Brazos River Flood Update Study

Flood Infrastructure Fund Category 1

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1 Executive summary

1.1 Study overview

This Brazos River Flood Update Study was sponsored by Waller County and funded through the Texas Water Development Board (TWDB) Flood Infrastructure Fund (FIF) as a Category 1 study. Category 1 studies are intended to develop flood risk information for regions with outdated or inaccurate data and identify potential flood risk mitigation solutions to reduce flood risk within the study area.

The key stakeholder for this study is Waller County. Other entities within the county that may benefit from the results include the cities of Hempstead, Brookshire, and Pattison.

Analysis performed as part of this study focused on two main goals: providing more accurate flood risk data and mapping for Waller County; and identifying areas with high flood risk and recommending projects to mitigate this risk. Recommended flood risk solutions were vetted to adhere to Technical Guidelines for Regional Flood Planning Exhibit C including ensuring no negative impact is created by the proposed projects and quantifying the benefits provided by the projects using the outlined flood risk reduction metrics, benefit-cost analysis process, and cost estimation considerations.

To evaluate current flood risk within the County, several sources of data were leveraged. Publicly available data such as TNRIS Lidar and NLCD Land Use rasters were gathered to provide a strong base for hydrologic and hydraulic modeling. Models developed in HEC-HMS and HEC-RAS as part of two previous studies were recalibrated and storm centered to represent historical conditions within Waller County. In addition to the data collected, a new 2D hydraulic model was created in HEC-RAS to evaluate flood risk along the Navasota River and the Brazos River upstream of Hempstead, Texas. This information was combined with the previous models to develop updated mapping and flood risk assessment for Waller County. Existing condition results were compared to FEMA Flood Insurance Study flows and water surface elevations as well as results from the previous studies along the Brazos River to validate the updated study.

The updated inundation mapping was used to evaluate flood risk from the Brazos River within Waller County. Structures, roads, and critical facilities at risk were identified based on the flow conditions at the USGS gage on the Brazos River in Hempstead. This analysis is summarized in Table 1-1, and shown visually in Exhibits 14 through 20.

Table 1-1. Summary of Existing Flood Risk in Waller County

Flow at Hempstead (cfs)	Structures at Risk	Major Crossings at Risk	Critical Facilities at Risk
54,000	0	0	0
80,000	2	0	0
99,000	18	0	0
122,000	190	0	0
143,000	414	2	0
161,000	623	3	1
196,000	915	3	1

1.2 Study recommendations

Areas with particularly high flood risk throughout the Brazos River watershed in Waller County were identified for additional assessment. Areas were selected based on the concentration of structures prone to flooding in the 1% ACE, historical flood claims, and confirmation of historical flooding issues by Waller County officials. The identified problem areas are summarized in Table 1-2. Three of the areas were selected for additional analysis in HEC-HMS and HEC-RAS to identify potential projects to reduce flood risk.

Table 1-2 Summary of Identified Problem Areas

	PA Name	Description of Flooding	Further Analyzed?
1	Peach Ridge Road	Low-lying neighborhood located in southern portion of County that experiences flooding from both Brazos River and Bessie's Creek.	No
2	Brookshire	City in southeastern portion of County. Experiences flooding from Bessie's Creek and several tributaries.	No
3	Adams Flat Road	Neighborhood along mainstem of Bessie's Creek that experiences flooding from two Bessie's Creek Tributaries.	Yes
4	Foots Wilson Road	Community located along Brazos River that experiences flooding from Brazos River overflow during extreme events.	No
5	Irons Creek Crossings	Crossings located between Brazos River and Irons Creek that flood in frequent events and prevent mobility for residents along Diemer Road.	Yes
6	FM 359	Flooding along FM 359 caused by overflow from Bessie's Creek, low-lying terrain preventing positive drainage, and several nearby ponds reaching capacity and contributing to flooding.	No
7	Rolling Hills Lake	Neighborhood located along Rolling Hills Lake that experiences flooding from lake and Gladish Creek overflows.	Yes
8	South Prairie View	Network of neighborhoods and communities located along Threemile Creek in northern portion of County. Experience flooding from creek overflow and local drainage issues.	No
9	Beaver Creek Road	Community located between Brazos River and Bessie's Bayou that experiences flooding caused by overflow from both the bayou and river.	No
10	Harris Headwaters	Community located at the headwaters of Harris Creek. Experiences flooding due to lack of terrain or drainage infrastructure to promote positive drainage.	No
11	Downtown Hempstead	Largest city within Waller County. Experiences flooding from multiple nearby creeks including Clear and Lewisville Creeks, as well as localized drainage issues.	No

A summary of the recommended projects is shown in Table 1-3. These projects were evaluated in accordance with the guidelines provided by the Texas Water Development Board (TWDB) to qualify them as Flood Mitigation Projects (FMPs) eligible for inclusion in the Lower Brazos Regional Flood Plan.

Table 1-3. Summary of Recommended Projects (FMPs)

Project		Brief Description	Summary of Benefits	Estimated Costs	BCR
FMP 1	West Diversion Channel	Construction of a channel to divert flows around neighborhood with significant flood risk.	Flood risk reduction to 67 structures in 1% ACE.	$9,500,000	1.2
FMP 2	East Diversion Channel	Construction of a channel to divert flows around neighborhood with significant flood risk.	Flood risk reduction to 62 structures in 1% ACE.	$3,200,000	2.1
FMP 3	Weir Improvements	Widening of existing weir to allow Rolling Hills Lake to drain more quickly during flood events.	Flood risk reduction to 15 structures in 1% ACE.	$9,700,000	0.5
FMP 4	Irons Creek Crossing	Improvements to crossing at Mt Zion Rd and Irons Creek to convey 2% ACE.	1 ft reduction in depth across roadway in 2% ACE.	$1,500,000	0.0*

*The project will provide mobility benefits. However, there are limited monetary benefits associated with increases in mobility.

The implementation of these projects would provide benefits to mobility as well as a reduction in flood risk to many residential and commercial structures. However, funding for the design and construction of these projects may take years to obtain. While the County is encouraged to begin seeking funding for the recommended projects as soon as possible, non-structural and flood response recommendations may be implemented in the short term to provide more immediate mitigation of flood risk.

A voluntary buyout program for structures in the 10% ACE Brazos River floodplain is one of the non-structural recommendations. This solution would provide an immediate reduction in the population at frequent flood risk from the Brazos River. Additionally, it would address flooding for areas that would be difficult to mitigate with structural measures due to their proximity to the Brazos River.

Drainage criteria updates could also be implemented by Waller County in the short term. Although this solution would not provide direct flood risk reduction to locations that already experience flooding, it would assist in addressing the potential for additional flood risk.

The structural recommendations, non-structural recommendations, and guidance outlined within the Flood Response Plan are all aimed at providing Waller County with the tools to identify and mitigate current flood risk within the County and prevent the creation of new flood risk.

2 Introduction and background

Waller County is experiencing rapid growth in a historically rural area. Much of this growth is focused near the current metropolitan areas within the County, Hempstead and Brookshire. Both of these cities, along with a substantial portion of the land area are within the Brazos River Watershed. Throughout Waller County, the Brazos River Watershed is characterized by flat terrain that exasperates riverine and localized flooding due to the inability of water to drain quickly. Additionally, there is an extensive network of Brazos River tributaries that contribute to riverine flooding outside of the Brazos River floodplain. Most recently, the watershed has seen several significant storm events in 2015, 2016, and 2017. Waller County recognized the importance of studying the area to assess the existing flood risk within the watershed which will provide information to better understand and regulate future growth as well as identifying projects that can be implemented to reduce flooding for existing residents. Figure 2-1 shows flooding along the Brazos River in Waller County during the 2015 storm.

This project is funded by a grant from the Flood Infrastructure Fund (FIF), administered by the Texas Water Development Board (TWDB) as authorized by the 86th Texas Legislature and approved by Texas voters by a constitutional amendment in November 2019. This study was funded under FIF Category 1, *Flood Protection Planning for Watersheds,* on January 1, 2021, and is scheduled to be complete on September 30, 2023.

Figure 2-1. Brazos River during 2015 Storm

2.1 Study area

Stretching 1,280 miles throughout the state of Texas, the Brazos River is one of the longest rivers in Texas and the United States. Its headwaters form in New Mexico, encompassing a watershed of almost 46,000 square miles down to the Gulf of Mexico. Towards the downstream end of the Brazos River, it forms the over 55-mile boundary between Waller and Austin counties. There are almost 30 tributaries contributing to the Brazos River Watershed within Waller County, including major creeks such as Irons Creek, Clear Creek, and Bessie's Creek.

The watershed within Waller County is mostly rural and predominately agricultural area. There are only 5 crossings over the Brazos River within the county: US 290, HW 159 E, FM 529, FM 1458, and I10. These crossings, providing east to west access across the Waller and Austin County lines, are primarily located near the pockets of higher density population.

The topography within the county is relatively flat, contributing to the widespread, shallow ponding flood risk that the County experiences. The Brazos River is characterized by its meandering pathway and sediment laden waters, leading to significant erosion and migration of the banks. Contributing tributaries within the County are primarily natural creeks with significant overgrowth and vegetation.

Flooding along the Brazos River and its contributing tributaries has been a well-documented problem several counties in the southern portion of Texas have experienced. Records of severe flooding along the Brazos River date back to the 1800s. Several significant flooding events have impacted the southern portion of the watershed in recent years including:

- Tropical Storm Allison (2001)
- Hurricane Ike (2008)
- Tax Day Event (2016)
- Memorial Day Event (2016)
- Hurricane Harvey (2017)

With the history of flooding and the ever-changing conditions of the Brazos River, Waller County prioritized the assessment of flood risk and identification of flood risk solutions for the Brazos River watershed in Waller County. To ensure the accuracy of the assessment of the Brazos River through Waller County, detailed modeling was completed for the primary tributaries upstream of the County: Yegua Creek, Navasota River, and the Brazos River between Bryan/College Station and Hempstead, Texas. The full extents of the study area can be seen in Exhibit 1. Figure 2-2 outlines the extents of the hydrologic and detailed modeling, which includes the 13 HUC-10s described below in Table 2-1.

The primary stakeholder for the study is Waller County. However, other entities within the county will benefit from the updated existing conditions analysis for the Brazos River floodplain. These entities include the cities of Brookshire, Pattison, and Hempstead.

