. Major flooding impacts were observed along bridges crossing the Brazos River with some bridges blocked off due to safety concerns. Many photos were taken on or near these bridges to visually document the high-water during the 2016 event. Several high-water marks were staked out during the site visits for survey crews to obtain water surface elevations. A photo of the Brazos River during the 2016 event along FM 529 is shown below in Figure 4. Appendix C contains additional information on the survey data collection.

Figure 4: Brazos River along FM 529 during the 2016 flood

4.0 Hydrologic Analysis

The total Brazos River Basin is approximately 44,620 square miles. According to the USGS, 9,600 square miles are classified as non-contributing. The headwaters of the Brazos River are located near the New Mexico/Texas border. The Brazos River initially runs east towards Dallas-Fort Worth, then the Brazos River turns south and east, passing through Waco, Bryan and College Station, and into the Gulf of Mexico in the marshes just south of Freeport. For the Lower Brazos Floodplain Protection Planning Study, the upper limits of the hydrologic model extended to the downstream face of the seven USACE reservoirs. The upstream limit of the Brazos River mainstem is the downstream face of the Lake Whitney Dam. Major tributaries in the hydrologic model study area included: the Navasota River, Little Brazos River, Brushy Creek, Big Elm Creek, Salado Creek, Davidson Creek, New Year Creek, Mill Creek, Big Creek, and Bessies Creek basins. Other major tributaries included in the study were Aquilla Creek (downstream of Lake Aquilla), Leon River (downstream of Lake Belton), Lampasas River (downstream of Stillhouse Hollow Lake), San Gabriel River (downstream of Lake Granger), and Yegua Creek (downstream of Somerville Lake).

For this study, the basin was divided into two major study areas. The upper portion was a limited detail study area that included the 8,160 square mile area above the Hempstead USGS gauge (USGS Gauge Station ID 8111500). The lower portion was a detailed study area that included the 1,610 square miles below the Hempstead USGS gauge. The upper portion of the basin is characterized by gently rolling topography with a well-defined stream and floodplain. The lower portion is characterized by flat coastal plains with wide floodplains. Figure 5 shows the hydrologic study area for the project.

The USACE Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HEC-HMS) Version 4.0 model was utilized for the rainfall-runoff modeling for the Lower Brazos River study area. Within the upper portion of the study (limited detail study area), the initial and constant loss method was selected for the rainfall loss rate along with the Snyder's unit hydrograph method. Within the lower portion of the study (detailed study area), the exponential loss method was selected for the rainfall loss rate along with the Clark's unit hydrograph method. These methods were chosen based on local design requirements, previous studies and successful application for other river basins near the Lower Brazos River study area.

Hydrologic routing for the mainstem Brazos River and Navasota Rivers used Muskingum routing. Modified Puls storage-outflow routing was used for all major tributaries in the limited detail study area. Modified Puls storage-outflow relationships were computed with the USACE HEC-River Analysis System (HEC-RAS) version 4.1.0 model. Major tributaries within the detailed study area utilized the Muskingum-Cunge Eight Point routing method. A summary of computed hydrologic parameters is included in Appendix D.

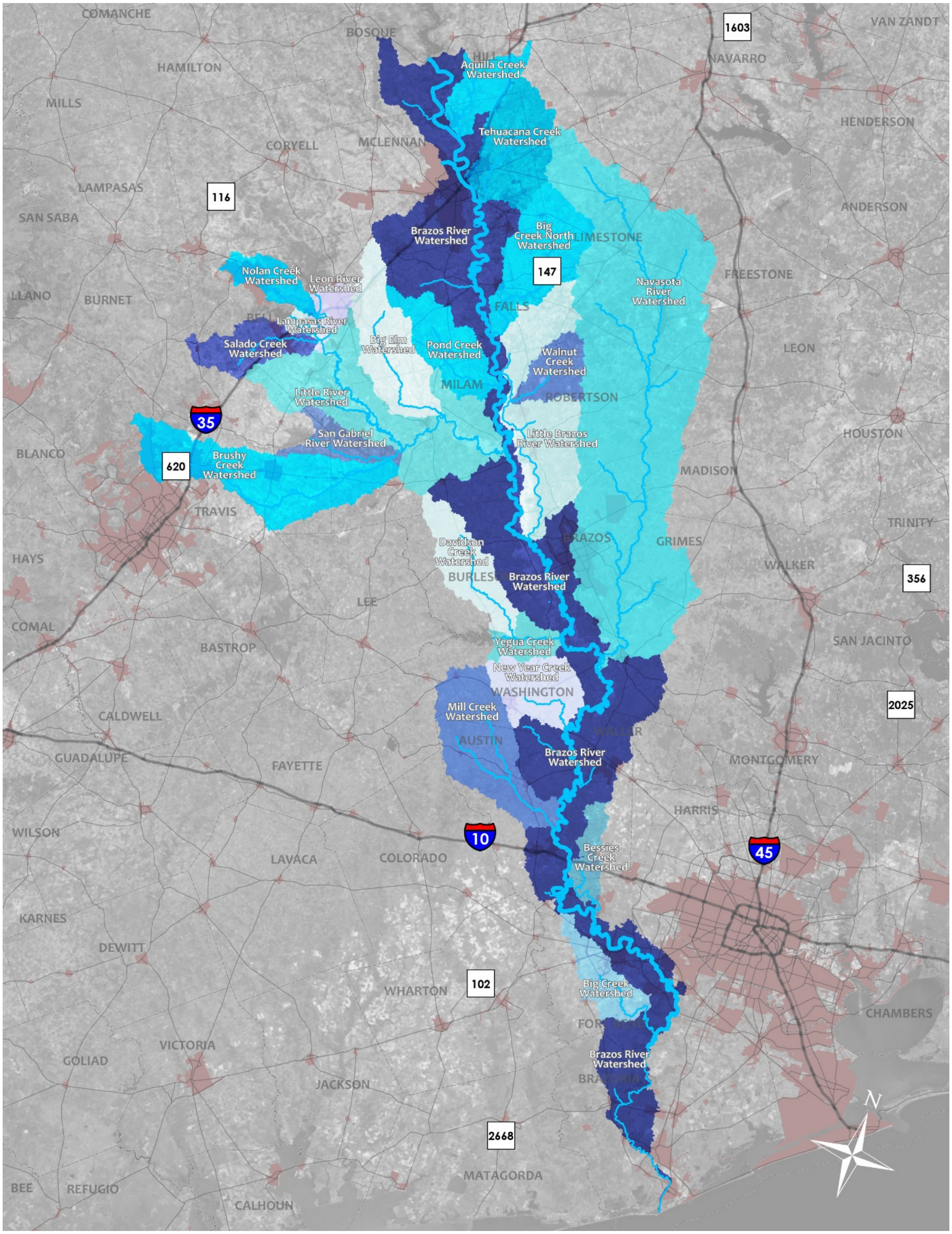
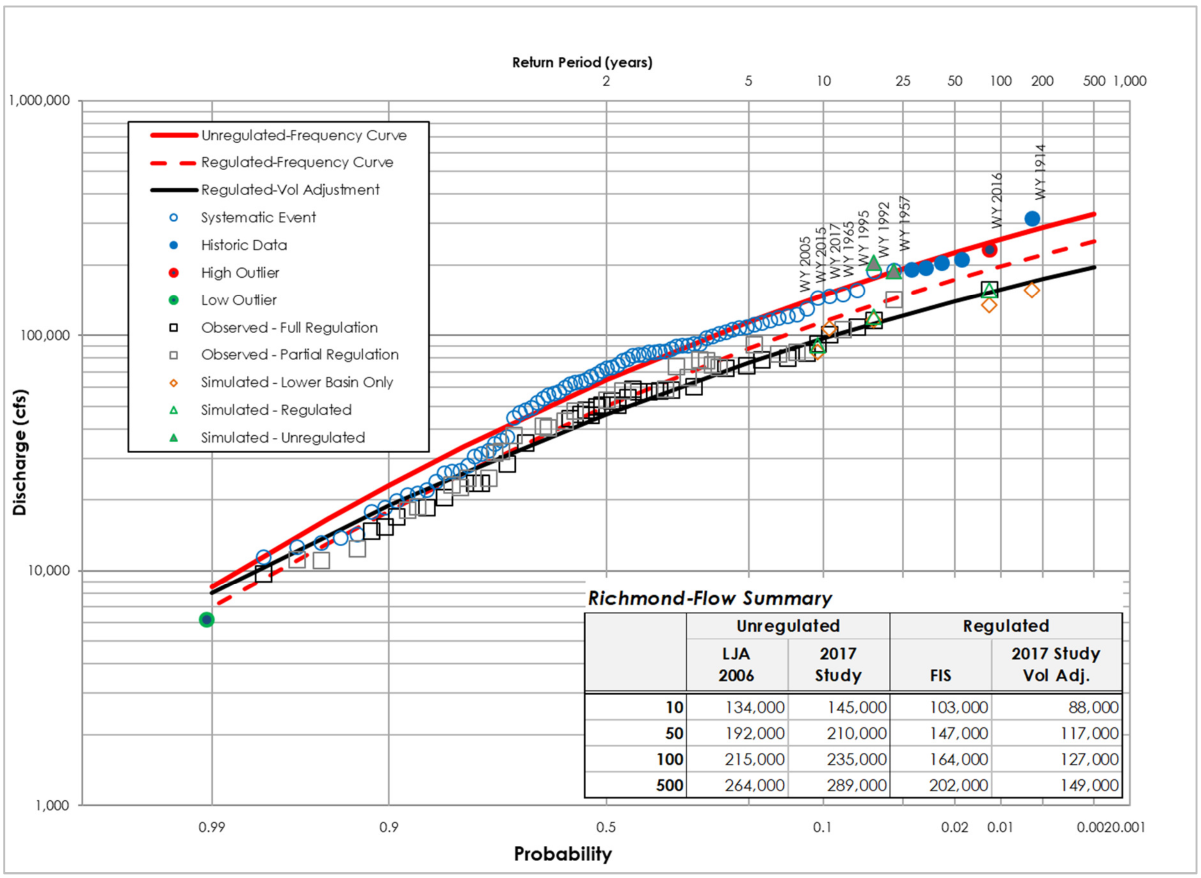


Figure 5: Hydrologic Study Area

The calibration strategy for the Lower Brazos River Basin was to simulate a wide range of storms that could be re-created with the historical rainfall, streamflow gauge data, and reservoir release data. The basin was separated into 18 calibration zones. Each calibration zone has observed data from the USGS streamflow gauges at the downstream end including either stream discharge or stage. When possible, observed discharge was used as a source at the upstream end of the calibration zones. This allowed the modeler to focus on the parameters of the zone being calibrated without introducing and accumulating differences from upper calibration zones.

In addition to calibration of historical events, a gauge frequency analysis was completed on the historically measured discharges at the Hempstead and Richmond USGS gauges to statistically define the frequency storm events. Figure 6 presents the unregulated and regulated frequency curves at the USGS Richmond gauge. With the upper limits of the study area controlled by USACE reservoirs, the difference between regulated and unregulated flows could be significant, especially for higher flows and smaller recurrence intervals. This study utilized methods from previous studies conducted in 1979 and 1984 by Espey, Huston & Associates, Inc. (EHA) and in 2006 by LJA Engineering and Surveying, Inc. Some minor modifications were made to the previous study methods to develop the frequency discharges at the Hempstead and Richmond gauges. Appendix D contains more information on the frequency analysis.



	Unregulated		Regulated	
	LJA 2006	2017 Study	FIS	2017 Study Vol Adj.
10	134,000	145,000	103,000	88,000
50	192,000	210,000	147,000	117,000
100	215,000	235,000	164,000	127,000
500	264,000	289,000	202,000	149,000

Figure 6: Unregulated and Regulated Frequency Curves at the USGS Richmond Gauge

In addition to the frequency gauge flow analysis a critically centered design storm location was found that produced the highest peak discharges and volumes in the lower basin. A critically centered design storm approach was needed due to the drainage area in the lower basin. The upper threshold for areal-storm reduction, as outlined in TP-40 and in HEC-HMS, is 400 square miles. This approach determined the storm location that produced the highest peak discharges at the Hempstead and Richmond USGS gauge locations. Figure 7 presents the critical storm centering location. The critical storm is centered near Highway 6 and 14 near Bremond, Texas. The storm is orientated at 330 degrees clockwise from north.

The hydrologic model with the critical storm centering generated peak flows that were consistent with the peak flows established with the gauge frequency analysis at the Hempstead and Richmond USGS streamflow gauges. The hydrologic analysis was successful in generating calibrated frequency flow hydrographs for use with other modeling tools associated with the Lower Brazos Floodplain Protection Planning Study.

5.0 Hydraulic Analysis

The Lower Brazos River was modeled using the USACE HEC-RAS version 5.0.3 to produce water surface elevations for historical storms and the design storm from the hydrologic analysis. The HEC-RAS model consists of a 1-D unsteady analysis of the Lower Brazos River from the Waller/Grimes County line down to the Gulf of Mexico. In addition to the Brazos River, other river systems in Fort Bend and Brazoria counties were included to account for the overflow conditions that exist within the Lower Brazos River Basin during large rainfall events. Figure 8 presents the detailed hydraulic study area.

Hydraulic model cross sections were derived from LiDAR and field survey collected for this study (see Appendix B and C). The model also incorporated geometry data from the 2009 Fort Bend hydraulic model. In addition to the Lower Brazos River, cross sections in overflow river reaches were created to simulate the interaction between both the Lower Brazos River and the overflow river reaches. The calibration storms consisted of the June–July 2007, the May–June 2016 and the August–September 2017 events.

The hydraulic model was calibrated to discharges and water surface elevations observed at USGS gauges for the 2007, 2016, and 2017 storm events along with consideration to high water marks. The calibration was accomplished primarily by adjusting the roughness factors along multiple reaches in the HEC-RAS model for each storm event. The roughness factors were averaged to give an overall existing condition of the Brazos River since the river changes over time due to gain/loss of vegetation, scour and sediment deposit. The hydraulic model with the average roughness factors was used to compute the water surface elevations and flows for the design storm. The calibration process produced results in the hydraulic model that responded well to the observed data. Appendix E contains more detailed information for the development of the hydraulic models and results for each of the historical storm event calibrations.