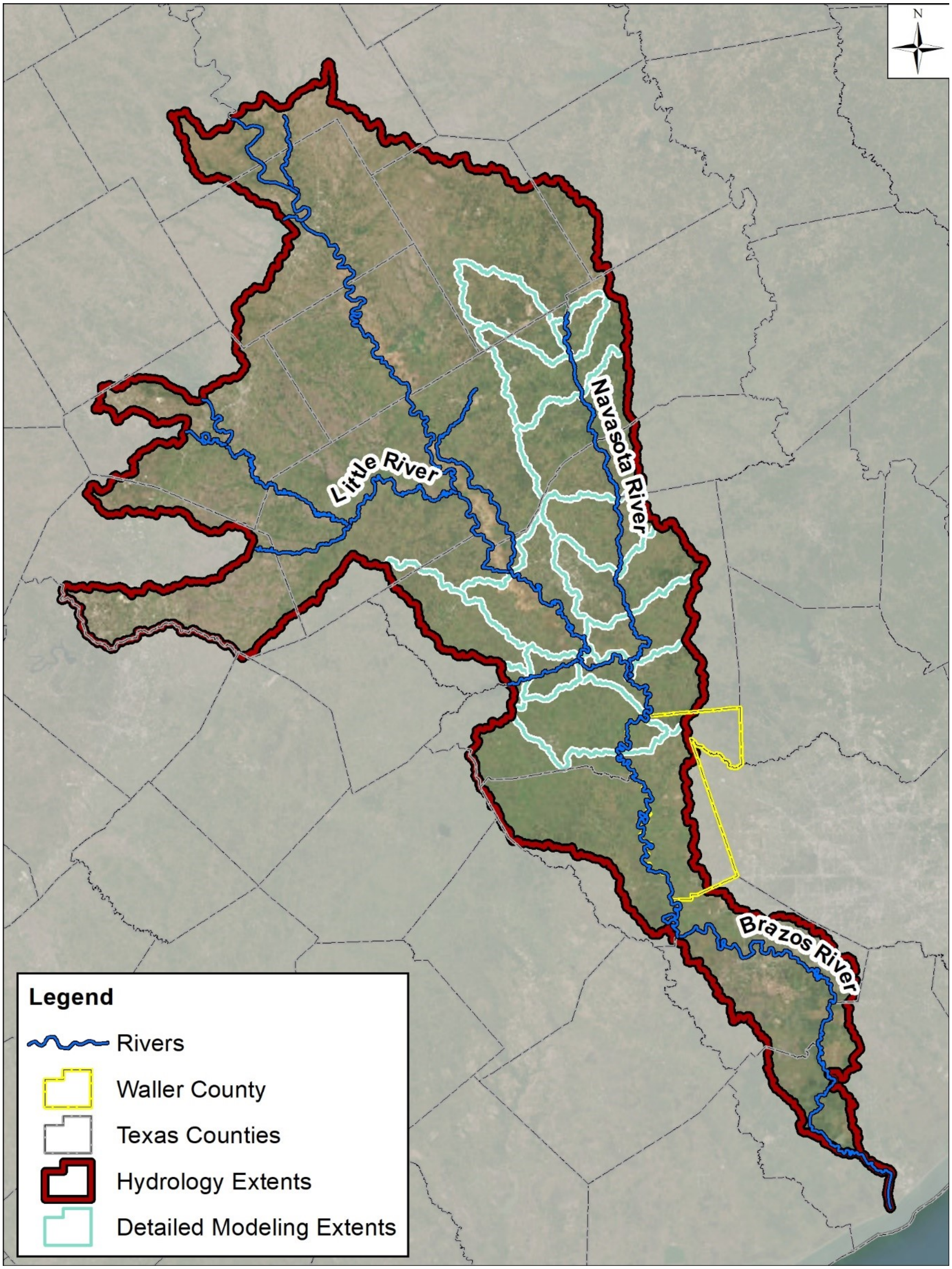


Figure 2-2. Study Area

Table 2-1 Detailed Study Area HUC-10s

HUC-10 Number	HUC-10 Watershed Name
1207010107	Old River-Brazos River
1207010108	Beason Creek-Brazos River
1207010109	New Year Creek-Brazos River
1207010203	Nails Creek-Yegua Creek
1207010204	Davidson Creek
1207010205	Yegua Creek
1207010302	Steele Creek
1207010303	Sanders Creek-Navasota River
1207010304	Duck Creek-Navasota River
1207010305	Cedar Creek-Navasota River
1207010306	Wickson Creek-Navasota River
1207010307	Gibbons Creek-Navasota River
1207010308	Rocky Creek-Navasota River
1207010107	Old River-Brazos River

2.2 Study goals

The study is designed to meet four primary goals:

- Update flood risk assessment along the Brazos River to focus on risk to Waller County, leveraging modeling and information gathered in previous studies.
- Provide inundation mapping for the 1% and 0.2% annual chance events (ACE).
- Determine flood prone areas within the Brazos River watershed in Waller County.
- Develop four flood mitigation and/or protection alternatives including structural and non-structural solutions to reduce flood risk for Waller County.

2.3 Previous studies

Due to its significant size and history of flooding, numerous studies have been performed to understand conditions along the Brazos River. In particular, two recent studies were leveraged to help guide the analysis of the Brazos River through Waller County.

2.3.1 Brazos River Flood Protection Plan

Flood hazards in the Lower Brazos region were explored in a Flood Protection Plan completed for the Brazos River Authority (BRA) in March 2019. The Richmond U.S. Geological Survey (USGS) gage in the Lower Brazos basin indicates over 24 major flood events in the basin, with discharges greater than 70,000 cubic feet per second (cfs), including major events in 2016 and 2017. Although there were many previously created local hydrologic and hydraulic models in the region, a comprehensive basin analysis was not available until the creation of the Brazos River Flood Protection Plan.

Data collection

Information provided by agencies such as the BRA, USACE, TWDB, TxDOT, and Fort Bend County was reviewed for relevant data that could be incorporated into the Flood Protection Plan.

Four FEMA FIS were determined to be contained within the detailed study area of the model in Austin, Brazoria, Fort Bend, and Waller counties. Historical data was collected for BRA and USACE reservoirs and 17 USGS gages located throughout the basin. Other flood data for the most recent major storm events in 2015, 2016, and 2017 was collected where available. Field survey was obtained for 11 stream crossings and 36 cross-sections on the Brazos River through Waller and Brazoria counties. Existing survey in Fort Bend County was also leveraged to complete the survey dataset.

Hydrologic model

The Lower Brazos Flood Protection Plan addressed the lack of flood risk knowledge in the region by creating a continuous, calibrated hydraulic and hydrologic model spanning from Lake Whitney in the southern portion of Hill County to the outlet of the Brazos River into the Gulf of Mexico in Brazoria County. The upper portion of the model, from Lake Whitney to the USGS gage at Hempstead was a limited study area. While the lower 1,610 square miles of the basin were modeled using a detailed approach.

For the limited study area initial and constant losses were used with Snyder's Unit Hydrograph. The detailed, lower portion of the study area utilized the exponential loss method paired with Clark's Unit Hydrograph. The USACE Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) version 4.0 was used to model rainfall-runoff for the entire basin.

For the mainstem of the Brazos and Navasota Rivers, Muskingum routing was used. Modified Puls storage-outflow relationships were computed using a Hydrologic Engineering Center – River Analysis System (HEC-RAS) version 4.1.0 model and applied to major tributaries in the limited detail study area. In the detailed study area, Muskingum-Cunge Eight Point routing was used for major tributaries.

The basin was separated into 18 zones to calibrate the discharges to the historical data gathered for 17 USGS gages. Additionally, a gage frequency analysis was performed using historical data for the Hempstead and Richmond USGS gages to determine standard frequency storm events. Data gathered for the BRA and USACE reservoirs was leveraged to create both regulated and unregulated frequency curves to account for the variance in the historical data due to the construction of the reservoirs between 1950 and 1982. The frequency storms were applied to an elliptical storm area and moved across the basin to determine the location and orientation of the storm area that produced the highest peak discharges and volumes in the lower portion of the basin.

The resulting hydrologic model produced peak flows consistent with the discharges established in the gage frequency analysis.

Hydraulic model

The calibrated flow hydrographs calculated in the hydrologic analysis were used in conjunction with a HEC-RAS version 5.0.3 model to produce water surface elevations for historical and design storms.

A 1-D unsteady flow analysis was performed on the Brazos River from the Waller/Grimes County line to its outlet into the Gulf of Mexico. Other river systems in the southern portion of the basin were included where overflow could affect the Brazos River's flow conditions in major events.

The hydraulic model was calibrated to the historical gage flows and water surface elevations for the 2007, 2016, and 2017 storm events. Flows calculated from the storm centered frequency events were then applied to the calibrated models to create water surface elevations and inundation extents for the 10 percent, 2 percent, 1 percent, and 0.2 percent annual chance exceedance (ACE) storm events.

Results

The analysis of the Lower Brazos basin resulted in flows, water surface elevations, and inundation extents for four frequency events. The results were compared to the FIS and found to result in similar water surface elevations, while having lower peak flows. Based on the flooding conditions shown by the modeling, flood mitigation alternatives were explored and recommended for several communities in Fort Bend and Brazoria counties. Inundation maps were also created to guide future development and regulation throughout the Lower Brazos basin.

2.3.2 Hydrologic and Hydraulic Analysis of the Brazos River in Fort Bend County

Soon after the completion of the *Lower Brazos Flood Protection Planning Study*, Fort Bend County initiated a continuation of the analysis of the Brazos River. The subsequent study, *Hydrologic and Hydraulic Analysis of the Brazos River*, was focused on updating the previously completed models to account for Atlas 14 rainfall, create new synthetic storms focusing on flooding conditions in Fort Bend County, and update the hydrologic parameters within the vicinity of Fort Bend County to match the methodologies recommended in the Fort Bend County Drainage Criteria Manual.

Hydrology

HEC-HMS version 4.3 was used to upgrade the hydrology model created for the *Lower Brazos Flood Protection Planning Study* (Brazos FPP). The subbasins delineated in the Brazos FPP were adjusted to include contributing drainage area from Oyster Creek and to align with other watershed studies in Fort Bend County.

The initial and constant loss method, used upstream of the Hempstead USGS gage in the Brazos FPP, was maintained for this subsequent analysis. However, downstream of the Hempstead gage, Green and Ampt losses were used in accordance with the latest Fort Bend County Drainage Criteria. In accordance with this change, Canopy loss rates were also calculated where Green and Ampt loss methodology was implemented. Both the Snyder and Clark Unit Hydrograph methods were preserved for the analysis.

Routing was adjusted to utilize Modified Puls routing between the Bryan and Hempstead gage along the mainstem of the Brazos River, as well as for Yegua Creek and the lower portion of the Navasota River. Although the parameters were recalculated as part of this analysis, the other methodologies were kept constant from the Brazos FPP.

Gage adjusted radar rainfall (GARR) data for the 2016 and 2017 major storms was obtained from Vieux Associates, Inc. (Vieux), and the hydrologic model parameters were recalibrated using the new rainfall data. Where the methodology from the Brazos FPP was preserved, the hydrologic parameters were calibrated directly from the final values from the previous report.

A historical gage frequency analysis was performed to determine frequency storms for the Richmond and Hempstead USGS gages. Data from after the installation of contributing reservoirs was adjusted to reflect unregulated conditions to create a homogenous dataset. 50 percent, 20 percent, 10 percent, 4 percent, 2 percent, 1 percent, and 0.2 percent ACE frequency events were determined based on the statistical analysis.

An elliptical aerial reduction of Atlas 14 rainfall was simulated around the basin to determine the placement and orientation that elicited flows that generally matched the 1 percent ACE frequency event at the Richmond gage.

Hydraulics

After updating and calibrating the hydrology model, a 1D-2D unsteady HEC-RAS version 5.0.7 model was created. To properly characterize both inflows and tailwater conditions, the model extend beyond the political limits of Fort Bend County. The model extends from the Hempstead USGS gage on the upstream end to approximately 18 miles south of FM 1462.

The hydraulic model was calibrated to the historical gage flows and water surface elevations for the 2007, 2016, and 2017 storm events. Flows calculated from the storm centered frequency events were then applied to the calibrated model to create water surface elevations and inundation extents for the 7 frequency storm events.

Modeling results

Study results indicated that 1% ACE flows on the Brazos River through Fort Bend County are lower than the flows published in the FEMA FIS, while water surface elevations are similar to the published values. These results do not deviate significantly from the results of the Brazos FPP.

2.4 Data collection

Much of the base data used for the Brazos River Flood Update Study was sourced from the *Brazos River Flood Protection Plan* (Brazos FPP) and the *Hydrologic and Hydraulic Analysis of the Brazos River in Fort Bend County* (2021 Brazos Analysis). Land use and terrain data were updated to include the latest datasets from the National Land Cover Database (NLCD) and Texas Natural Resources Information System (TNRIS). Recent soil data was collected from the United States Department of Agriculture (USDA).

Additional infrastructure data localized to Waller County was collected to identify what may be impacted by floods. Flood damage data for Harvey in 2017 was also obtained from the Waller County Fire Marshall to be used for both validation and problem spot identification.

2.4.1 Survey and field visits

Survey obtained during the Brazos FPP was leveraged for this analysis. The survey data is referenced to the North American Horizonal Datum 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 the horizontal and vertical measurements is U.S. feet.

Bathymetry was collected for cross-sections of the Brazos River upstream and downstream of Fort Bend County. This data was collected by boat which traversed the channel multiple times to obtain depths using sonar. Field survey was collected along the riverbanks at the cross-section locations. A total of 36 cross-sections were obtained and incorporated into the lidar for the development of the hydraulic model.

Field visits were also performed to gather measurements of key infrastructure. Information about the size, condition, and exact location of key drainage structures in neighborhoods located in the headwaters of Bessie's Creek and near Rolling Hills Lake was gathered to ensure accurate modeling of existing conditions.

2.5 Correspondence

Coordination, progress update, and public meetings were held throughout the study to coordinate information and provide public transparency.

2.5.1 Public meetings

Three public meetings were held to inform the public on the project findings and receive feedback on identified high flood risk locations and potential flood mitigation solutions. Notices were posted in the Katy Times and Waller Times at least 2 weeks before the meeting was to take places for all public meetings. Additionally, physical notices of the upcoming meetings were posted to bulletin boards within the Waller County courthouse and on their website.

The first public meeting was held April 27th, 2022. This meeting provided the public with an overview of the scope, goals, and initial progress on the project including model development and calibration. Although several members of the public attended, there was no comment on the information provided.

The second public meeting was held July 5th, 2023. This meeting reiterated the goals and scope of the study and focused on the identification of areas with high flood risk within the County as well as preliminary project ideas for flood mitigation within these regions. Two members of the public attended the meeting and provided feedback on the proposed projects, sharing personal and historical experience with the timing and source of flooding issues within one of the identified areas of high flood risk.

The final public meeting will be held September XX. This meeting will provide an overview of the proposed projects and flood response plan.

3 Hydrology

A hydrologic analysis was conducted to calculate discharge rates through the Brazos River and simulate both frequency storm and historical storm events. HEC-HMS Version 4.10 and Atlas 14 point-precipitation data were used to model the rainfall-runoff conditions. The model created for the Brazos FPP and updated for the 2021 Brazos Analysis was utilized as a baseline.

In these previous models, the focus was on the southern portion of the watershed with targeted calibration at the USGS Gage in Richmond. The purpose of this study is to add detail to the previously completed studies and refine the flow data on the Brazos River between the Bryan and Hempstead USGS gages, and the contributing flows from the Navasota River. Since this lower portion of the basin had been calibrated in detail for the previous studies, the hydrology for portions of the Lower Brazos basin south of the Hempstead USGS gage was not re-evaluated. The extent of the hydrologic model in relation to Waller County can be seen in Figure 3-1.

3.1 Subbasins

Subbasins for the Lower Brazos basin were obtained from the 2021 Brazos Analysis. The subbasins were initially delineated for the Brazos FPP using HEC-GeoHMS Version 10.1, then adjusted to include portions of Oyster Creek and to align with subbasins being utilized in Fort Bend County for other studies.

The subbasins were reviewed for consistency with the new terrain datasets and determined to be adequate for the purposes of this study. A total of 165 subbasins were utilized in the HEC-HMS model, with varying sizes from 9.5 to 194 square miles. Subbasins were named to indicate the major stream or river contributing to the subbasin and numbered in increasing order from upstream to downstream per stream name. Figure 3-1 shows the subbasin delineations.

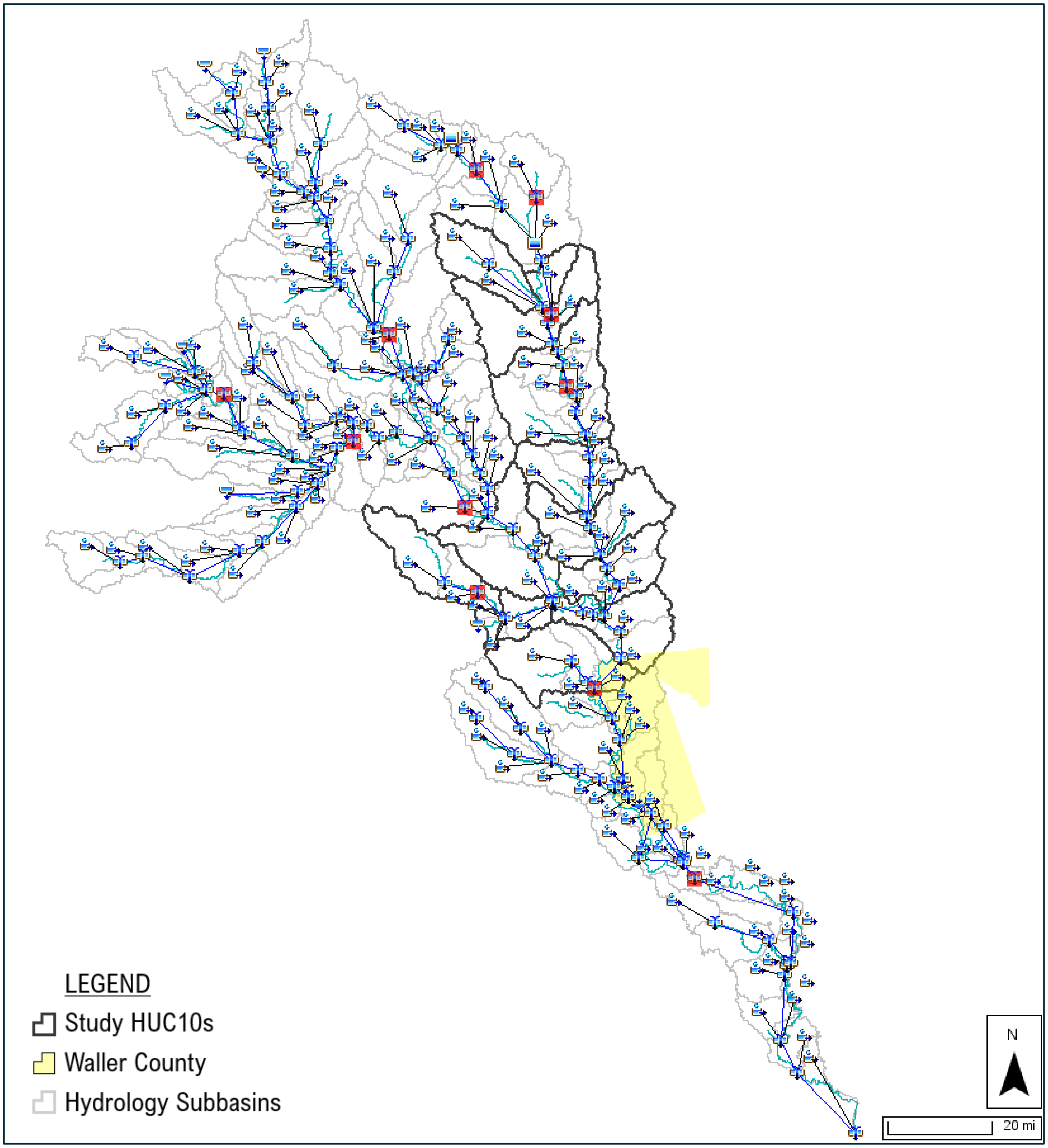


Figure 3-1. HEC-HMS Layout

3.2 Losses

Since the study incorporated hydrology from previous efforts, various loss rate methods were used depending on the location of the subbasin. Initial and Constant losses were used upstream of the Hempstead Gage at US 290 as was used in the 2019 Brazos Study. Downstream of the Hempstead gage, Green & Ampt method as was used in the 2021 Brazos Analysis and the Exponential Loss method was used downstream of Fort Bend County.

3.2.1 Initial and Constant Loss

Initial loss rates represent the volume of water needed to saturate the soil at the beginning of a rainfall event. These losses are highly dependent on antecedent moisture conditions but can be estimated based on the land use of the subbasin. Initial losses were calculated to be 20 percent of the total rainfall for subbasins with wooded areas as the dominant land use, and 15 percent of the total rainfall for subbasins with urban or pasture types as their dominant land use.

Constant losses are representative of the rate at which water will infiltrate the soil after its initial saturation. This parameter is dependent on the soil types of a subbasin. Weighted constant loss rates were calculated using a composite soil type weighting and the range of constant loss rates seen in Table 3-1.

Table 3-1. Constant Loss Rates

Soil Group	Soil Description	High Loss Rates (in/hr)	Average Loss Rates (in/hr)	Low Loss Rates (in/hr)
A	Deep sand, deep loess, aggregated silts	0.45	0.375	0.3
B	Shallow loess, sandy loam	0.3	0.225	0.15
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	0.15	0.1	0.05
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0.05	0.025	0.00

Initial and constant loss parameters were recalculated for the entire study area to account for the latest soil and land use information. The final, calibrated parameters calculated from these baseline parameters, are discussed in Section 5 and can be found in Appendix B.

3.2.2 Green & Ampt Loss

This methodology relies on values of suction and hydraulic conductivity, based on soil types. The Canopy Loss Method was used in conjunction with Green and Ampt to account for losses due to vegetation. Table 3-2 shows the range of values used for each Green and Ampt parameter.

Table 3-2. Green and Ampt Parameter Value Ranges

Soil Group	Soil Description	Range of Suction Values (in)		Range of Hydraulic Conductivity Values (in/hr)	
		Min	Max	Min	Max
A	Deep sand, deep loess, aggregated silts	1.95	2.41	2.35	9.27
B	Shallow loess, sandy loam	3.50	6.57	0.27	0.86
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	8.22	10.75	0.08	0.12
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	9.41	12.45	0.02	0.05

3.2.3 Exponential Loss

The Exponential Loss method was also utilized for a few subbasins contributing the outlet of the Brazos River into the Gulf of Mexico. This empirical method utilizes 5 parameters – initial range, initial coefficient, coefficient ratio, precipitation exponent, and percent impervious – to relate rainfall intensity and accumulated losses to a loss rate. As discussed previously, the hydrologic parameters downstream of the Hempstead USGS gage were not adjusted for this study, so these values remain unchanged.