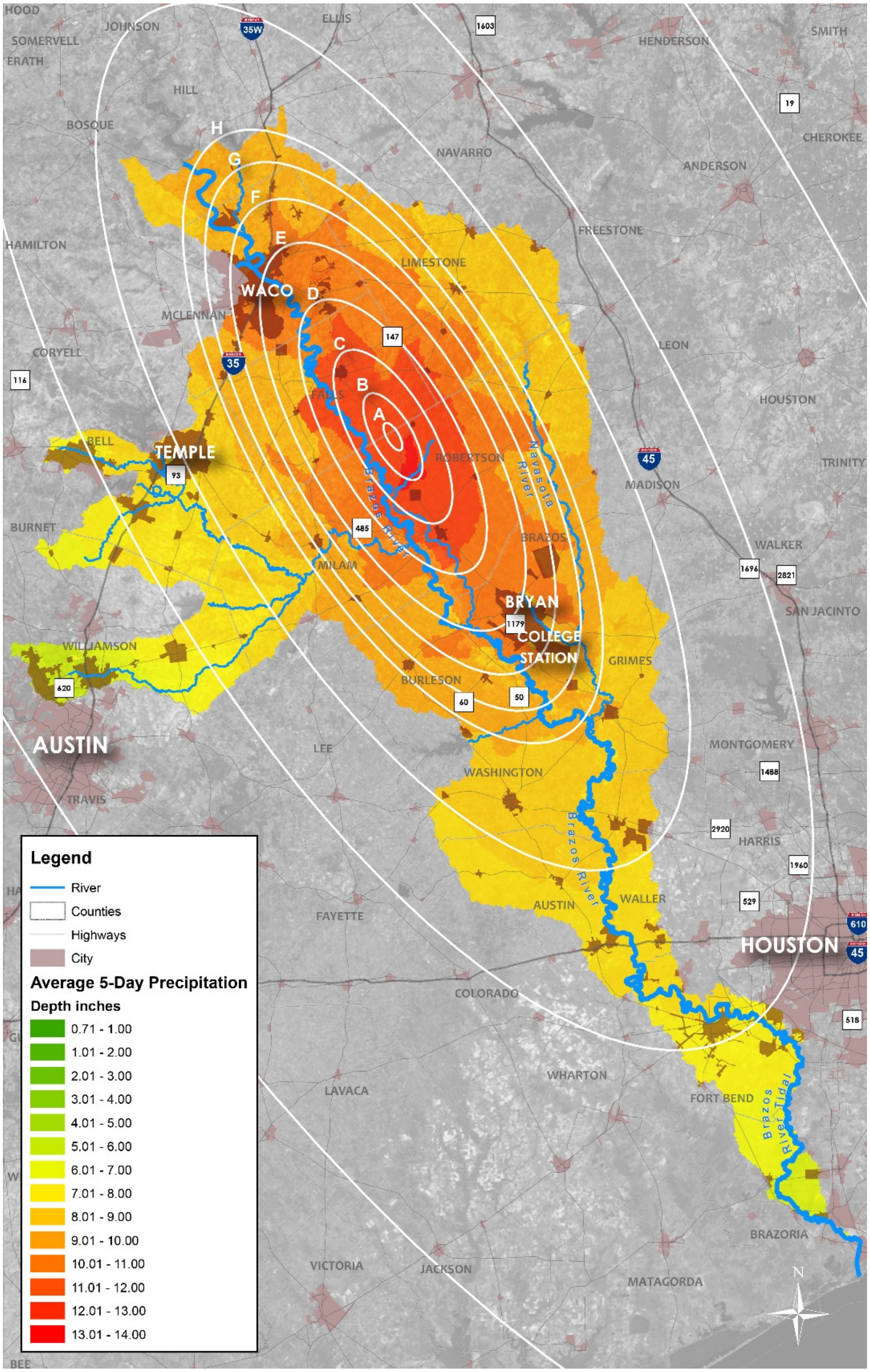


Figure 7: Critical Storm Centering

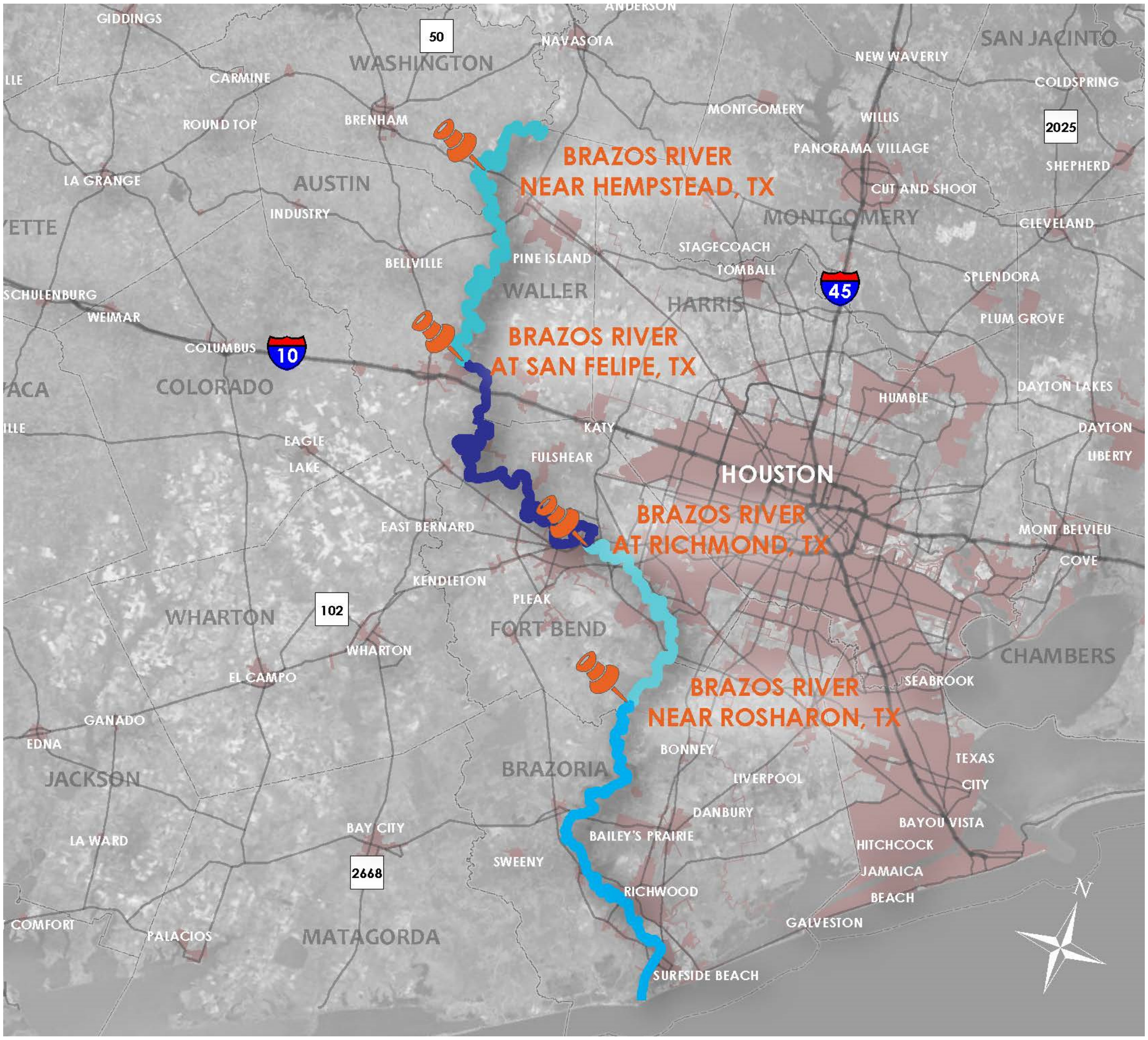


Figure 8: Detailed Hydraulic Study Area

6.0 Modeling Results

The Lower Brazos River and tributaries are a complex system of flow transfers that were not considered in previous modeling efforts. These areas of interaction include transferring flow to other river systems or storing volume to be released back into the Lower Brazos River. High flow events of greater than 80,000 cfs can trigger these overflows and create a vast network of impacted streams and areas. Other factors such as vegetative cover, changing banks and flowline elevations directly impact how the river system responds to flows as well as the impacted streams.

The calibration process created more confidence in the updated results for the design storm and provided vital information regarding the existing conditions of the Lower Brazos River and its tributaries. Flows and water surface elevations for the 10%, 2%, 1% and 0.2% ACE storm events were calculated from the calibrated Lower Brazos River hydraulic model. Comparisons between the FIS published flows and elevations, gauge frequency analysis, and model results were made at the Hempstead, San Felipe, Richmond, and Rosharon USGS gauges.

6.1 Hempstead

The Hempstead USGS gauge is located just downstream of US 290 along the Waller County Line and has a contributing drainage area of approximately 43,880 square miles. The gauge has been in service 78 years. Comparisons were made between the 2009 Waller County FIS (Appendix A), the gauge frequency storm analysis (Appendix D) and the design storm analysis (Appendix E). A comparison of the 10%, 2%, 1% and 0.2% ACE storm events discharges and water surface elevations at Hempstead are shown in Table 33.

Table 3: Hempstead Discharge and Elevation Comparisons

Storm Event	Discharge (cfs)			Water Surface Elevation (feet NAVD 88)		
	2009 Waller Co. FIS	Gauge Frequency Analysis	HEC-RAS Design Storm Analysis	2009 Waller Co. FIS	HEC-RAS Design Storm Analysis	USGS Rating Curve*
10% ACE	110,000	97,000	98,000	163.00	158.62	160.04
2% ACE	182,473	140,000	142,000	167.80	162.05	162.65
1% ACE	206,962	157,000	161,000	169.20	162.92	163.24
0.2% ACE	260,000	195,000	227,000	171.70	165.66	-**

**Water surface elevations are derived from the Hempstead USGS Rating Curve (Version 15) using the Design Storm Analysis discharges*
***Design Storm Discharge not found within USGS rating curve*

Based on the results shown in Table 3, the design storm analysis closely aligned with the gauge frequency storm analysis. The only major difference in these results was for the 0.2% ACE storm event which varied from over 30,000 cfs when compared to previous results. Comparisons to elevations also showed a decrease in water surface elevations for all storm events at Hempstead compared to the 2009 Waller County FIS. The maximum difference between the FIS and design storm analysis water surface elevations was calculated to be 6.28 feet for the 1% ACE storm event. The decrease in water surface elevations could be attributed to lower discharge rates, new terrain, and averaged calibration parameters affecting the hydraulic modeling. Table 3 shows much lower discharge rates from the design storm analysis when compared to the FIS in Waller County. The lower discharge rates could be attributed to the gauge frequency analysis and more detailed modeling of storage in the floodplain above Hempstead. The 1% ACE inundation area with the overflow areas near the Hempstead USGS gauge is shown in Figure 9.

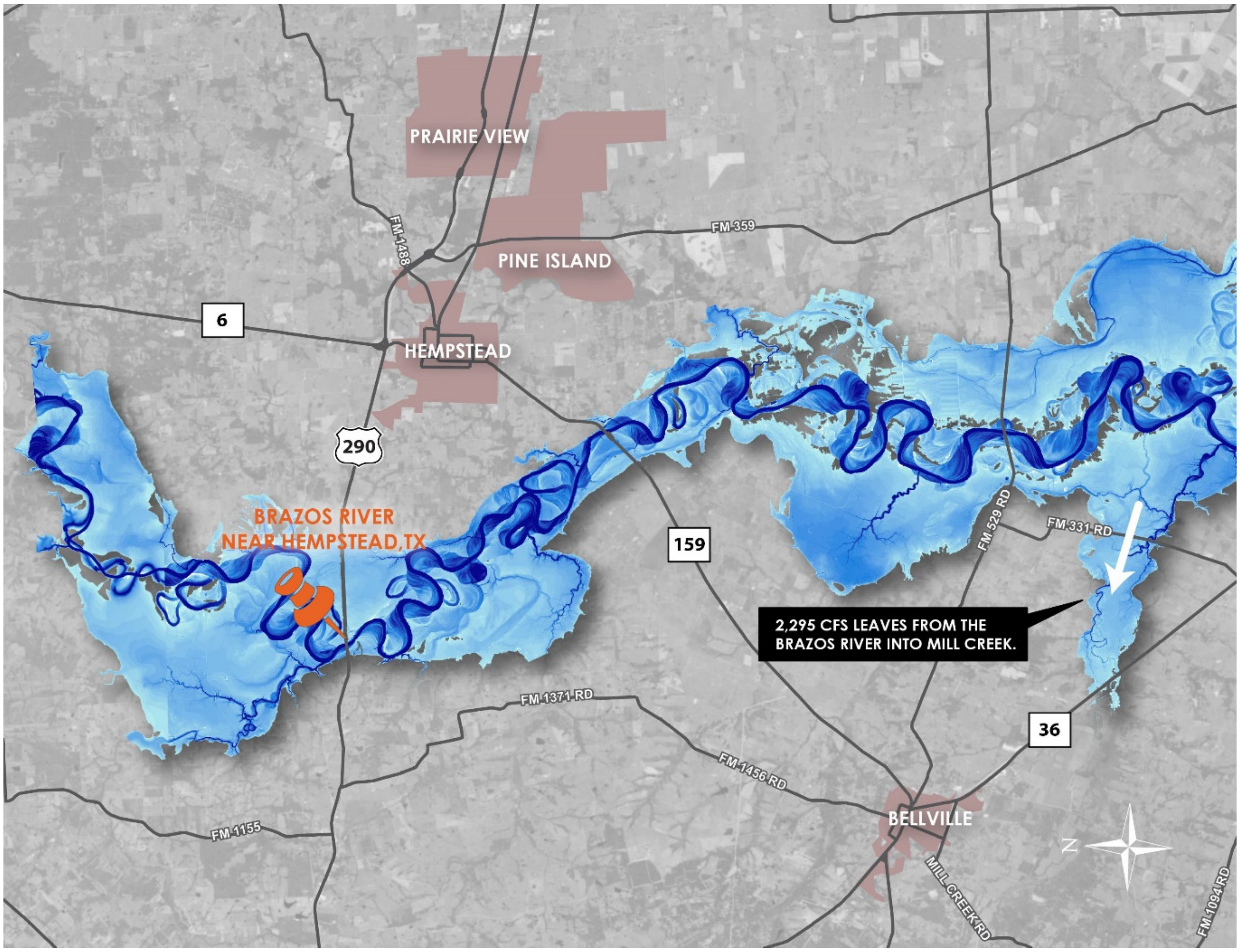


Figure 9: 1% ACE Inundation Area near Hempstead USGS Gauge

6.2 San Felipe

The San Felipe USGS gauge is located at FM 1458 in Waller County and has a contributing drainage area of 44,670 square miles. The gauge was installed in 2013. A gauge frequency analysis could not be completed for this gauge because the period of record was too short (less than 30 years). Comparisons were only made between the 2010 Austin County FIS (Appendix A) and the design storm analysis (Appendix E). A comparison of the 10%, 2%, 1% and 0.2% ACE storm events discharges and water surface elevations at San Felipe are shown in Table 44.