3.3 Transform

Due to the significantly large watershed and leveraging multiple studies, varying transform methodology was used in the basin. Upstream of the Hempstead gage, Snyder Unit Hydrograph was utilized as the transform method for this study. Downstream of the Hempstead gage, the Clark Unit Hydrograph method was used to characterize the distribution of the rainfall.

3.3.1 Snyder Unit Hydrograph

Although this was mostly carried over from the 2021 Brazos River Analysis, the two New Year Creek subbasins were updated to Snyder Unit Hydrograph for consistency. This alteration ensured that all of the subbasins within the detailed study area used the same transform method.

Snyder's Unit Hydrograph analyzes the runoff response of the rainfall by utilizing lag time and Snyder's peaking coefficient. The lag time is calculated based off river mileage along the longest flow path in the subbasin, and a coefficient that represents the basin characteristics, as seen in the equation below.

$$t_p = C_t(L * L_{ca})^{0.3}$$

Where

t_p = basin lag time (hr)

C_t = basin coefficient, derived by the USACE and others

L = river mileage from the outlet of the subbasin to the furthest high point

L_{ca} = river mileage from the outlet of the subbasin to the centroid of the subbasin

The basin coefficient, C_t, is varied based on the average slopes found in the region. Typical values range from 0.4 to 2.3, with an average of around 1.1. For this study, a C_t value 0f 1.0 was used as a base for all the subbasins in the detailed region. In the 2021 Brazos River Analysis and the Brazos River Flood Protection Plan, a similar value was used as a starting point for the calibration of the Snyder parameters but was adjusted during calibration. These calibrated C_t values outside the detailed study were used as the baseline for this study.

Snyder's peaking coefficient, C_p, is another value that is based off the characteristics of the region. The flood wave and storage conditions are used to determine coefficient, but typically larger values of C_p are associated with smaller values of C_t and vice versa. C_p ranges from 0.3 to 1.2, with an average value of 0.69. Table 3-3 shows the relation between drainage area characteristics and Snyder's peaking coefficient.

Table 3-3. Snyder's Peaking Coefficient

Typical Drainage Area Characteristics		C_p
Undeveloped Areas with Storm Drains	Flat Basin Slope (less than 0.50%)	0.55
	Moderate Basin Slope (0.50% to 0.80%)	0.58
	Steep Basin Slope (greater than 0.80%)	0.61
Moderately Developed Areas	Flat Basin Slope (less than 0.50%)	0.63
	Moderate Basin Slope (0.50% to 0.80%)	0.66
	Steep Basin Slope (greater than 0.80%)	0.69
Highly Developed / Commercial Area	Flat Basin Slope (less than 0.50%)	0.70
	Moderate Basin Slope (0.50% to 0.80%)	0.73
	Steep Basin Slope (greater than 0.80%)	0.77

Due to the regional characteristics of the portions of the Navasota River and Brazos River being studied, a value of 0.55 was used as the C_p for the detailed study area. In the previous studies Snyder's peaking coefficient had been used as a calibration factor and was varied across the subbasins. Outside of the detailed study area, these values were preserved.

3.3.2 Clark Unit Hydrograph

This methodology uses time of concentration, Clark's storage coefficient, subbasin slope of the longest flow path, and length of the longest flow path to generate a time-area curve.

Since this method was only used for subbasins downstream of Hempstead, the values calibrated in the 2021 Brazos River analysis were preserved.

3.4 Hydrologic routing

For the 2021 Brazos River Analysis, routing of peak flows along the Brazos River were simulated within the HEC-HMS model using Modified Puls and Muskingum routing methods down to the Hempstead gage. Downstream of this gage, the hydraulic model was used to simulate routing along the Brazos River and some of its major tributaries. Muskingum and Muskingum-Cunge Eight Point Routing were also used to characterize incoming flows from some Brazos River tributaries not included within the hydraulic model in the downstream portion of the study.

Similarly, this study simulated routing for the detailed study area directly in the hydraulic model. For subbasins upstream of the detailed study area, the previously calibrated Modified Puls routing was preserved.

3.4.1 Modified Puls Routing

Modified puls storage-outflow relationships were computed in the previous studies for the major Brazos River tributaries upstream of Hempstead. This methodology was selected due its accuracy in modeling reaches characterized by extensive storage which the modeled area is prone to due to the lack of topographic relief resulting in wide and shallow floodplains.

A 2D model was developed as part of the 2021 Brazos River Analysis to generate the storage-discharge relationship for the reaches. Maximum water surface elevation rasters computed for a range of applied flows were generated from the 2D model. From these, volumes of storage held within the reaches for each flow condition were calculated and aligned with peak flows on the downstream end of the respective reaches to create storage-discharge curves.

More detail on the resulting parameters used for routing of contributing tributaries upstream of Bryan/College Station and subbasins contributing to the Navasota River upstream of Lake Limestone, can be found in Appendix B.

3.4.2 Muskingum-Cunge Eight Point Routing

Muskingum-Cunge routing was developed for Big Creek and Bessie's Creek, two major tributaries contributing the Brazos River downstream of Hempstead. Lidar was used to developed eight-point cross sections for the creeks and manning's n values were determined using land use data. Channel length and slope were defined using measurements obtained from a combination of topographic and aerial imagery.

More detail on the resulting parameters used for routing Big Creek and Bessie's Creek flows can be found in Appendix B.

3.4.3 Muskingum Routing

Initial results indicated that Modified Puls routing did not accurately characterize timing along the Brazos River or Mills Creek, causing historical storms to peak hours later than records indicate. Due to this, the routing methodology for the Brazos River upstream of Bryan / College Station and Mills Creek were changed to Muskingum Routing. This methodology uses two parameters to define flow conditions along a modeled reach: the Muskingum K value is a storage constant that represents the ratio between storage and discharge while the Muskingum X value is dimensionless and represents the importance of inflow and outflow to storage. Observed travel times during historical storms were used to estimate these parameters for Mills Creek and the Brazos River.

Table 3-4 summarizes the hydrologic methodologies used per subwatershed within this study.

Table 3-4. Hydrologic Methodologies per Subwatershed

Subwatershed	Number of Subbasins	Loss Methodology	Transform Methodology	Routing Methodology
Aquilla Creek	3	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Bessies Creek	2	Green and Ampt	Clark Unit Hydrograph	Muskingum-Cunge Eight Point
Big Creek	2	Green and Ampt	Clark Unit Hydrograph	Muskingum-Cunge Eight Point
Big Creek – North	3	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Big Elm	7	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Brazos River – Upstream of BCS	20	Initial and Constant	Snyder Unit Hydrograph	Muskingum
Brazos River – Between	7	Initial and Constant	Snyder Unit	2D Hydraulic

Hempstead and BCS			Hydrograph	Model
Brazos River – Downstream of Hempstead	18	Green and Ampt	Snyder Unit Hydrograph	1D/2D Hydraulic Model
Brushy Creek	9	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Davidson Creek	3	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Ditch H	1	Green and Ampt	Clark Unit Hydrograph	1D/2D Hydraulic Model
Jones Creek	1	Green and Ampt	Clark Unit Hydrograph	1D/2D Hydraulic Model
Lampasas River	1	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Leon River	2	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Little Brazos River	8	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Little River	13	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Lower Oyster Creek	2	Green and Ampt	Clark Unit Hydrograph	1D/2D Hydraulic Model
Mill Creek	9	Green and Ampt	Snyder Unit Hydrograph	Muskingum
Navasota River – Upstream of Lake Limestone	9	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Navasota River – Downstream of Lake Limestone	23	Initial and Constant	Snyder Unit Hydrograph	2D Hydraulic Model
New Year Creek	2	Initial and Constant	Snyder Unit Hydrograph	2D Hydraulic Model
Nolan Creek	2	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Oyster Creek	3	Green and Ampt	Clark Unit Hydrograph	1D/2D Hydraulic Model
Pond Creek	2	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Salado Creek	3	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
San Gabriel River	3	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Tehuacana Creek	3	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Walnut Creek	3	Initial and Constant	Snyder Unit Hydrograph	Modified Puls
Yegua Creek	2	Initial and Constant	Snyder Unit Hydrograph	2D Hydraulic Model

3.5 Historical frequency analysis

A frequency analysis was performed at the Bryan and Hempstead gages to calculate the frequency storm discharges based on historical storms. This analysis utilized the historical records at the gage to extrapolate a flood frequency curve. This curve was then used to identify flows at the gages for the 20 percent, 10 percent, 4 percent, 2 percent, 1 percent, and 0.2 percent ACE events.

3.5.1 Methodology

The Log Pearson Type III Analysis, outlined in Bulletin 17-B, published by the United States Water Resources Council in 1981 was used. This methodology is based on a fully unregulated basin, meaning no dam or control structures that would reduce or control flows downstream. However, during the period of record for the Hempstead gage, the Lower Brazos basin went from being fully unregulated to fully regulated, with the construction of lakes in the upper watershed. The presence of these USACE reservoirs causes variances in the historical flow patterns being analyzed.

To create an equitable comparison of flows prior and subsequent to the construction of the reservoirs, a method was developed to convert regulated flows to non-regulated flows. Event volume and peak flow relationships were developed for the peak flow events of each year in gauge record. For unregulated years, the total volume was the total volume recorded at the gauges. For regulated years, the volume of change within the reservoir during the event was added to the recorded volume at the gauge to estimate what flow would have reached the gauge if there was no storage at the reservoir. These volume versus peak flow relationships were then plotted for the unregulated, partially-regulated, and regulated periods. Exponential trendlines were developed to characterize the resulting plots. From these results, a ratio of unregulated to regulated flows was developed to convert between the conditions.

Using this method, unregulated flows were developed for each water year in the period of record and input into Hydrologic Engineering Center – Statistical Software Package (HEC-SSP). A simulation was run using Bulletin 17-B methods to generate an unregulated flood frequency curve, and related unregulated frequency flows. These unregulated flows were then transformed back to regulated flows using the ratios developed from the event volume vs peak flow curves. Table 3-5 and Table 3-6 show the frequency flows for the Bryan and Hempstead gages resulting from this analysis.

Table 3-5. Frequency Flows at the Bryan USGS Gage

Frequency Event	Unregulated Flows	Regulated Flows	95% Confidence Interval (High)	95% Confidence Interval (Low)
0.2% ACE	158,910	74,840	100,290	54,350
1% ACE	131,422	63,680	84,110	48,160
2% ACE	118,410	58,280	76,260	44,980
4% ACE	100,140	50,540	64,920	40,120
10% ACE	85,030	43,980	55,480	35,770
25% ACE	62,890	34,030	41,430	28,540
50% ACE	42,940	24,600	29,100	20,920

Table 3-6. Frequency Flows at the Hempstead USGS Gage

Frequency Event	Unregulated Flows	Regulated Flows	95% Confidence Interval (High)	95% Confidence Interval (Low)
0.2% ACE	301,820	195,230	221,200	144,740
1% ACE	241,980	161,060	179,610	122,310
2% ACE	214,490	144,820	160,190	111,420
4% ACE	176,420	121,700	132,960	95,570
10% ACE	145,930	102,680	111,010	82,170
25% ACE	102,590	81,910	79,520	61,570
50% ACE	65,860	49,830	52,950	42,140

The flows resulting from the frequency analysis at Hempstead were higher than the results of the flood frequency analysis performed for the 2021 Brazos Analysis. The inclusion of the additional data from the most recent flood years provided more weight to higher flows over the historical analysis, resulting in slightly higher frequency events at the gage. A comparison of the gage analysis results from this study and the previous study at the Hempstead gage is provided in Table 3-7.