Table 4: San Felipe Discharge and Elevation Comparisons

Storm Event	Discharge (cfs)	Water Surface Elevation (feet NAVD 88)		
	HEC-RAS Design Storm Analysis	2009 Waller Co. FIS	HEC-RAS Design Storm Analysis	USGS Rating Curve*
10% ACE	94,000	120.20	123.57	122.89
2% ACE	136,000	123.40	127.96	127.99
1% ACE	157,000	127.20	129.84	130.03
0.2% ACE	225,000	129.50	132.71	-**

**Water surface elevations are derived from the San Felipe USGS Rating Curve (Version 2.1) using the Design Storm Analysis discharges*
***Design Storm Discharge not found within USGS rating curve*

Based on the 1% ACE water surface elevation results shown in Table 4, the design storm analysis had higher elevations when compared to the 2010 Austin County FIS. The higher elevations were attributed to the averaged roughness factor in the hydraulic model which were multiplied by a factor greater than one for the high flow events. While the water surface elevations were shown to be higher at this gauge, the results were deemed more accurate due to the calibration process conducted for this study. The 1% ACE inundation area along with the overflow areas near the San Felipe USGS gauge is shown below in Figure 10.

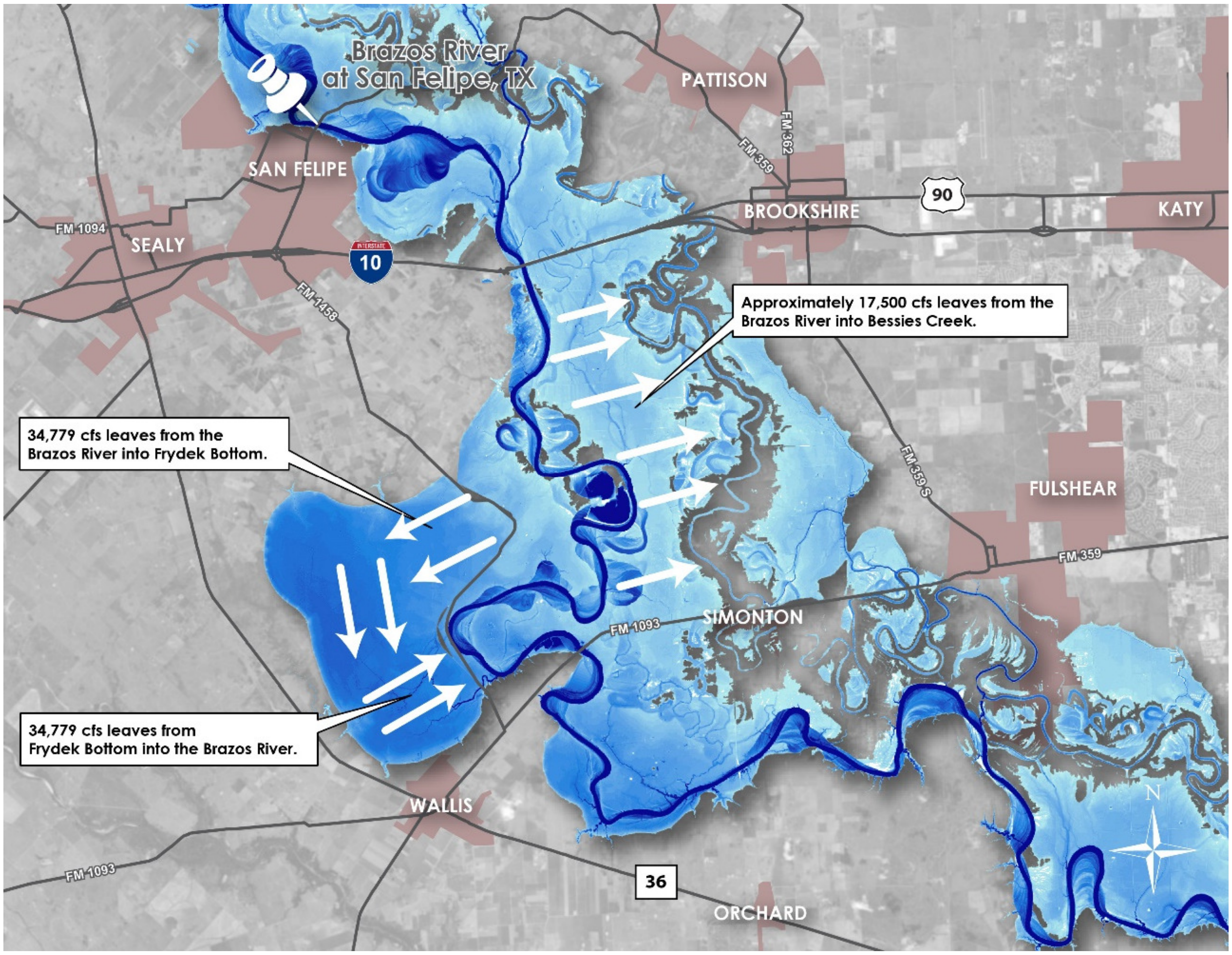


Figure 10: 1% ACE Inundation Area near San Felipe USGS Gauge

6.3 Richmond

The Richmond USGS gauge is located downstream of US 90A in Fort Bend County and has a contributing drainage area of 45,107 square miles. The gauge has been in service for 94 years. Comparisons were made with the 2014 Fort Bend County FIS (Appendix A), the gauge frequency analysis (Appendix D) and the design storm analysis (Appendix E). A comparison of the 10%, 2%, 1% and 0.2% ACE storm events discharges and water surface elevations at the Richmond USGS gauge are shown in Table 5.

Table 5: Richmond Discharge and Elevation Comparisons

Storm Event	Discharge (cfs)			Water Surface Elevation (feet NAVD 88)		
	2014 Fort Bend Co. FIS	Gauge Frequency Analysis	HEC-RAS Design Storm Analysis	2014 Fort Bend Co. FIS	HEC-RAS Design Storm Analysis	USGS Rating Curve*
10% ACE	103,000	88,000	86,000	76.70	77.04	76.84
2% ACE	147,000	117,000	123,000	81.30	82.76	81.14
1% ACE	164,000	127,000	139,000	82.80	84.43	82.65
0.2% ACE	202,000	148,000	183,000	85.20	87.70	-**

**Water surface elevations are derived from the Richmond USGS Rating Curve (Version 18) using the Design Storm Analysis discharges*
***Design Storm Discharge not found within USGS rating curve*

Based on the results shown in Table 4, the design storm analysis closely aligned with the gauge frequency storm analysis for the 1% ACE and more frequent events. Comparisons to the water surface elevations showed increases during the design storm events. These increases in water surface elevations were attributed to both the hydrology and roughness factors. Average roughness factors were above one for higher flows causing water surface elevations to rise. The design storm analysis primarily focused on peak discharges. In addition to the peak discharges, a comparison was made between the 1% ACE event design storm volume and historic events. Figure 11 shows that the design storm volume is comparable to several historic events at the Richmond USGS gauge. The 1% ACE inundation area with the overflow areas near the Richmond USGS gauge is shown below in Figure 12.

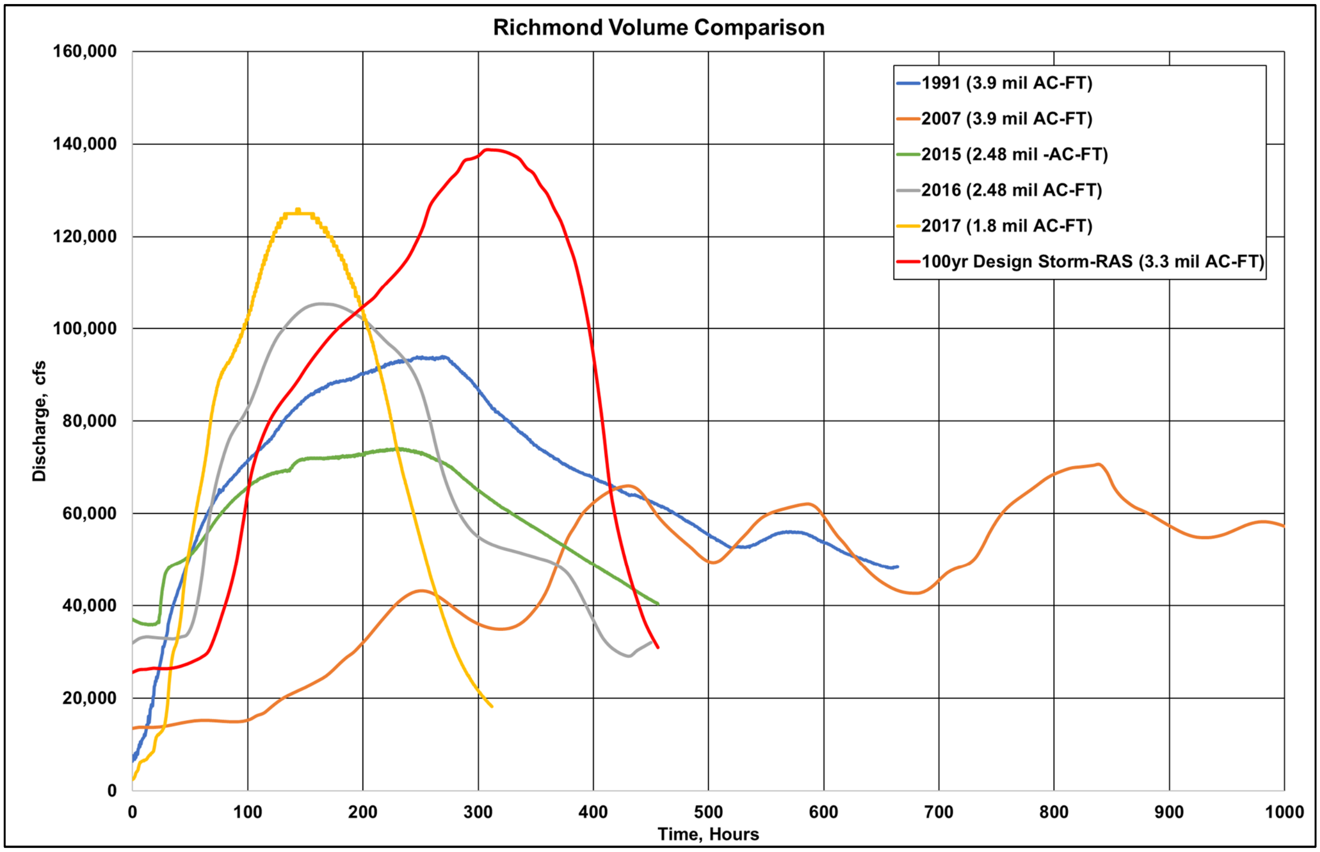


Figure 11: Richmond USGS Gauge Volume Comparison

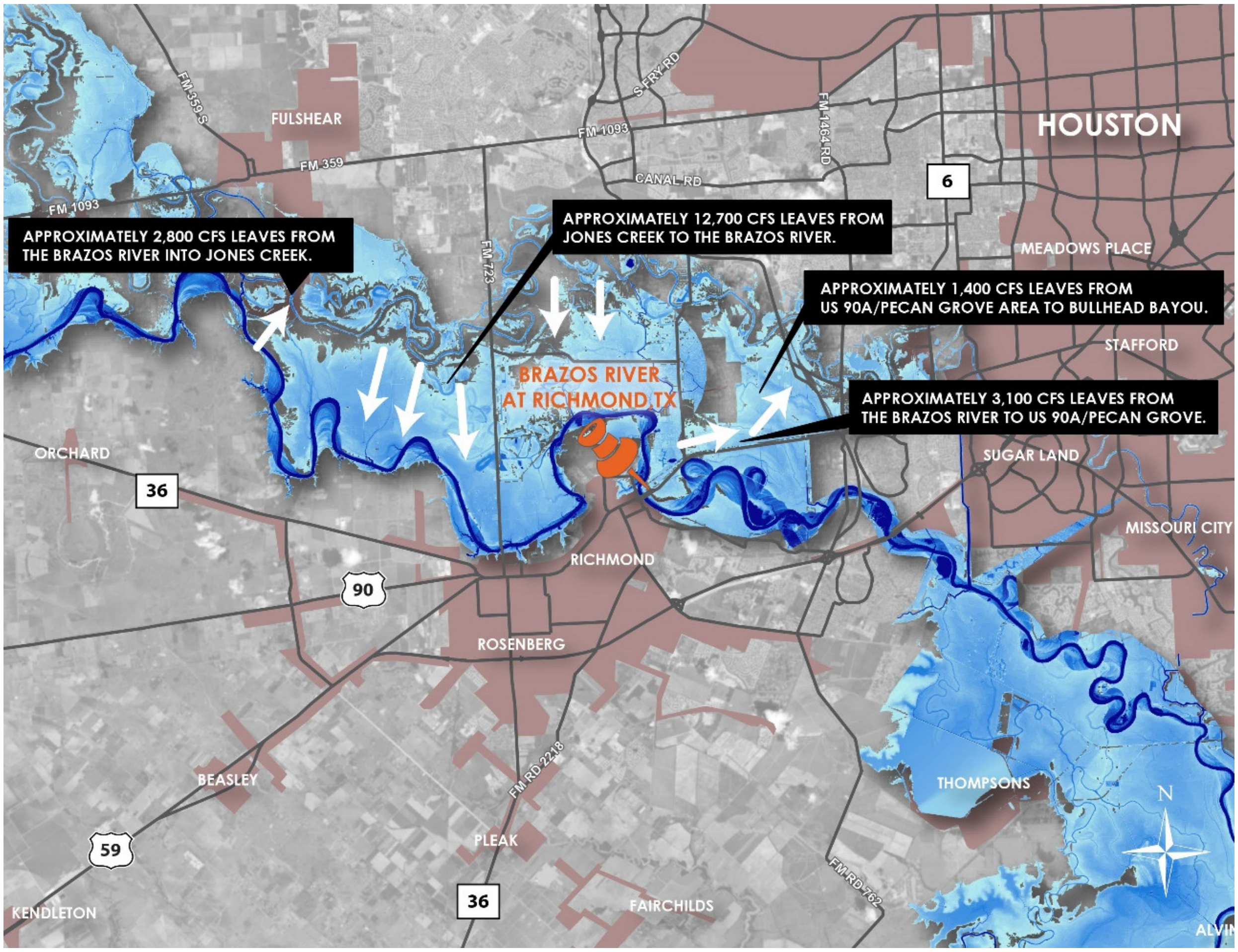


Figure 12: 1% ACE Inundation Area Near Richmond USGS Gauge

6.4 Rosharon

The Rosharon USGS gauge is located downstream of FM 1462 in Brazoria County and has a contributing drainage area of 45,339 square miles. The gauge has been in service for 49 years. The Brazos River in this area overflows into Oyster Creek resulting in a very wide floodplain. Discharge is measured across the floodplain for both the Brazos River and Oyster Creek at the USGS gauge. As a result, discharge hydrographs from the hydraulic model for both the Brazos River and Oyster Creek were combined to compare to the gauge data. Comparisons were made between the 2014 Fort Bend County FIS (Appendix A) and the design storm analysis (Appendix E) from this study. A comparison of the 10%, 2%, 1% and 0.2% ACE storm events and water surface elevations at the Rosharon USGS gauge are shown in Table 66.

Table 6: Rosharon Discharge and Elevation Comparisons

Storm Event	Discharge (cfs)		Water Surface Elevation (feet NAVD 88)		
	2014 Fort Bend County FIS	HEC-RAS Design Storm Analysis	2014 Fort Bend County FIS	HEC-RAS Design Storm Analysis	USGS Rating Curve*
10% ACE	103,000	86,000	51.00	50.73	51.98
2% ACE	145,000	125,000	51.50	51.17	52.59
1% ACE	162,000	145,000	51.50	51.29	-**
0.2% ACE	200,000	204,000	51.80	51.62	-**

**Water surface elevations are derived from the Rosharon USGS Rating Curve (Version 16) using the Design Storm Analysis discharges*
***Design Storm Discharge not found within USGS rating curve*

Based on the results shown in Table 6, the discharges for Rosharon showed decreases in every storm event except the 0.2% ACE event. The water surface elevations were comparable to each other between the storm events because much of the discharge upstream in the Lower Brazos River overflows into Oyster Creek. This overflow widens the floodplain and it therefore requires a substantial amount of flow to increase the water surface elevations. The 1% ACE inundation area along with the overflow areas near the Rosharon USGS gauge is shown in Figure 13.

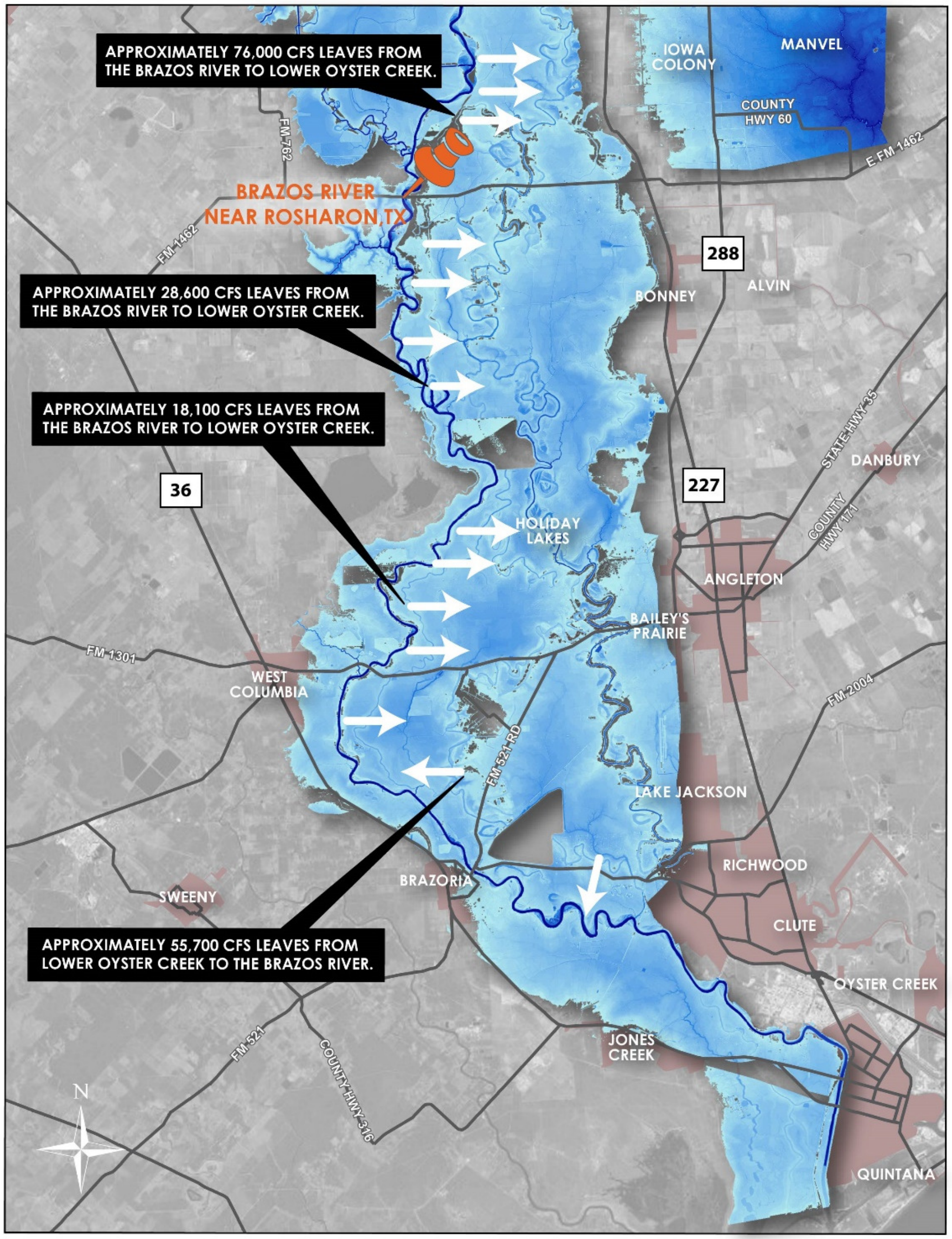


Figure 13: 1% ACE Inundation Area near Rosharon USGS Gauge

7.0 Environmental Analysis

As a component of the Lower Brazos Flood Protection Planning Study, a GIS based evaluation of environmental resources and potential environmental constraints near the Lower Brazos River was conducted. For this analysis, a constraint was defined as something that may affect the location of, or be affected by the location of, a flood mitigation project. Certain activities pertaining to flood risk reduction have the potential to be regulated under Section 404 of the Clean Water Act, Section 7 of the Endangered Species Act, Section 106 of the National Historic Preservation Act, the National Environmental Policy Act (NEPA), as well as various state, regional, and municipal regulations.

The environmental analysis study area was defined as approximately 2,700 square miles along the Lower Brazos River corridor in Austin, Brazoria, Fort Bend, Waller, and Washington counties. Through this GIS-based evaluation process, a geographic dataset was compiled for the entire study area representing environmental features with the potential to present regulatory constraints (i.e. potential permitting and/or mitigation constraints) including stream impoundments, wetlands, soil types, impaired water surfaces, groundwater resources, water management entities, groundwater wells, endangered species, critical habitat, cultural resources, oil and gas, prime farmland and USACE Galveston District nationwide permit regional conditions. The purpose of this dataset was to provide BRA and stakeholders with a planning and scoping tool for prospective flood mitigation projects within the Lower Brazos River Basin. Additional information about the GIS based environmental analysis is included in Appendix F.

8.0 Flood Mitigation Alternatives

A broad range of conceptual hydraulic alternatives were evaluated to mitigate flooding to structures located along the Lower Brazos River. These hydraulic alternatives include structural buyouts, the construction of levees, raising existing levees, large scale detention, channelization, and a diversion channel to reduce the area inundated by the 1% ACE water surface elevation. Alternatives were selected based on the ability to provide benefits to a large number of impacted structures. Any proposed alternatives should not result in measurable increases in the extent and magnitude of flooding in another area, should avoid adverse impacts to buildings, and the total average annual benefits should equal or exceed total average annual costs for an alternative to be recommended. Any downstream adverse impacts or increases in water surface elevation associated with hydraulic alternative options should be evaluated and mitigated if any of the projects contemplated in this analysis are recommended for further evaluation. The conceptual flood mitigations alternatives in this report are presented as projects that local sponsors may consider and evaluate further to help reduce flood risk. As such, the conceptual flood mitigations alternatives presented do not reflect the position of the Brazos River Authority or study partners as to whether these alternatives should be implemented or how they should be prioritized.

8.1 Structure Buyouts

Potential structure buyout areas were selected based on areas with FEMA repetitive losses (more than one FEMA flood claim for the structure) present in the FEMA flood claims and within the Lower Brazos Floodplain Protection Planning 1% ACE inundation area. Additional consideration was given to areas with severe repetitive loss properties (more than three FEMA flood claims for the structure). A flood claim density map is shown in Figure 14. Property values were determined from each county's Appraisal District.

Twelve buyout locations were determined along the Brazos River with 1,061 potential buyout structures for a total cost of $193,000,000. Structural buyouts are less expensive than other flood mitigation alternatives and have the flexibility of being implemented as funding becomes available. A structure buyout program offers the shortest time of implementation and allows for prioritization of the most at-risk structures. In addition to these benefits, this alternative had the least environmental impact to the Lower Brazos River. Buyouts can be completed under the FEMA Hazard Mitigation Grant Program (HMGP) or Hazard Mitigation Assistance (HMA) programs. Appendix G contains addition information on structure buyouts.

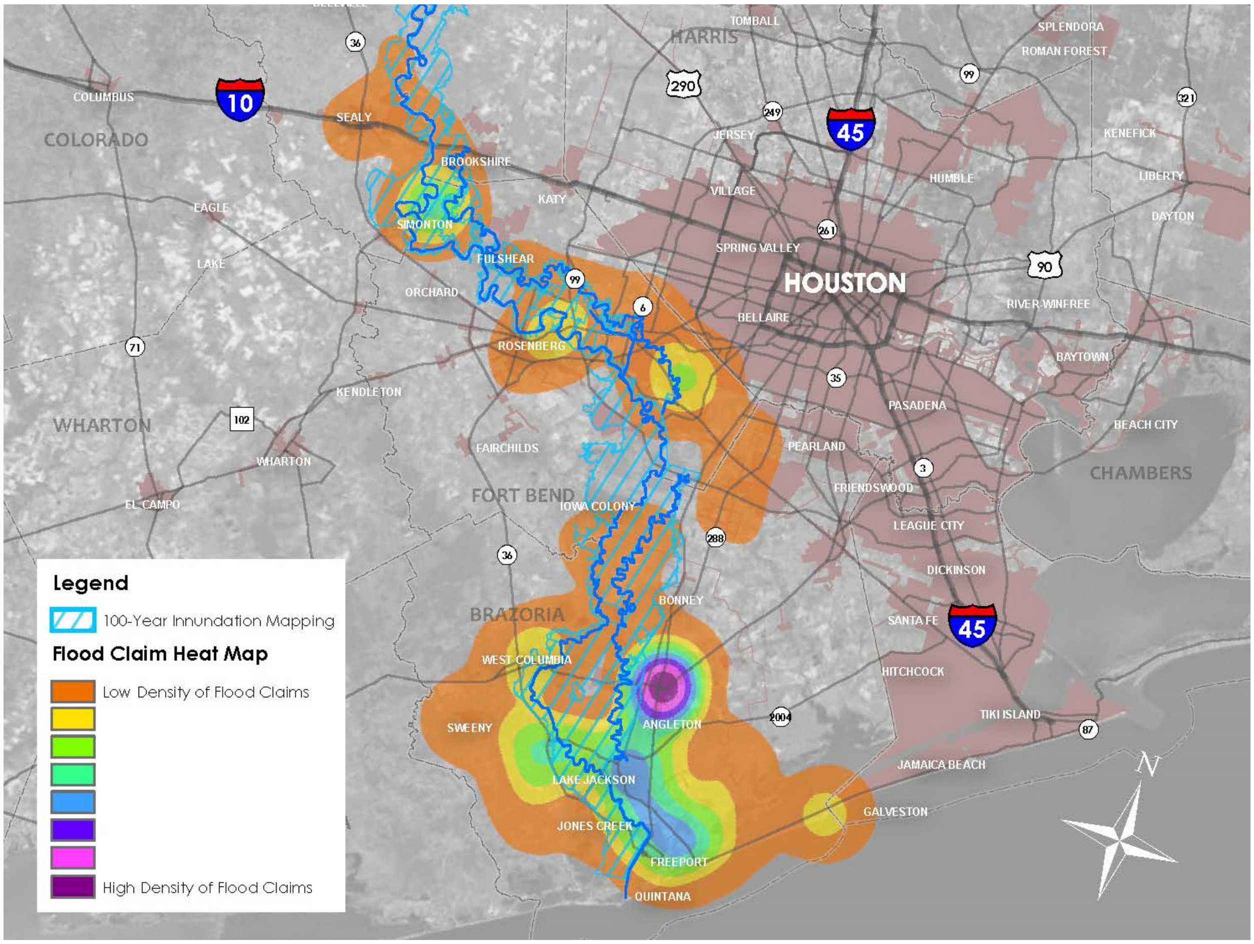


Figure 14: FEMA Flood Claim Density Map

8.2 Levee Freeboard

The updated 1% ACE water surface elevations from the Lower Brazos Floodplain Protection Planning Study were compared to existing levee elevations from study LiDAR to confirm that FEMA's minimum freeboard requirements are met. The minimum FEMA freeboard required is three feet above the 1% ACE water surface elevation, an additional one foot within 100 feet of structures, and an additional 0.5 feet at the upstream end of a levee. Appendix G shows the freeboard range for levees within the Fort Bend area. The analyses showed that seven levees, with less than three feet of freeboard, may require further investigation to confirm that the minimum freeboard requirements are met based on the 1% ACE water surface elevation determined with this study. Appendix G contains additition information on levee freeboard.