Table 3-7. Frequency Flow Comparison

Frequency Event	Current Regulated Flows	2021 Brazos Analysis Regulated Flows	Percent Change in Flows
0.2% ACE	195,000	193,000	1.0%
1% ACE	161,000	155,000	3.9%
2% ACE	145,000	138,000	5.1%
4% ACE	122,000	119,000	2.5%
10% ACE	103,000	96,000	7.3%
25% ACE	82,000	77,000	6.5%
50% ACE	50,000	48,000	4.2%

4 Hydraulics

The hydraulics portion of the study incorporated the updated hydrologic parameters and flood frequency analysis into a detailed 2D model to calculate water surface elevations and flow rates of the Brazos River through Waller County. The Brazos and Navasota Rivers were modeled using the Hydrologic Engineering Center – River Analysis System (HEC-RAS) version 6.3.1. The final model extents include the Brazos River from Bryan, Texas to 17 miles downstream of Fort Bend County. The extents also include the Navasota River from Lake Limestone to the confluence with the Brazos River. Exhibit 1 shows the extents of the detailed study performed as part of this analysis, as well as the updates made to previous models.

1D/2D modeling completed as part of the 2021 Brazos Analysis provided a detailed assessment of flood risk through Fort Bend County. This was achieved by routing flows through the hydraulic model from the Brazos River at Hempstead down through Fort Bend County.

To focus the analysis on Waller County, a two-dimensional (2D) model was developed in this study to route Brazos River flows between Hempstead and Bryan / College Station, as well as the Navasota River from Lake Limestone and Yegua Creek from Lake Somerville. The flows at the downstream end of the 2D model developed as part of this study were then routed through the previously created 1D/2D model to calculate water surface elevations and flow rates for the entire extents of Waller County. The hydraulic models provide coverage of over 250 miles of the Brazos River and include portions of 11 counties including:

- Leon
- Robertson
- Madison
- Brazos
- Burleson
- Grimes
- Washington
- Austin
- Waller
- Fort Bend
- Brazoria

4.1 Terrain

Terrain for the analysis was primarily sourced from light detection and ranging (Lidar) data obtained by the United States Geological Survey (USGS) and Federal Emergency Management Agency (FEMA). This data was obtained through TNRIS which stores spatial data for many federal and state agencies.

One limitation of Lidar datasets is the ability to pick up in the terrain below water. Additional information was incorporate into the terrain to define the bathymetry of the Brazos and Navasota riverbeds to compensate for missing information from Lidar. Survey obtained in the previous studies provided bathymetric cross sections of the Brazos River within Waller County. This data was incorporated directly into the Lidar topography. Additional modifications were made to the Navasota River and upstream portion of the Brazos River in the HEC-RAS model. FEMA FIS profiles were used to define the riverbed dimensions at select cross sections. The terrain was modified to incorporate these dimensions at the measured locations and interpolate depths between them.

The resulting terrain layer was projected in Texas State Plan South Central with a 3x3 foot cell resolution, matching the most detailed data that was incorporated.

4.2 Land use

The NLCD obtained during data collection was used as a basis to develop Manning's n values for the HEC-RAS model. These roughness values are used to quantify resistance to overland flow in hydraulic modeling. Higher n values are representative of land uses that provide greater resistance to flow, while lower values represent land uses that allow water to more easily flow. Base n values for each land use type are shown in Table 4-1. These values are heavily based on the guidance provided in the HEC-RAS 2D User's Manual and supplemented with additional information obtained from *Open-Channel Hydraulics* [Ven Te Chow, 1989].

Table 4-1. Base Manning's N Values

Land Use Type	Manning's N Base Value
Barren Land	0.03
Open Water	0.03
Developed, High Intensity	0.17
Developed, Medium Intensity	0.13
Developed, Low Intensity	0.09
Developed, Open Space	0.045
Deciduous Forest	0.16
Evergreen Forest	0.15
Mixed Forest	0.17
Shrub-Scrub	0.13
Grassland-Herbaceous	0.04
Pasture-Hay	0.05
Cultivated Crops	0.05
Woody Wetlands	0.12
Emergent Herbaceous Wetlands	0.07

These base values characterize the resistance of the land use to shallow overland flow. However, as the depth of flow increases, the percentage of the flow in contact with the land use gets smaller. This decreases the overall impact of the land use on the flow. To capture this variance, override regions were used to adjust the n values for areas that experience deeper flow during significant storm events.

Two types of override regions were utilized to reflect flow patterns. The first was any region that experienced deep flow, equal to or exceeding 10 feet. The second, was the footprint of the main channels for the Brazos River, Navasota River, and Yegua Creek. Flow within the channels closely resembles flow patterns characterized in 1D modeling; therefore, traditional 1D n values provided in the HEC-RAS User Manual were used for these regions.

The areas experiencing deep flow mostly consist of the overbanks of the channels. This flow experiences some resistance due to the land cover; however, only a small percentage of the flow is in contact with the land cover compared to shallower flow. To reflect this difference, values for the deep flow regions fall between the typical values for 1D and 2D flow patterns.

Override regions were also varied between the Navasota River, Brazos River, and Yegua Creek. This variation reflects the geographic differences in the channels. The n values used for the override regions are shown in Table 4-2 and Table 4-3. Since these regions were delineated manually using aerial imagery, the land use types do not align exactly with the land uses provided in the NLCD layer.

Table 4-2. Deep Overbank Calibrated Manning's N Values

Land Use	Manning's Values per Calibration Region			
	US Brazos	DS Brazos	Navasota	Yegua
Cultivated Crops	0.0275	0.03	-	-
Concrete	-	0.015	-	-
Developed, Low Intensity	0.10	-	-	-
Wooded	0.07	0.10	0.13	0.11
Woody Wetlands	0.06	0.06	0.085	-

Table 4-3. Channel Calibrated Manning's N Values

Land Use	Manning's Values per Calibration Region		
	Brazos	Navasota	Yegua
Brushy	0.0275	0.04	0.0375
Grassy	0.0275	0.04	-
Wooded	0.03	0.0425	0.045

4.3 Model development

A 2D model was created for the detailed study area using HEC-RAS version 6.3.1. The Navasota River has been identified by the previous studies in the Lower Brazos Watershed as having complex flow patterns that make defining traditional hydrologic routing parameters difficult. By utilizing a 2D model, these dynamic flow patterns can be simulated without having to make assumptions or simplifications to define parameters. Additionally, with the recent improvements to modeling capabilities within HEC-RAS, key structures can be modeled directly in the 2D mesh, without the need for a 1D/2D model.

4.3.1 Geometry

The terrain and land use data described in the previous sections were used as the baseline for the 2D model. The details of the geometry and flows developed for the model are described in the section below.

2D area

The extents of the 2D area were initially defined by using the ten HUC-12s that constitute the detailed study area. Within the 2D area the model evaluates flow patterns on a cell-by-cell basis leveraging the underlying terrain and land use. Each cell face acts as a 1D cross section to evaluate the incoming and outgoing flows of each cell. Due to this method of evaluation, the size of the cell grid can influence the accuracy and detail of the results. A 200 by 200-foot grid cell size was selected to accurately assess flow patterns while maintaining a manageable run time.

Break lines

Cell alignment with high points, such as roads, levees, and berms, is important in order for the model to accurately portray the flow. Break lines were used to delineate these topographic features to force the cell mesh to follow these high points.

Break lines were also used to orient cell faces perpendicular to the flow within the main channels. This methodology ensures that the calibrated n values for the channels are aligned with the cells. Additionally, model stability is increased by the alignment of the cells allowing for more direct inflow and outflow calculations.

Boundary conditions

Hydrology was incorporated into the hydraulic model using flow hydrographs. At the upstream extents of the model, the combined incoming flows from all the contributing drainage area were applied externally to the model. Subbasins that inflow directly into the detailed study area were applied individually, directly to the stream centerlines.

The hydraulic model created for the 2021 Brazos Analysis was leveraged to develop a downstream boundary condition. Results for each frequency event were analyzed to produce a rating curve representing the relationship between flow and water surface elevations. These rating curves were used as an outlet boundary condition along the extents of the Brazos River floodplain downstream of the detailed study area.

4.3.2 Combination with 1D/2D model

The updated flows at Hempstead were incorporated into the 1D/2D model created as part of the 2021 Brazos Analysis. This model evaluates flow patterns for the Brazos River, and some of its major tributaries, from Hempstead down to Lake Jackson. Outflows from the detailed 2D model developed as part of this study were applied as boundary conditions to the upstream portion of the 1D/2D model. Other boundary conditions along the Brazos River and its tributaries, pulling flows from the hydrology model, were kept constant.

These more accurate incoming flows were used to evaluate existing conditions flood risk for the Brazos River floodplain in Waller County.

5 Calibration

The analysis of historical storms ensures the existing conditions flood hazard assessment provides reasonable results by comparing to past flood events. The analysis established a sound basis for risk identification and mitigation needs for the Brazos River through Waller County. Calibrations consists of obtaining and analyzing the historical storm data, calibrating the existing conditions models to match the historical data, and simulating the calibrated models for frequency storm events to assess the flood hazard risk throughout the basin.

The HEC-HMS model had been calibrated during both the Brazos FPP and 2021 Brazos River Analysis. For both studies, the model was calibrated for Memorial Day 2016 and Harvey 2017, with a focus on the USGS gages in Richmond and Hempstead. To keep continuity with the previous studies, and leverage the previous calibration efforts, the same storm events were used for calibration. However, for this study efforts were focused on getting accurate shape, volume, and timing of the hydrographs at the Hempstead and Bryan/College Station USGS gages.

In another effort to preserve continuity between the previous efforts, the gage adjusted radar rainfall data obtained from Vieux Associated, Inc. (Vieux) for the 2021 Brazos River Analysis was utilized for historical calibration. The baseline hydrologic parameters described in Section 2 - Hydrology were used as a starting point for calibration. From there, hydrologic and hydraulic parameters were adjusted to develop flow and water surface elevation results similar to the gage records. Figure 5-1 shows the location of the Bryan and Hempstead gages within the hydraulic model, as well as the locations of several other gages used to guide and improve calibration.