8.3 Bank Station Changes

Large amounts of bank erosion have been observed in recent years. When banks erode, the material is deposited downstream, changing both the alignment and hydraulic properties (water surface elevations) of the Brazos River. The goal of the bank station change analysis was to show how the Lower Brazos River has changed with time via meanders, scour, and deposition. To accomplish this goal, the Lower Brazos River banks were delineated based on Google Earth aerial imagery from 2006, 2008, 2015, and 2017. The results were then compared against each other to show the rate at which the banks have changed. Figure 15 shows an example of the bank comparison from 2006 to 2017 near Sugar Land. A complete workmap of bank station changes within the study area are provided in Appendix G. Design of proposed flood mitigation alternatives as well as future development in the area should consider the geomorphology of the Lower Brazos River.

Figure 15: Bank Changes in Fort Bend County (2006-2017)

8.4 Proposed Flood Mitigation Levees

Levees can be effective flood mitigation solutions as they prevent flood waters from reaching flood prone areas. FEMA criteria require levees to have a minimum freeboard (height above the 1% ACE water level) of at least three feet for the entire length of the levee and 3.5 feet of freeboard at the upstream and downstream tie-in locations. Proposed levees would include a 15-foot-wide crest with an all-weather access/maintenance road on top. The height of the levee was assumed to be four feet above the 1% ACE water level to ensure that FEMA freeboard requirements were met. The proposed levee was assumed to have 4:1 side slopes and right-of-way would be acquired for 20 feet beyond each toe. An inspection trench would also be constructed.

A high-level feasibility analysis was prepared with a cursory look at potential alignments, hydraulic impacts, environmental permitting impacts, costs, and benefits. A more detailed analysis (beyond the scope of this project) would be required to more thoroughly identify constraints and refine the design concept and cost estimates.

8.4.1 Simonton Ring Levee

A levee around portions of Simonton could protect the Brazos Valley Development between Bessies Creek and the Brazos River from the 1% ACE floodplain. The levee would be bounded by Rue Road to the north, Chisholm Road to the East, and FM 1093 to the south. The western portion of the Brazos Valley Development was not included with this proposed flood mitigation alternative due to the location of the area in relation to the Brazos River. The estimated average height of the levee would be seven feet with a maximum height of nine feet and a length of 23,700 feet (4.5 miles). An internal drainage system would be required to mitigate approximately 580 acres of runoff inside the levee. The levee alignment accounts for the approximate area required for pump stations and a sump. The proposed alignment can be seen in Figure 16.

The estimated project cost for the proposed Simonton Ring Levee was $57,200,000. The proposed levee could have impacts to wetland areas present along the northeastern and southwestern limits of the proposed levee. The levee was proposed in areas with "Columbia Bottomlands" soil types and may not be authorized by a USACE nationwide permit (see Appendix F and G). Right-of-way required for the potential levee would be 6,150,000 square feet (141 acres). The proposed levee could be utilized to eliminate structure flooding for approximately 200 homes from the 1% ACE event, 25 which are repetitive loss structures and one severe repetitive loss structure.

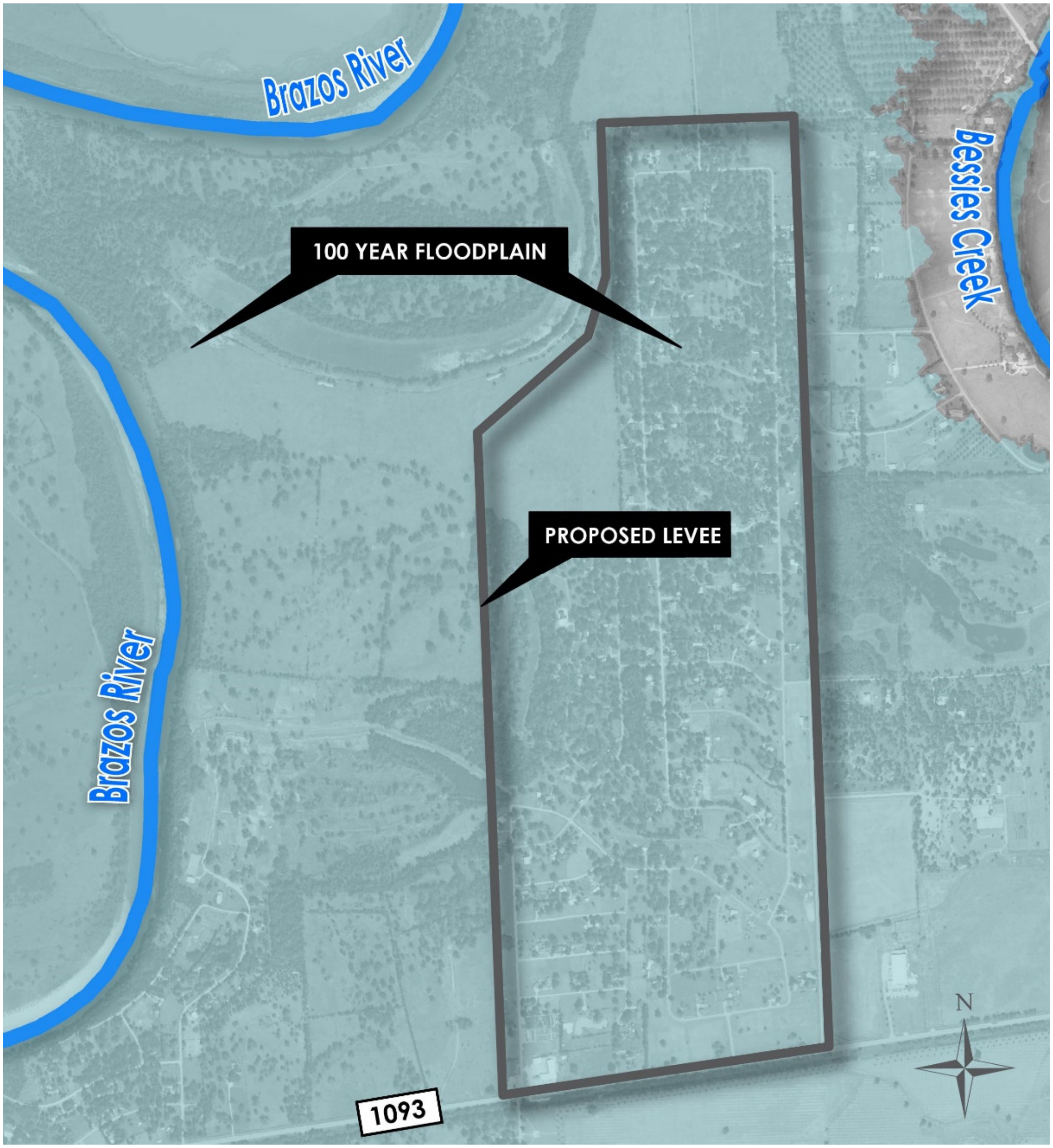


Figure 16: Proposed Simonton Ring Levee

8.4.2 Weston Lakes Levee

The Weston Lakes subdivision near Fulshear, Texas is at risk for flooding from both the Brazos River and Bessies Creek. A ring levee around the entire subdivision was determined to be impractical due to the large area, about 2,000 acres. For this reason, two separate levees were analyzed. The northern portion of the development discharges into Pecan Lake (an old tributary to Bessies

Creek). Runoff is stored within Pecan Lake and eventually discharges north into Bessies Creek via a spillway at FM 1093. During large events the Brazos River spills into Bessies Creek. The spill causes FM 1093 to be overtopped and begins to back up into Pecan Lake as well as the northern portion of the Weston Lakes development. The southern portion of the Weston Lakes development floods due to the Brazos spilling its banks during large events.

The first levee would begin approximately 600 feet west of the intersection of Woodbine Drive and Wellspring Lake Drive, continue south to the Brazos River, and extend downstream along the Brazos River to a point approximately 1,000 feet northeast of Waterhouse Court. The estimated average height of the levee is seven feet with a maximum height of 15 feet. The levee would have a length of 11,000 feet (2 miles).

The second levee along Bessies Creek would begin approximately 450 feet west of Waterford Crest Lane at FM 1093, runs along FM 1093 to Bessies Creek, and follow Bessies Creek for approximately 1,400 feet. The estimated average height of the levee is five feet with a maximum height of 11 feet. The levee would have a length of 5,100 feet (one mile). The proposed alignments can be seen in Figure 17.

The estimated project cost for the proposed Weston Lakes Brazos alignment is $9,300,000 and Weston Lakes Bessies Creek alignment is $5,700,000 with a combined project cost of $15,000,000. Cost estimates did not include internal drainage systems. There are numerous potential environmental impacts including a record occurrence of the bald eagle within the potential levee alignments and potential impacts to waters of the U.S. Right-of-way required for the potential levee would be 1,600,000 square feet (37 acres). The proposed levee could be utilized to eliminate structure flooding for approximately 370 homes from the 1% ACE event.

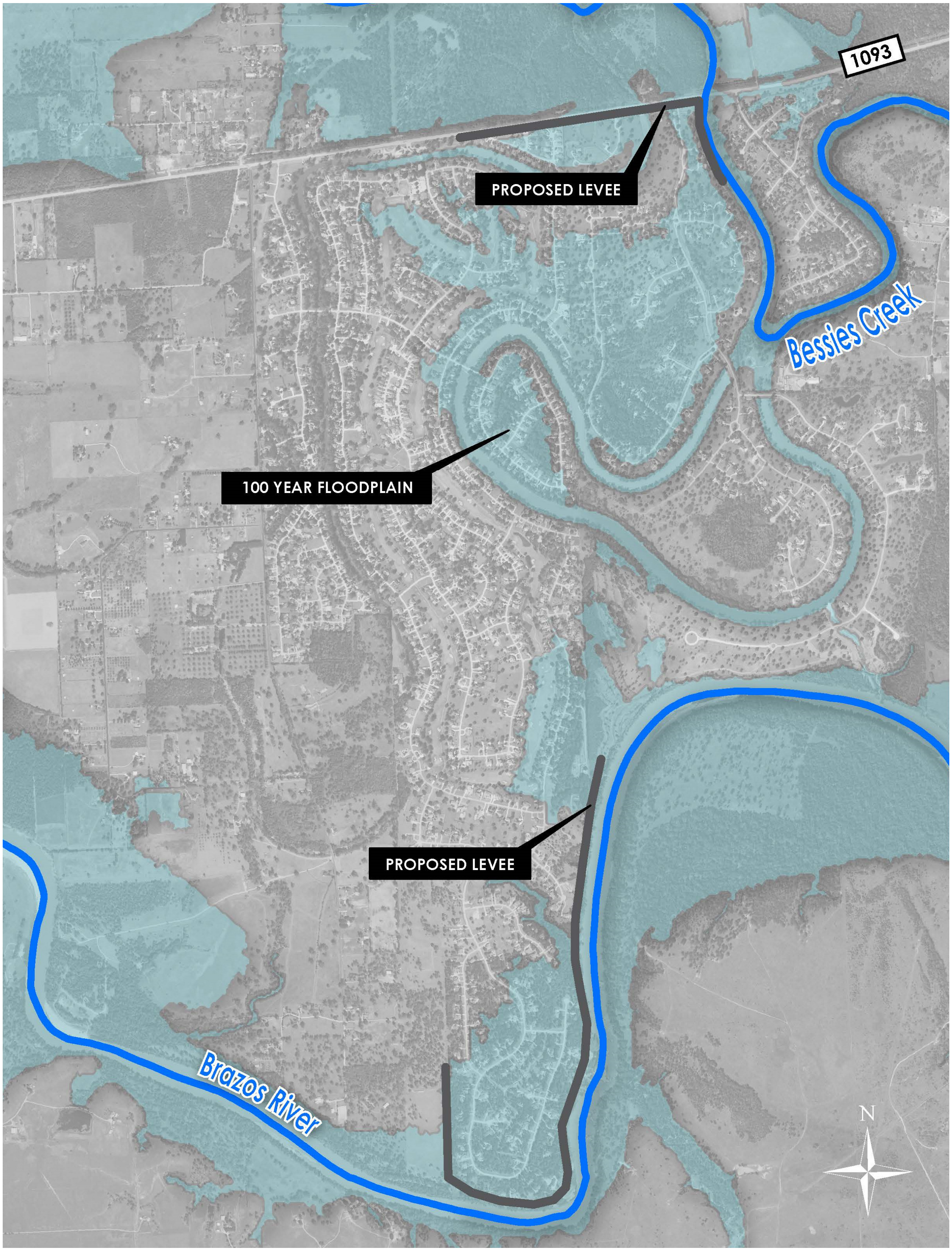


Figure 17: Proposed Weston Lakes Levee

8.4.3 Columbia Lakes Levee

The Columbia Lakes Development is in Brazoria County just north of the town of West Columbia. This alternative considers raising the existing levee to exceed the freeboard requirements when compared to the updated Brazos River 1% ACE water surface elevation. Two separate sections of the existing levee would need to be raised an average of four feet to meet the FEMA freeboard requirements. The levee would be raised for approximately 17,000 feet (3.2 miles) or 49% of the existing levee. The proposed locations are shown in Figure 18.

The estimated project cost for the proposed Columbia Lakes Levee was $9,800,000. There are numerous potential environmental impacts to water quality, wildlife, and trees. Right-of-way required for the potential levee would be 520,000 square feet (12 acres). The proposed levee could be utilized to eliminate structure flooding for approximately 400 homes from the 1% ACE event including 4 repetitive loss structures, 1 severe repetitive loss structure, and 1 critical facility.