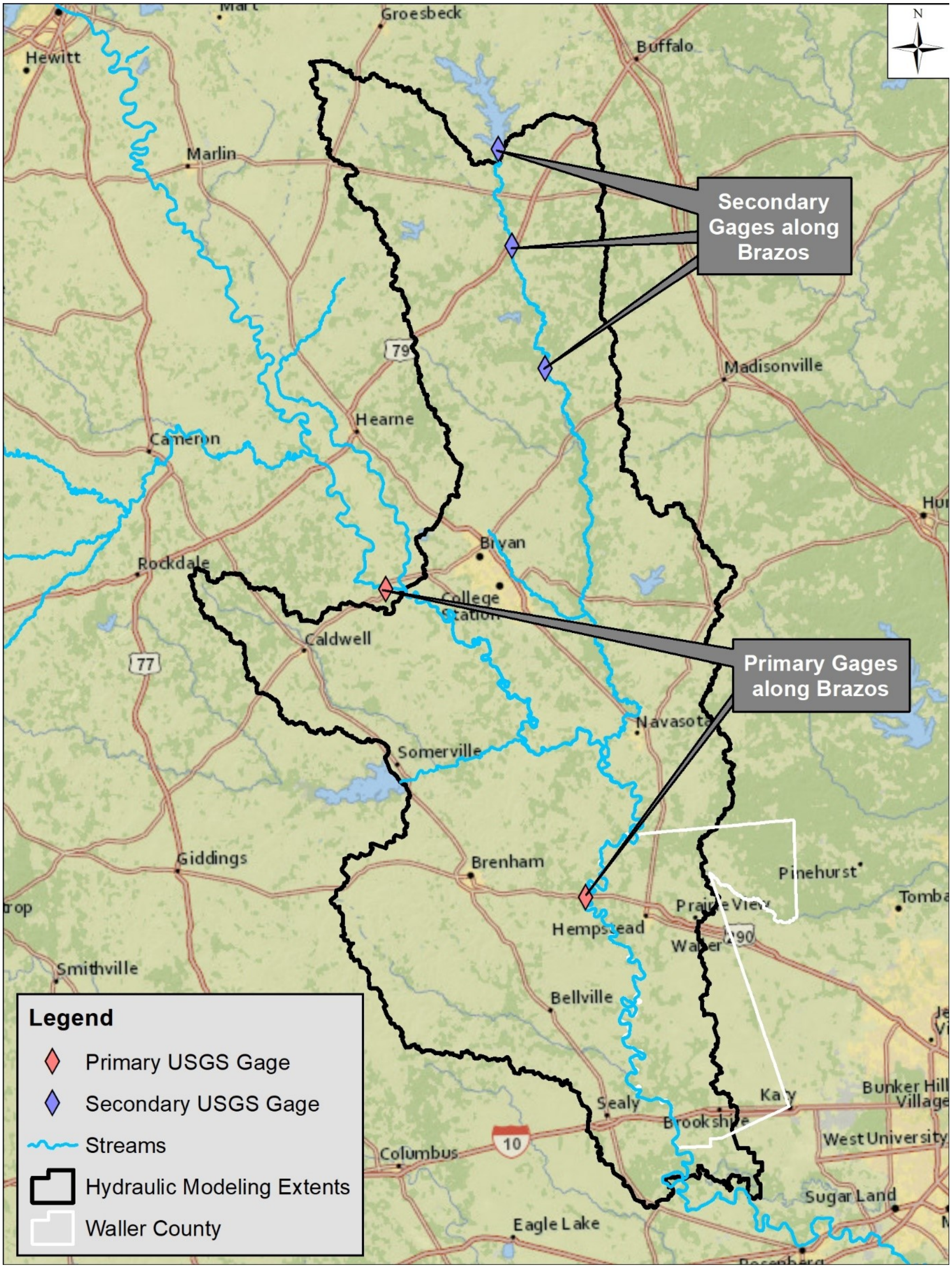


Figure 5-1. USGS Gages used for Calibration

5.1 Calibration process

Calibration of hydrologic and hydraulic models relies heavily on the availability and accuracy of historical data. While USGS gages provide data on both flow and water surface elevations at 15-minute intervals, only the water surface elevation data points are live measurements. Flows are estimated based on rating curves created from direct and indirect flow measurements during storm events. Direct measurements include radar or traditional sensors being measured by boats within the stream of interest, while indirect measurements are generally taken by collecting high water marks within the vicinity of the gage and developing a hydraulic model to determine the flow that is required to match the water surface elevation. These data points are used to create a rating curve that characterizes the relationship between water surface elevation and flow. Due to this difference, the models were calibrated more heavily to the historical water surface elevation gage data than the flow data.

Calibration was performed by making reasonable adjustments to both the existing conditions hydrologic and hydraulic models to reproduce observed data. Different parameters were utilized to influence different aspects of the calibration such as total volume, timing, and shape.

The loss parameters were used to calibrate the overall volume of flow or move the average water surface elevation up or down. Since antecedent moisture conditions drive how much infiltration is experienced within a watershed, these parameters were calibrated independently for each storm. As discussed in Section 2.2 – Losses, the Initial and Constant Loss methodology was used for the all the subbasins that contribute to flow at Hempstead.

The transform parameters were used to calibrate the timing of flow. Characterized by the Snyder Unit Hydrograph upstream of Hempstead, these parameters are used to define how quickly rainfall becomes runoff. Since these parameters are primarily influenced by soil and land use types, they were kept the same across the historical storms.

Finally, hydraulic calibration was used to calibrate the shape of the hydrograph at the gages of interest. Since the hydrologic model had previously been calibrated, routing parameters outside of the hydraulic model were not changed as part of this effort. Within the detailed 2D hydraulic model extents, the manning's n values were adjusted to calibrate to the results at the Hempstead USGS gage. These values help model the attenuation of water in low lying areas and the flow rate of water overland and through the channels, both of which influence the timing of the flow and ultimate shape of the resulting hydrograph. Since manning's n values are tied to land use type, they were kept constant across storm events and within the accepted ranges discussed in Section 3 – Hydraulics.

Figure 5-2 shows the effects changes to different parameters within the hydrologic and hydraulic models have on the resulting hydrographs.

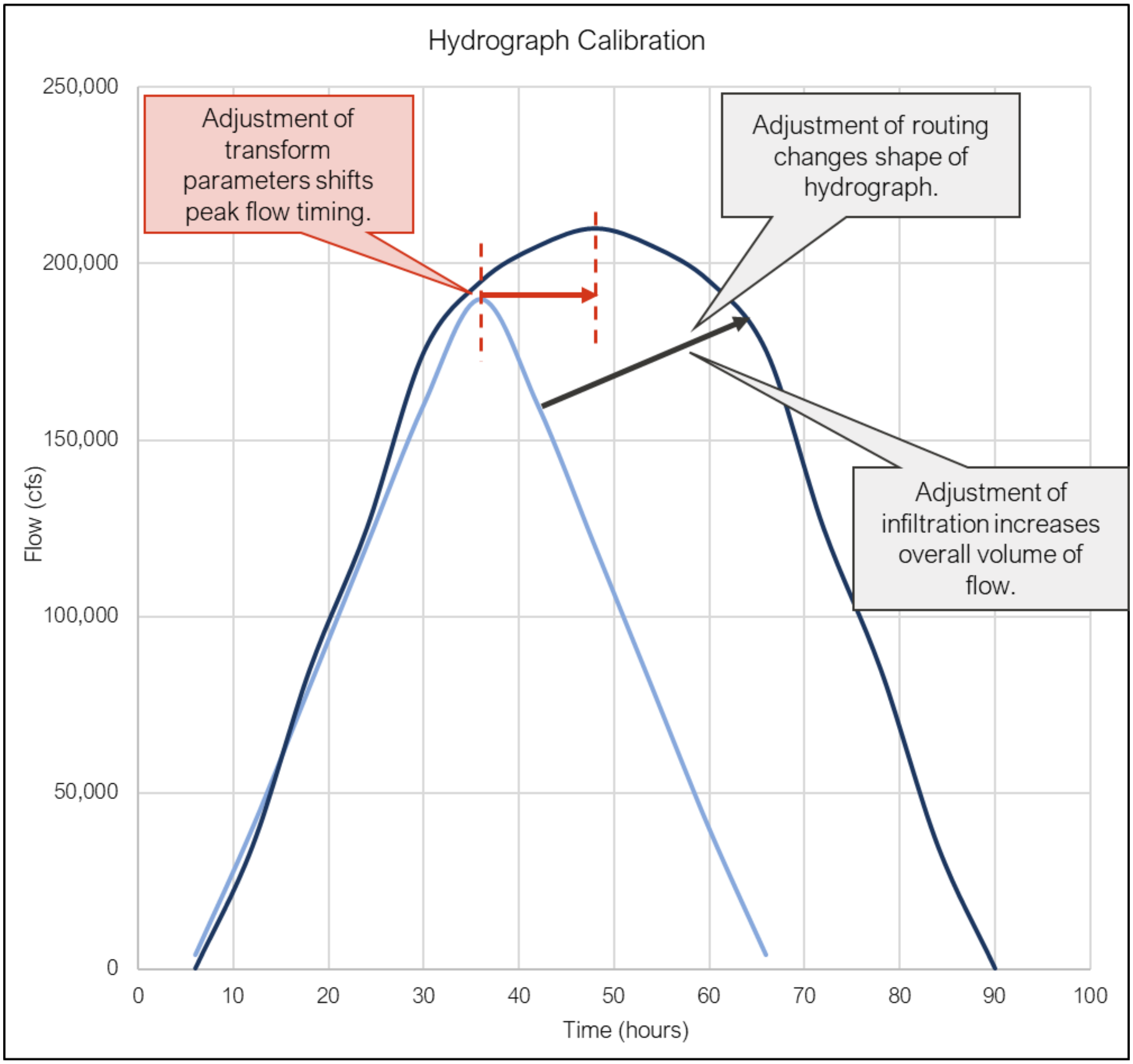


Figure 5-2. Hydrograph Calibration

5.2 Memorial Day 2016

5.2.1 Bryan / College Station gage

The Brazos River gage at SH 21 near Bryan and College Station, Texas had a peak stage flow of 162.8 feet during the Memorial Day 2016 storm. Throughout the storm, over 480,000 acre-feet of volume was estimated to flow through HWY 290. Uncalibrated simulations of this event at the Bryan / College Station Gage showed similar flow results, but low stages. Since the previous studies had only calibrated hydrologically to this point, the lack of calibration for historical stages was expected. To adjust these results, initial and constant loss parameters were increased for subbasins contributing to this data point. Additionally, the initial hydrograph at the Bryan / College Station Gage had a rounded, even shape in contrast to the delayed peak of the historical hydrograph. Snyder Unit Hydrograph parameters were adjusted to calibrate the peak of the storm.

- Initial losses for subbasins contributing to the Bryan / College Station Gage were increased from an average of 0.05 in/hr to 0.1 in/hr.
- The Snyder Unit Hydrograph Peak Coefficient was increased from an average of 0.2 to 0.44 for the contributing subbasins.
- Due to the position of the gage within the hydraulic model, the calibration at the Bryan / College Station Gage was not heavily influenced by changes to Manning's n values.

The calibrated model flow is within 2,000 acre-feet of the historical volume and the peak water surface elevation (WSEL) is within 0.11 feet of historical records. Calibration of water surface elevation was prioritized to ensure the models aligned with the direct measurements recorded for the gage. However, although the gage and modeled peak flows do not closely align, the overall volume of flows aligns. Figure 5-3 and Figure 5-4 show the calibration results for Memorial Day 2016 at the Brazos River gage near Bryan / College Station, Texas.