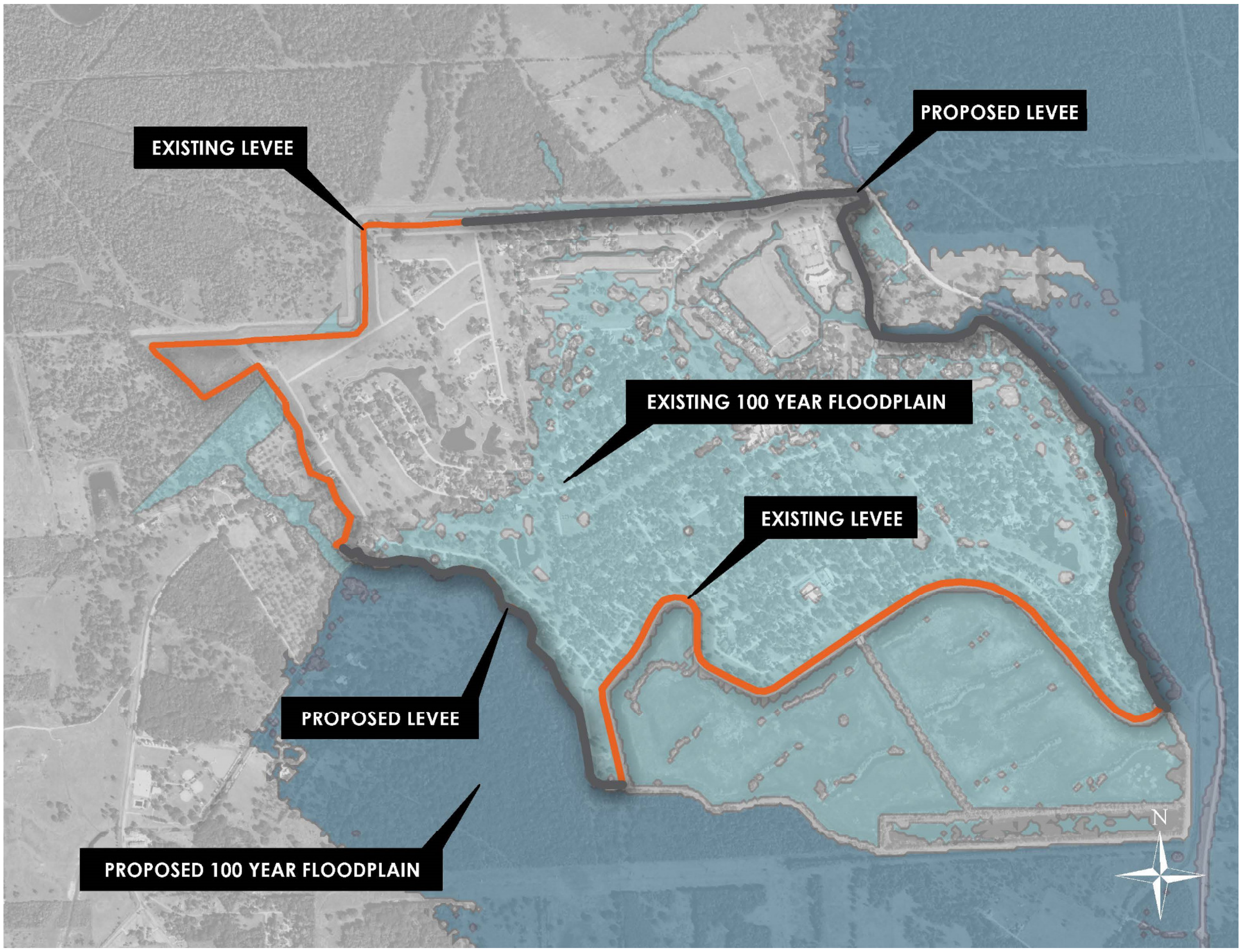


Figure 18: Proposed Levee at Columbia Lakes

8.4.4 Brazoria Reservoir – Oyster Creek Levee

A ring levee for the Lake Jackson Farms development between the Brazoria Reservoir and Oyster Creek may prevent flooding from occurring in the neighborhood and prohibit the transfer of over flow from Oyster Creek to the Brazos River. The levee would be located along the bank of Oyster Creek and to the east of the Lake Jackson Farms development. The levee would then follow along the northern edge of the neighborhood, join with the Brazoria Reservoir levee and then follow along the southern edge of the neighborhood parallel to Brazoria Road. Buffalo Camp Bayou runs through the Lake Jackson Farms development and would have to be gated to prevent water from backing up into the development from both the Brazos River and Oyster Creek. The estimated height of the levee is approximately seven feet with a maximum height of 13 feet and a length of 50,000 feet (9 miles). An internal drainage system would be required to mitigate approximately 3,000 acres of runoff inside the levee. Figure 19 shows the Oyster Creek Levee alignment at Brazoria Reservoir. The estimated project cost for the proposed Brazoria Reservoir – Oyster Creek Levee is $160,000,000. The proposed levee could potentially have impacts to wetland areas present along the western extent of the levee, waters of the U.S., and gas pipelines. Right-of-way required for the potential levee would be 5,300,000 square feet (122 acres).

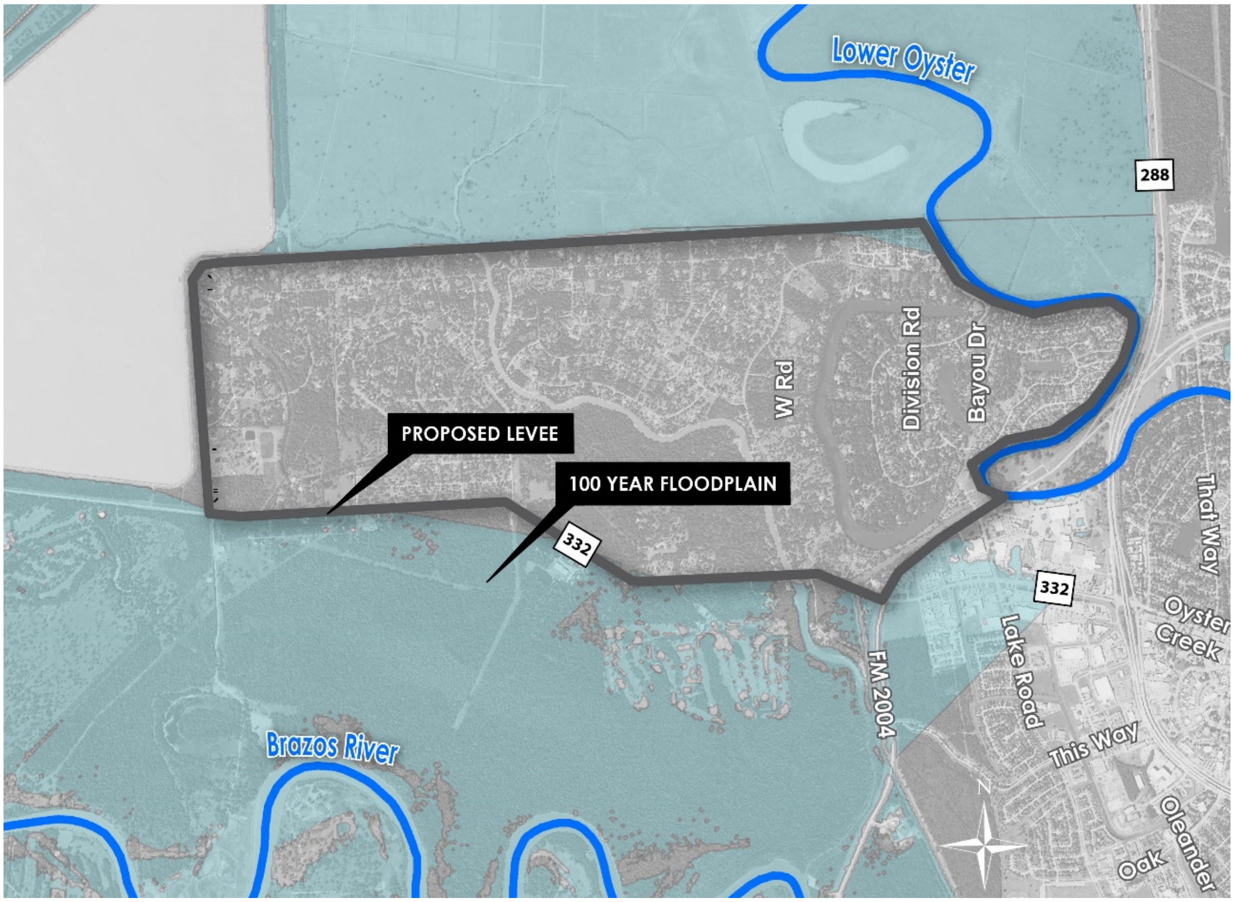


Figure 19: Proposed Brazos Reservoir-Oyster Creek Levee

8.4.5 Pecan Grove Levee

A ring levee around the area near Bullhead Bayou and Pecan Grove could prevent flooding within the area. The levee would be placed along the right overbank of the Brazos River near Rio Vista and Rivers Edge to Autumn Ridge to prevent overflow from the Brazos River. A levee would also be placed along Pitts Road to prevent overflow from Bullhead Bayou. The estimated height of the levee is approximately seven feet with a maximum height of 18 feet and a length of 26,000 feet (5 miles). In addition, an internal drainage system would be required to mitigate approximately 1,000 acres of runoff within the levee. The estimated project cost for the proposed Pecan Grove levee was $76,000,000. The proposed levee could have impacts to wetland areas present along the western extent of the levee and waters of the U.S. Right-of-way required for the potential levee would be 3,000,000 square feet (68 acres).

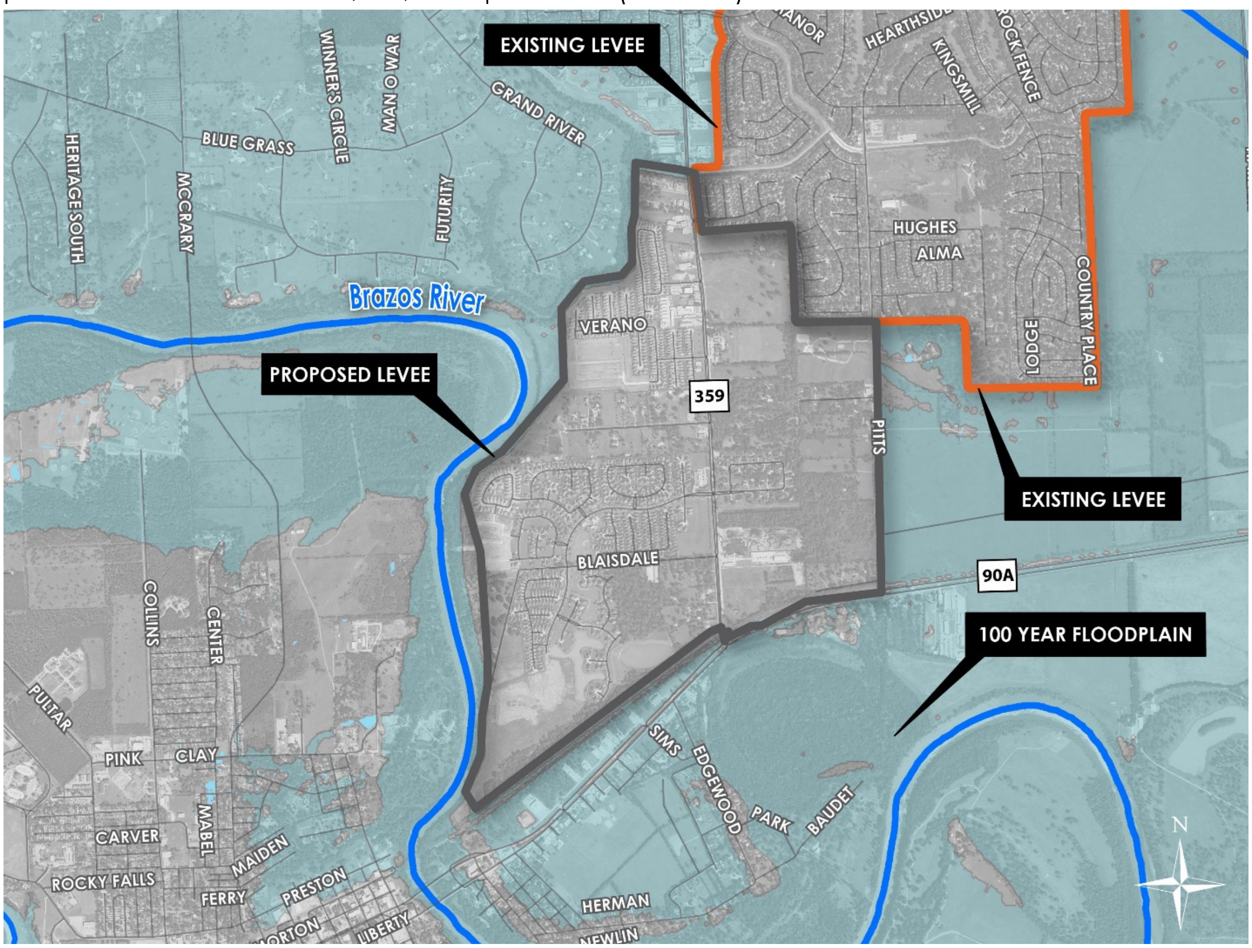


Figure 20: Proposed Pecan Grove Levee

8.5 Large Scale Flood Alternatives

A high-level feasibility analysis was prepared for three large scale flood alternatives that could reduce flood impacts for a wide area of impacted structures along the Lower Brazos River including large scale detention, channelization and a bypass channel. The large-scale alternatives included potential alignments, hydraulic impacts, environmental permitting impacts, costs, and benefits. A more detailed analysis (beyond the scope of this project) would be required to more thoroughly identify constraints and refine the design concept and cost estimates if the alternative were to be utilized.

8.5.1 Large Scale Detention

A large-scale detention alternative was evaluated to determine the volume of water that would need to be diverted and detained from the Brazos River to minimize flooding impacts along developed areas for the 1% ACE event. Detention was evaluated in both Waller and Brazoria county to mitigate flooding in repetitive loss areas. The engineering design of the detention areas was not considered in this analysis. Only the volume required to reduce the 1% ACE flood impacts on the Brazos River calculated. In Waller County, the diversion point was set just upstream of San Felipe while the diversion point for Brazoria County was set downstream of Sienna Plantation development. The volume required to minimize flooding impacts along developed areas for the 1% ACE event would be approximately 2 million acre-feet of storage for Brazoria County and approximately 1 million acre-feet of storage for Fort Bend County.

Figure 21 shows comparisons of the detention area footprint to Somerville Lake to visualize the magnitude of the large-scale detention options. Somerville Lake is located in Burleson County west of the Lower Brazos River Basin. Somerville Lake currently covers 24,000 acres (38 square miles) and has an approximate volume of 507,000 acre-feet. The proposed detention areas were assumed to have a depth of 20 feet when determining the surface area.

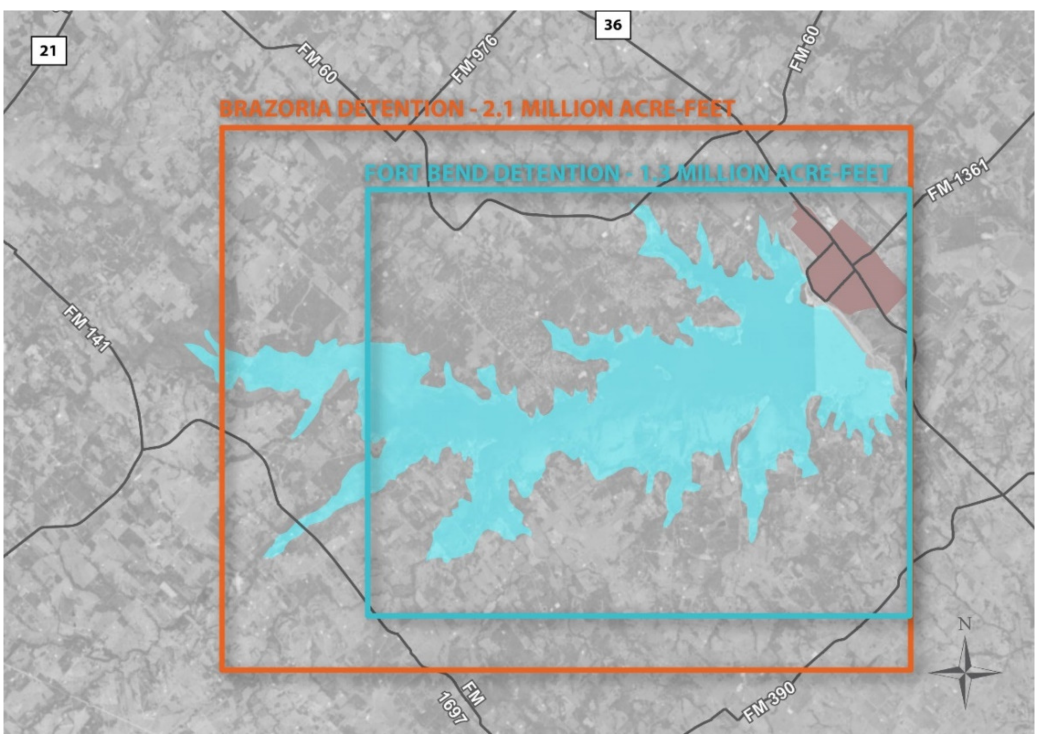


Figure 21: Large Scale Detention Volume Comparison

8.5.2 Channelization

Channelizing the Brazos River consisted of locating reaches along the river that would mitigate flooding impacts at locations where a high density of FEMA flood claims were located and areas of high development within the 1% ACE floodplain. Two channelization alternatives were analyzed which included locations within Fort Bend County and Brazoria County. The channel geometry consisted of a trapezoidal section with a bottom width of 600 feet at 4:1 (horizontal: vertical) side slopes. The bed slope was determined by utilizing the existing downstream and upstream channel inverts and grading the slope between those points to create the channel profile.

In Fort Bend County, the proposed channel begins just downstream of the Fort Bend/Waller County Line and ends just upstream of the USGS Richmond Gauge near Rivers Edge as shown in Figure 22. Channel sections were adjusted to ensure the alternative would not encroach into existing properties along the river. The goal of the proposed channel was to lower water surface elevations in Simonton, Rosenberg and the Richmond area. Water surface elevations are lowered in the Brazos River from the San Felipe USGS gage to US 90A in Richmond ranging from 0.01 feet to 11 feet.

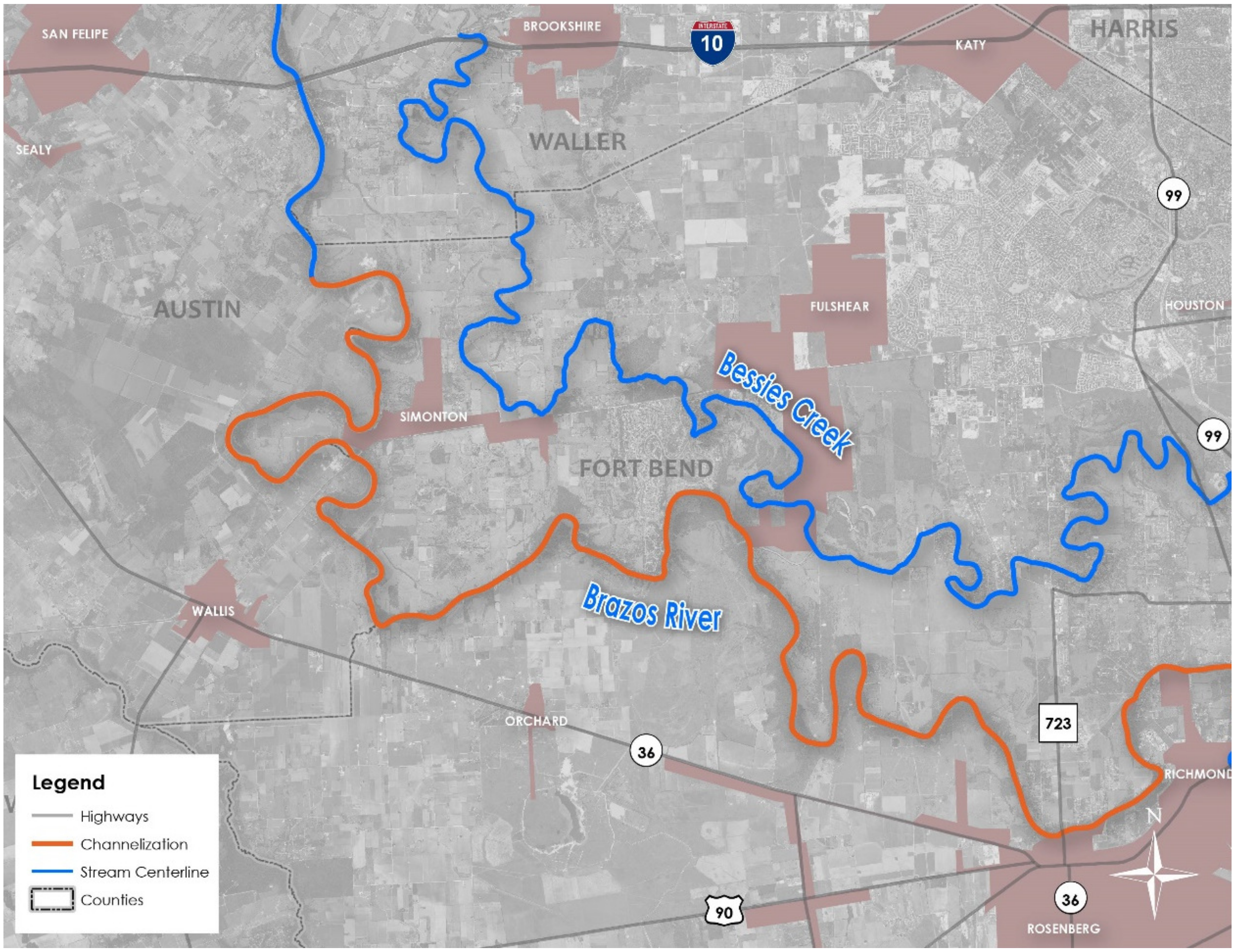


Figure 22: Channelization in Fort Bend County

In Brazoria County, the proposed channel was separated into two sections. The first section begins downstream of FM 1462 and ends near the unincorporated community of Otey. The second section begins just upstream of the Columbia Lakes subdivision and ultimately ends at the Gulf of Mexico as shown in Figure 23. The goal of this channel was to lower water surface elevations for Columbia Lakes, West Columbia, Brazoria and Jones Creek. Water surface elevations are lowered on the Brazos River near Sienna Plantation to the Gulf of Mexico ranging from 0.01 feet to seven feet.

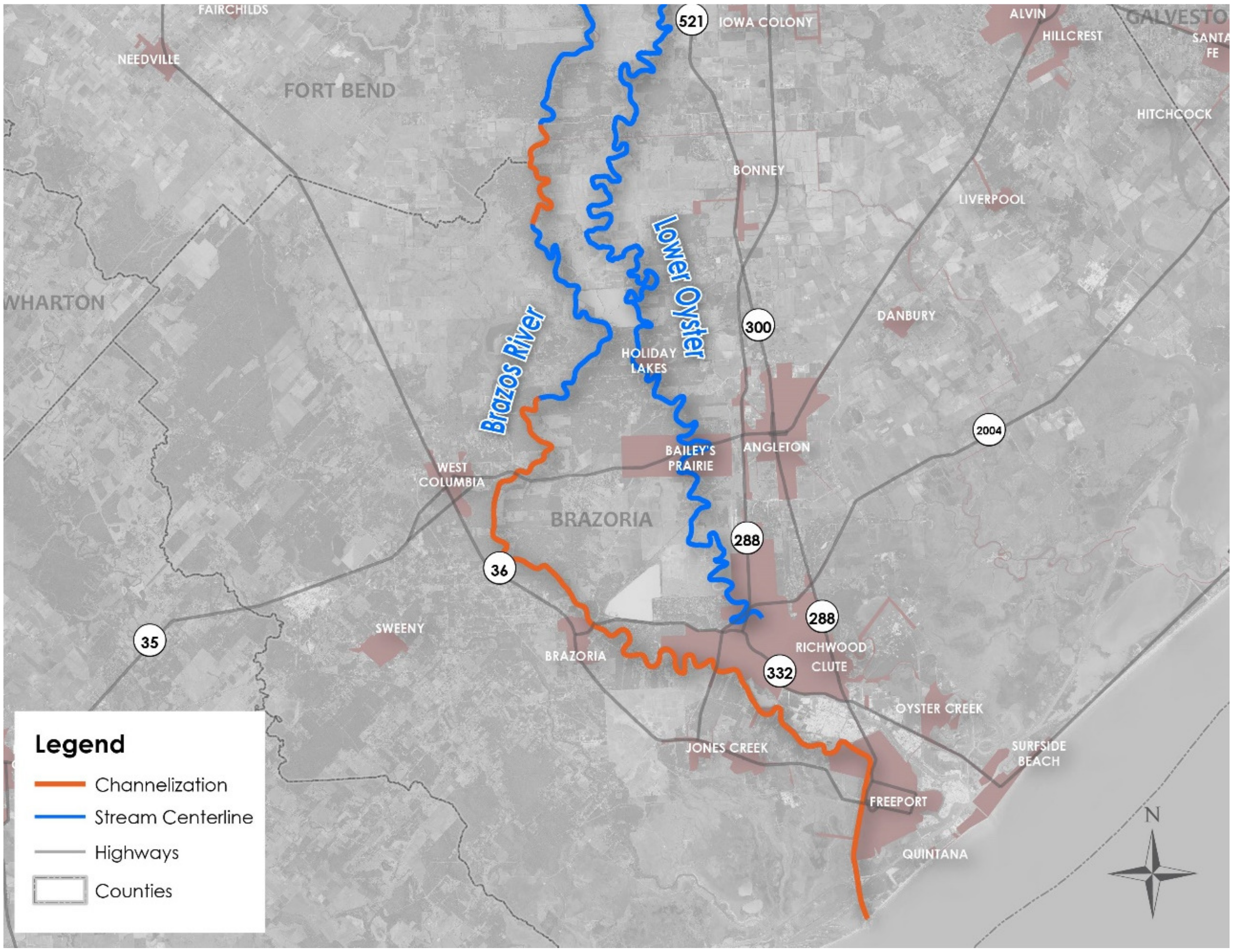


Figure 23: Channelization in Brazoria County

8.5.3 Bypass Channel

The Bypass Channel alternative consists of diverting water from the Brazos River through a proposed channel from Fort Bend County downstream towards the Gulf of Mexico. The bypass channel would be located west of Rosenberg with the alignment staying clear of existing water bodies. The proposed bypass channel alignment is shown in Figure 24.