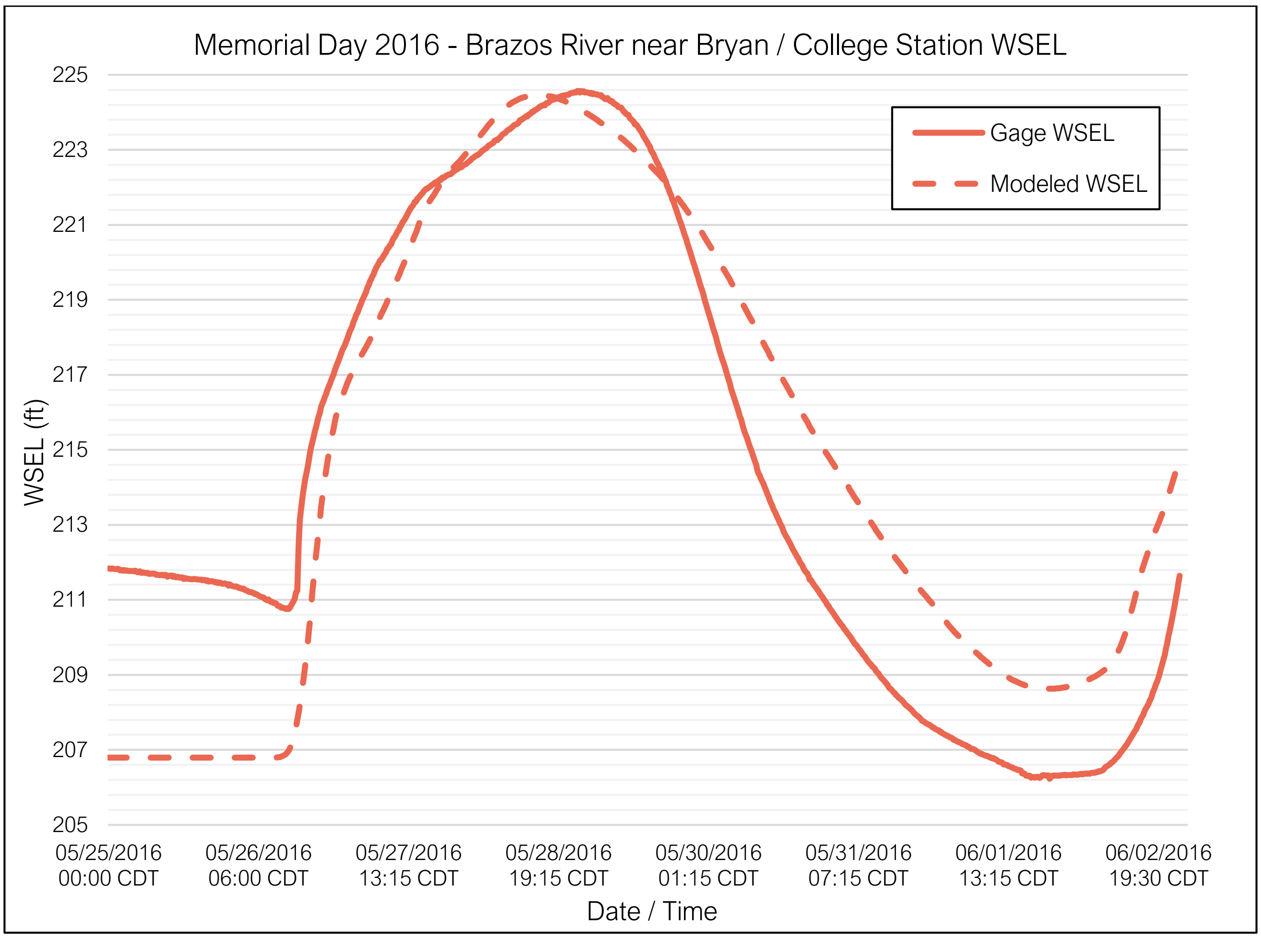


Figure 5-3. Memorial Day 2016 - Brazos River near Bryan / College Station WSEL

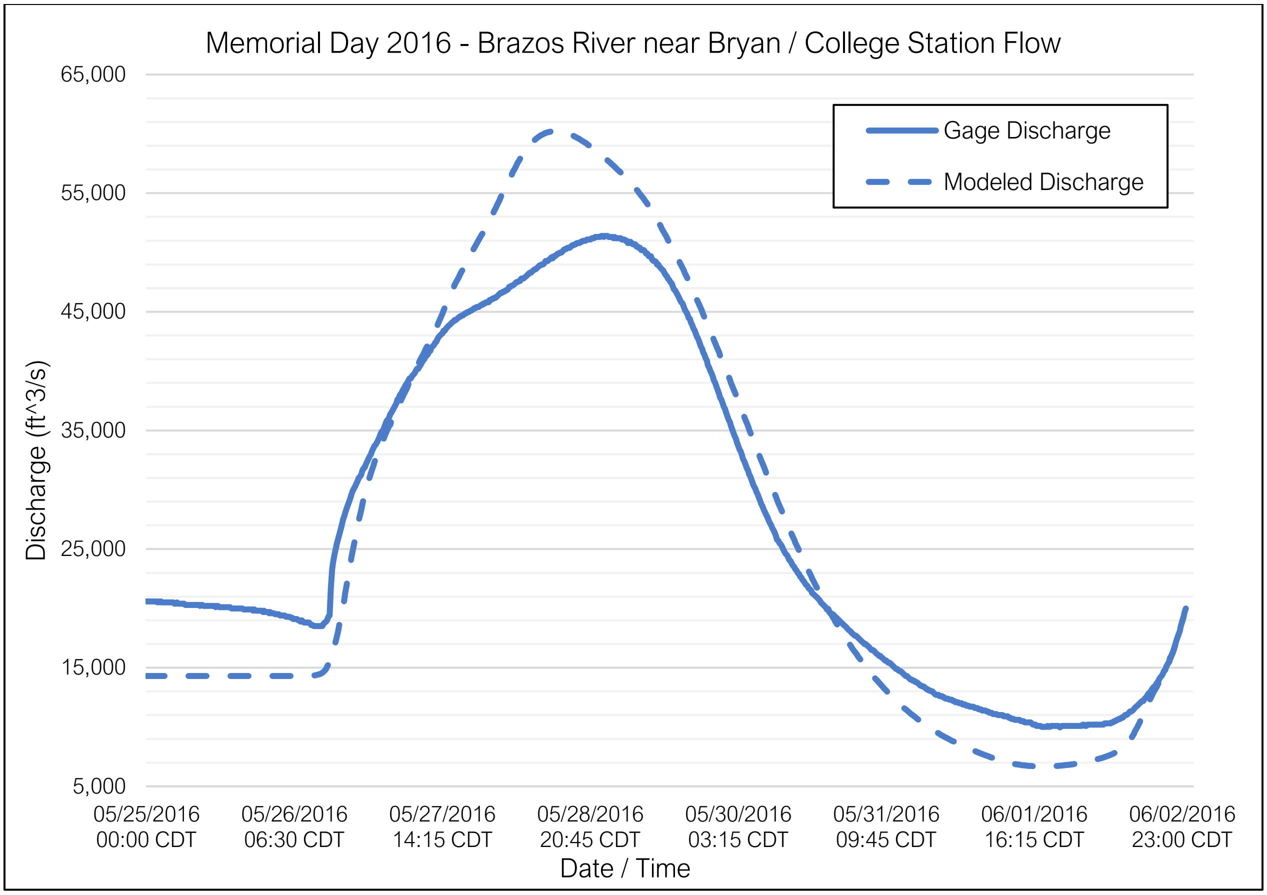


Figure 5-4. Memorial Day 2016 - Brazos River near Bryan / College Station Flow

5.2.2 Navasota River gages

Several gages were used to inform calibration along the Navasota River. These gages were used for reference when adjusting incoming flows to Hempstead, which is downstream of both the Bryan / College Station gage and the confluence of the Navasota and Brazos Rivers.

The three Navasota River gages used for secondary calibration within this study are Lake Limestone near Marquez, Navasota River near Easterly, and Navasota River at Old San Antonio Road. Calibration for the Lake Limestone gage was done purely through the hydrologic model, and therefore, only considered flow conditions. Manning's n values as well as hydrologic parameters were adjusted to perform calibration for flow and water surface elevation at both gages directly on the Navasota River.

Initial and constant losses for the Navasota River subbasins were increased during calibration efforts. Snyder Unit Hydrograph parameters were also adjusted to delay the peak flows as well as create a steeper peak. However, the largest adjustment was primarily applied to the manning's n values to delay the flow of water along the Navasota River in reflection of the historical gage hydrograph shapes.

- Initial losses along the Navasota River subbasins were increased from an average of 0.08 inches to 0.12 inches.

- Snyder Unit Hydrograph lag times for the southern Navasota River basins were increased from an average of 7 hours to an average of 9 hours. The peaking coefficients were increased from an average of 0.5 to 0.55 for all Navasota River subbasins.
- The Manning's n values for the Navasota River channel and overbanks were increased to reflect the delay in flows caused by the dense woods along the riverbanks and the meandering nature of the river.

Flow calibration results for the Lake Limestone gage, and water surface elevation calibration results for the Easterly and Old San Antonio gages can be seen in Figure 5-5, Figure 5-6, and Figure 5-7. Modeled flow results at Lake Limestone are within 3% of the observed gage data. Peak water surface elevations at the Navasota River gages are both within 1 foot of observed gage data.