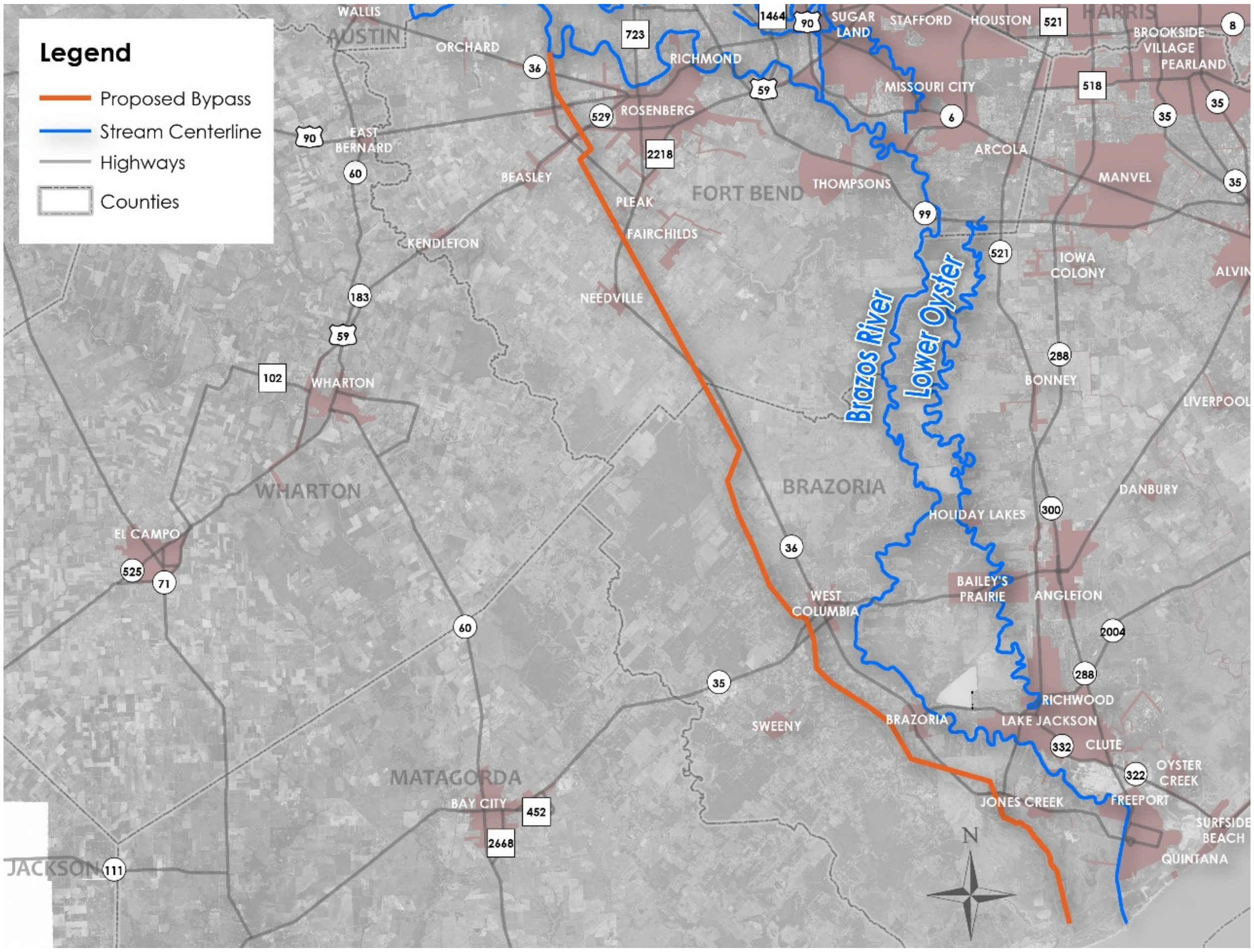


Figure 24: Proposed Bypass Channel

The Bypass Channel was proposed to lower 1% ACE water surface elevations in both Fort Bend and Brazoria County and reduce flood inundation in areas with a high density of FEMA flood claims. The Bypass Channel was designed as a trapezoidal section with a bottom width of 800 feet and a side slope of 4:1 (horizontal to vertical) at a channel depth of 12 feet. The proposed bypass channel is outside of the Lower Brazos River Basin where current terrain was unavailable. The proposed by-pass channel was cut down at a uniform slope from the invert elevation at the Gulf of Mexico. The upstream invert elevation was determined diversion point through iterations in the hydraulic modeling to ensure the channel reached maximum capacity. The proposed bypass channel would potentially lower the 1% ACE water surface elevations in the Brazos River through the entire reach (Waller County Line to Gulf of Mexico) ranging from 0.3 feet to 10 feet.

8.5.4 Potential Alternative Environmental Constraints

Flood mitigation alternatives could have potential impacts to waters of the U.S., regulated under Section 404 of the Clean Water Act. The USACE utilizes nationwide permits for categories of activities that cause only minimal individual and cumulative adverse impacts. Nationwide Permit 3 – Maintenance (NWP 3) is often used to authorize levee rehabilitation, replacement, or improvement projects where the proposed action involves the placement of fill in waters of the U.S. In determining the applicability of nationwide permits, the project must also assess the project effects on threatened and endangered species and cultural resources, each of which can often be mitigated if present. According to the nationwide permit regional conditions for the USACE Galveston District, the District will not issue a nationwide permit authorization for activities that occur in the Columbia Bottomland land cover type. NWP 3 is an exception to this condition; however, the applicant must notify the USACE prior to commencing the project. Appendix F and G contains additional information of potential alternative environmental constraints.

9.0 Benefit Cost Analysis

An economic analysis was developed to identify and quantify the extent of flood problems and, on a comparable basis, evaluate solutions to reduce flood losses. The USACE HEC Flood Damage Reduction Analysis (HEC-FDA, Version 1.2.5, March 2010) software was utilized to develop the economic analysis of the flood reduction alternatives. For each alternative, a base flood damage assessment was developed to represent the expected average annual damages if no alternatives were implemented based on the water surface elevations computed with the hydraulic model developed for this study (see Appendix E). A “with project” flood damage assessment was developed to represent the expected annual damages if the alternative was fully constructed.

A Benefit-Cost Analysis (BCA) was performed for the local flood mitigation alternatives. The BCA was established as the standard to provide technical and financial assistance for implementation of flood or hazard mitigation undertakings. The minimum criteria for state and federal funding is a BCA of 1.0 or greater meaning that the benefit of the proposed project would match the annual cost of the project. Benefit is increased if flooding occurs at structures during more frequent events. Table 77 presents the Benefit Cost Analysis for the Lower Brazos Floodplain Protection Planning Study.

Table 7: Cost Benefit Analysis Results

Alternative	Estimated Total Project Cost	Average Annual Project Cost	Damages Prevented	BCA
Simonton Ring Levee	$57,200,000	$2,700,000	$448,000	0.2
Weston Lakes Levee	$15,000,000	$700,000	$650,000	0.9
Columbia Lakes Levee	$9,800,000	$600,000	$600,000	1.32
Brazoria Reservoir -Oyster Creek Levee	$160,000,000	$7,500,000	$8,500,000	1.1
Pecan Grove Levee	$76,000,000	$3,500,000	$4,800,000	1.4

10.0 Potential Next Steps

A goal of the Lower Brazos Floodplain Protection Planning Study was to assess the lower Brazos River Basin from a comprehensive basin wide perspective. The study results showed that modeling the river from this perspective provided a better understanding of the elevations and flows on the river and the entire basin system must be considered due to the complex system of overflows. Considerable time, cost and effort have been invested in this study. Now that the study is complete, potential next steps should be considered by the study stakeholders including:

- *Levee Improvement Districts and communities adopt study results*

  Multiple LIDs are located along the Brazos River. These LIDs are in the process of making upgrades to their internal drainage systems and pump stations. The results from this study should be adopted for their designs. Communities along the river should also consider adopting the findings of this study to improve floodplain management, flood warning, and flood response.

- *Update Hydrology with Atlas 14 Rainfall*

  The National Oceanic and Atmospheric Agency published *NOAA Atlas 14, Volume 11 Precipitation-Frequency Atlas of the United States, Texas* which shows that rainfall rates have increased dramatically in the Houston region. For example, the 1% AEP 24-Hour rainfall depth of 13 inches in the Houston area has increased to 18 inches. Therefore, the hydrologic and hydraulic modeling may need to be updated to determine the impact of increased rainfall rates on the Lower Brazos River basin flows and water surface elevations.

- *Update model with post-Harvey topography*

  The Lower Brazos Study was initiated in 2014, well before the significant storm events of 2015, 2016, and 2017. As a result of those storm events, the Brazos River has experienced erosion in many areas. The changes in the river have resulted in loss of bank up to 200 feet. The Fort Bend County effective model was incorporated into the overall hydraulic analysis. The Fort Bend model was developed using survey and topography data captured in 2007. The Fort Bend County model was incorporated without updating the topographic data and is therefore based on outdated information. The hydraulics through Waller/Washington/Austin Counties as well as through Brazoria County are also based on pre-Harvey topography. Therefore, we recommend that the model be updated with post Harvey topography to reflect current conditions of the river.

- *Extend the detailed study area to College Station*

  The hydrologic model developed for the flood protection planning study extends well upstream of the hydraulic model which begins near the USGS Gauge near Hempstead. Extending the hydraulic model upstream to the USGS Gauge near College Station will enhance the accuracy of the model and provide additional flood response information through critical areas. The hydraulic modeling extension would require an updated historical gauge frequency analysis at the USGS Bryan Gauge, calibration of the hydrologic and hydraulics models at the USGS Bryan Gauge, as well as an updated critical design storm.

- *Develop a hydraulic model of the Navasota River*

  The Navasota River is a major tributary of the Lower Brazos River Basin. During large storm events, it contributes significant discharge to the Brazos River. It also conveys discharges from Lake Limestone. During 2016 and Harvey, this river experienced significant flooding. Developing an updated hydraulic model of the Navasota River will provide essential information of the discharge timing from the Navasota River to the Lower Brazos River.

- *Model reservoir inflows/outflows and operations*

  Inflows and outflows from the upstream reservoirs in the Lower Brazos River Basin are critical to calculating the discharges through Waller, Washington, Austin, Fort Bend, and Brazoria Counties. Updating the models to include the operations of these reservoirs would provide important information for flood response and warning.

- *Expand the stream gauge network along the Lower Brazos River and develop additional rating curves*

  The USGS gauges on the Lower Brazos River are important to the communities along the banks. In Fort Bend County, levees along the river protect large residential, commercial and industrial areas. During recent storm events, it became evident that improvements need to be made to flood response and flood warning. There was some uncertainty from these communities on when to evacuate and how deep the water might be in a flood event. The addition of stream gauges in the basin would provide communities with more information on the water surface elevations and respective discharges in the river. These gauges could then be tied to inundation mapping based on the hydraulic model developed for this study. Below is a list of recommended gauge locations.

  - Brazos River at State Highway 105 near Navasota
  - Brazos River at Interstate Highway 10 near Brookshire
  - Brazos River at US 59 near Sugar Land
  - Brazos River at US 35 near West Columbia
  - Brazos River at FM 2004 near Lake Jackson
  - Oyster Creek at FM 1462 near Rosharon
  - Oyster Creek at US 35 near Angleton
  - Navasota River at State Highway 6 near Navasota

  The addition of gauges would require the development of rating curves. The rating curves provide a relationship between water surface elevations and discharges at the gauge location.

- *Incorporate model results into FEMA FIS and Flood Insurance Rate Maps*

  The inundation mapping developed for this study provides 1% ACE water surface elevations for many areas along the Brazos River where communities only have approximate elevations. The results of this study also provide better information for the communities who do not have current hydrologic and hydraulic modeling along the Brazos River. Steps should be taken to develop new effective FEMA floodplain mapping utilizing this study. This process would require developing a floodway for the river and going through the FEMA process for a physical map revision for multiple areas.

- *Develop a Lower Brazos River Coalition to maintain the model of the Brazos and adopt similar criteria where applicable*

  The Lower Brazos River Basin has areas which are considered some of the fastest growing in Texas. There are multiple counties and municipalities along the river which all adhere to different drainage criteria and standards. As these communities continue to develop, unintended impacts to the basin wide hydrology and hydraulics will arise. Communities along the river from Waller County to Brazoria County should consider forming a coalition of the Lower Brazos River. This coalition or "vision" group of communities could work together to address issues such as impacts of development, common criteria, land conservancy, erosion, river migration, flood warning, flood response, and flood reduction. The coalition would need to establish a lead agency to moderate the group such as the BRA, Houston-Galveston Area Council (H-GAC), or the USACE.

  In the Dallas/Fort Worth (DFW) Area, the Corridor Development Certificate (CDC) process was developed with the intent to stabilize flood risk along the Trinity River. Any land development within the regulatory zone (FEMA 100-year floodplain) requires a CDC permit. Land development is not prohibited but the process aims to ensure that any development will not increase water surface elevations or reduce flood storage in the Trinity River Basin.

  Local governments have ultimate control over floodplain permitting decisions. Through the CDC process, other communities along the Trinity River are given the opportunity to review projects in neighboring jurisdictions. In the 30-year history of the CDC in the DFW area, over 200 projects have been reviewed for compliance by neighboring jurisdictions to assure no detrimental impacts occur upstream or downstream. Benefits to participating in the CDC process include the following: cooperative management among the local governments resulting in a comprehensive approach to flood damage reduction and environmental quality; improved communication along the corridor; expanded technical assistance from the USACE; continual updating of the regulatory model; and preservation of flood storage.

  A local coalition along the Brazos River should seek to establish a process similar to the CDC process. As development increases along the Brazos River, the process could help mitigate increased flood risk.

- *Engage the NWS to enhance flood warning capabilities using the new hydrologic and hydraulic models*

  The NWS currently provides forecasts of potentially damaging water surface elevations along the Brazos River during large rainfall events. These forecasts are made using internal models. The hydrologic and hydraulic models provided in this study can be used by the NWS to improve Flood Early Warning Systems and forecasts. This information is crucial for local emergency management officials who make decisions notifying citizens of potential flood dangers.

- *Engage the USACE to further develop the hydraulic model and flood warning capabilities*

  The USACE is currently investigating erosion that has occurred along the banks of the Brazos River due to large flood events in 2016 and 2017. The hydrologic and hydraulic models developed for this study will be useful to the USACE as part of their investigations. It is recommended that the USACE obtain the models developed for this study.

- *Evaluate development impacts in basin by considering projected growth and* discharge *volumes*

  As the Houston area continues to expand, development will continue to increase in the Lower Brazos River basin. Projected growth in the basin should be considered for potential impacts on the basin-wide river hydraulics. General practice has been to allow runoff to discharge directly into the river without detention. The approach has been to allow runoff from local storm events to pass before the river itself reaches its peak. In some cases, along the river, runoff that is detained may increase water surface elevations. Further study should be performed to investigate the impacts of future development in the Lower Brazos River Basin. As impervious areas increase along the river due to development, so do runoff volumes. The increase in runoff volume over time may impact the elevations in the river regardless of detention.

- *Identify conservancy areas along the river*

  Conservancy groups have worked with land owners and local communities to set aside land for conservation purposes. In the Houston area, there has been success in the protection of natural land along the banks of many streams. Protecting land can reduce the risk of increased flooding due to development.

- *Update Hazard Mitigation Plans in region*

  Multiple flood reduction alternatives have been proposed as part of this study. The projects range from large scale detention and channelization options to construction of local levees. Local communities should consider using these projects to update their Hazard Mitigation Plans. With further refinement of the proposed alternatives, these communities may be able to pursue federal or state funding for implementation.