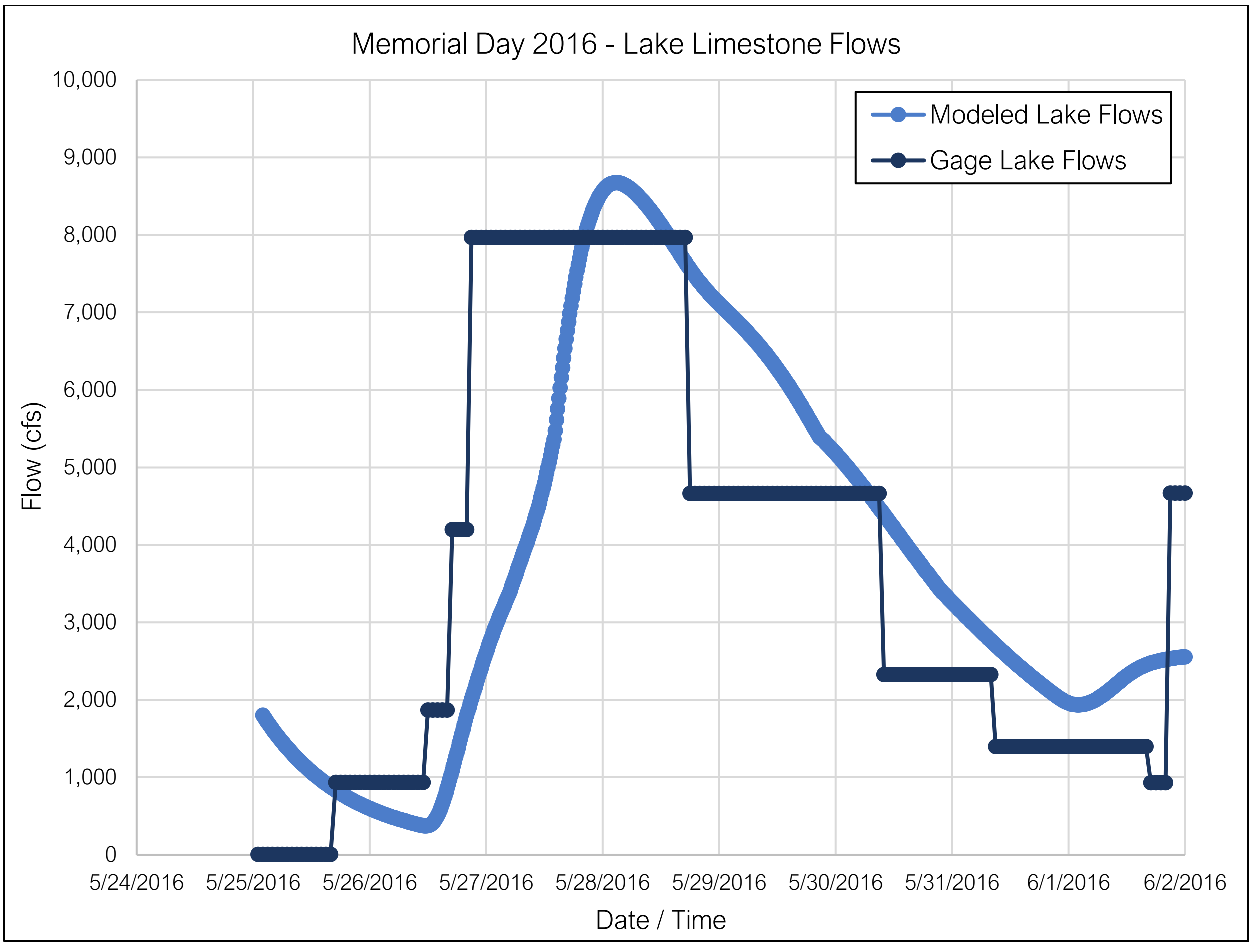


Figure 5-5. Memorial Day 2016 - Lake Limestone Flows

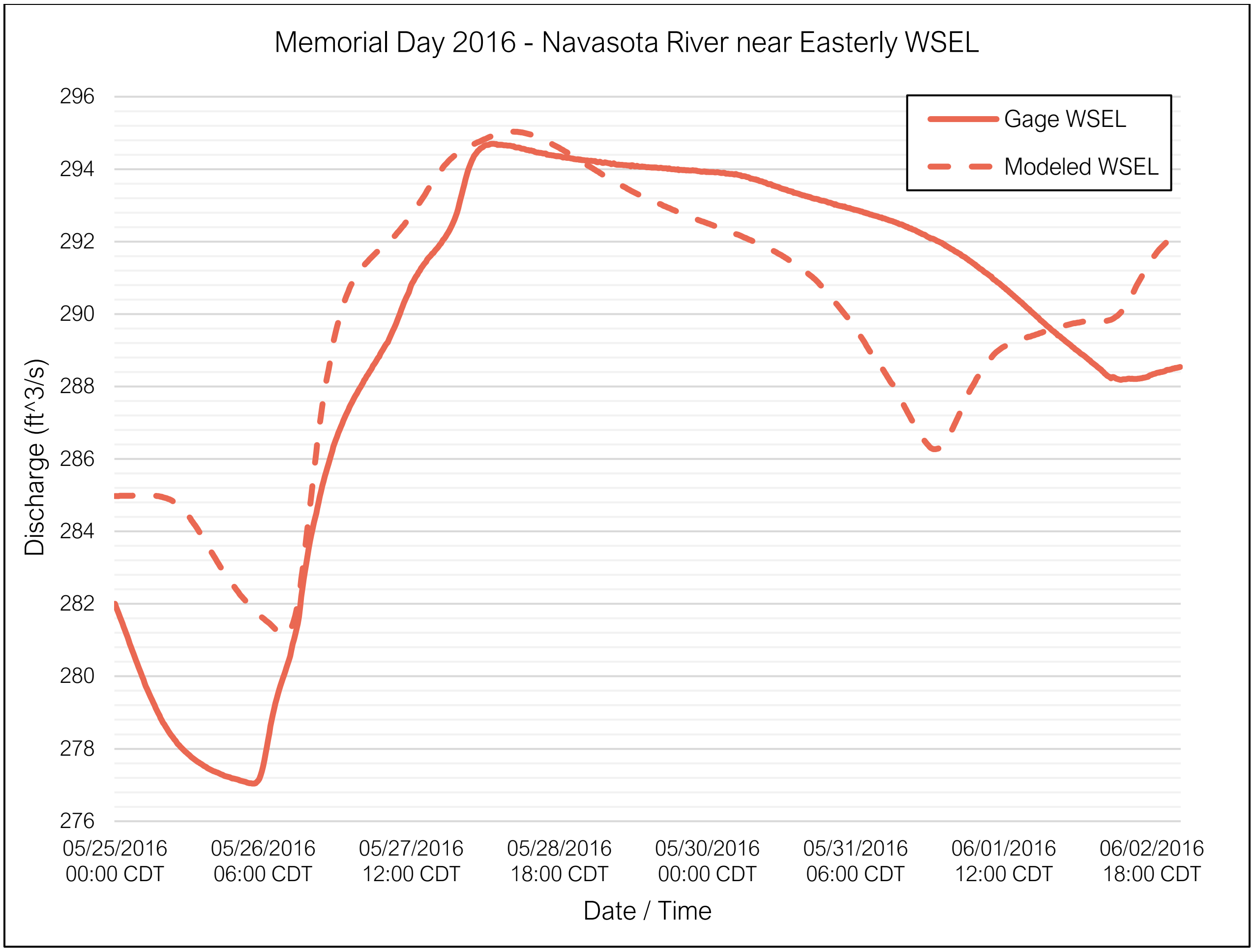


Figure 5-6. Memorial Day 2016 - Navasota River near Easterly WSEL

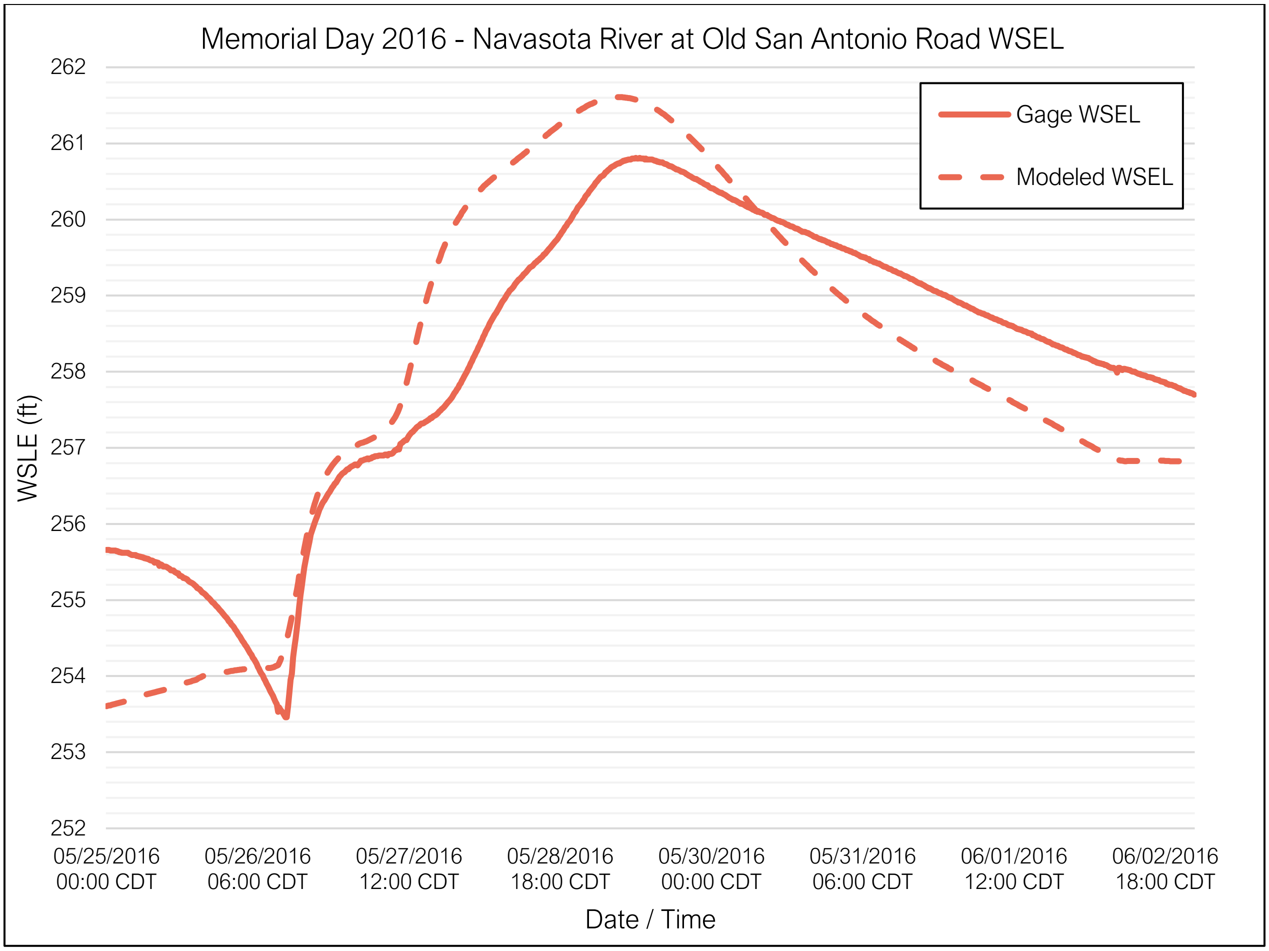


Figure 5-7. Memorial Day 2016 - Navasota River at Old San Antonio Road WSEL

5.2.3 Hempstead gage

The final gage calibrated to for the Memorial Day 2016 historical storm is the Brazos River gage near Hempstead. This gage is located downstream of both the Bryan / College Station and Navasota River gages. Due to this, the calibration at the upstream gages directly affects the results at Hempstead. An iterative process between calibration of the upstream gages and Hempstead was performed to ensure results at all gages were within an acceptable range. Initial and constant loss parameters were increased during calibration to align total flow volumes with historical data. Snyder Unit Hydrograph parameters adjustments were also made to create a steep, early peak as seen in the gage hydrograph. Manning's n values were minorly adjusted to allow flow to move towards Hempstead quickly and mirror the historical early peak.

- Constant losses were increased from an average of 0.03 inches/hour to 0.08 inches/hour and initial losses were increased from 0 inches for most contributing subbasins, to an average of 0.4 inches.
- Snyder Unit Hydrograph peaking coefficients were increased from a 0.4 average to 0.55 for most of the contributing subbasins.
- Manning's n coefficients were lowered for many overbanks values to increase the speed

of overland flow to Hempstead.

The calibrated model resulted in modeled storm volume within 9% of the gage data and a peak water surface elevation only 0.4 feet different from the historical data. Figure 5-8 and Figure 5-9 show the calibration results for Memorial Day 2016 at the Brazos River gage near Hempstead.

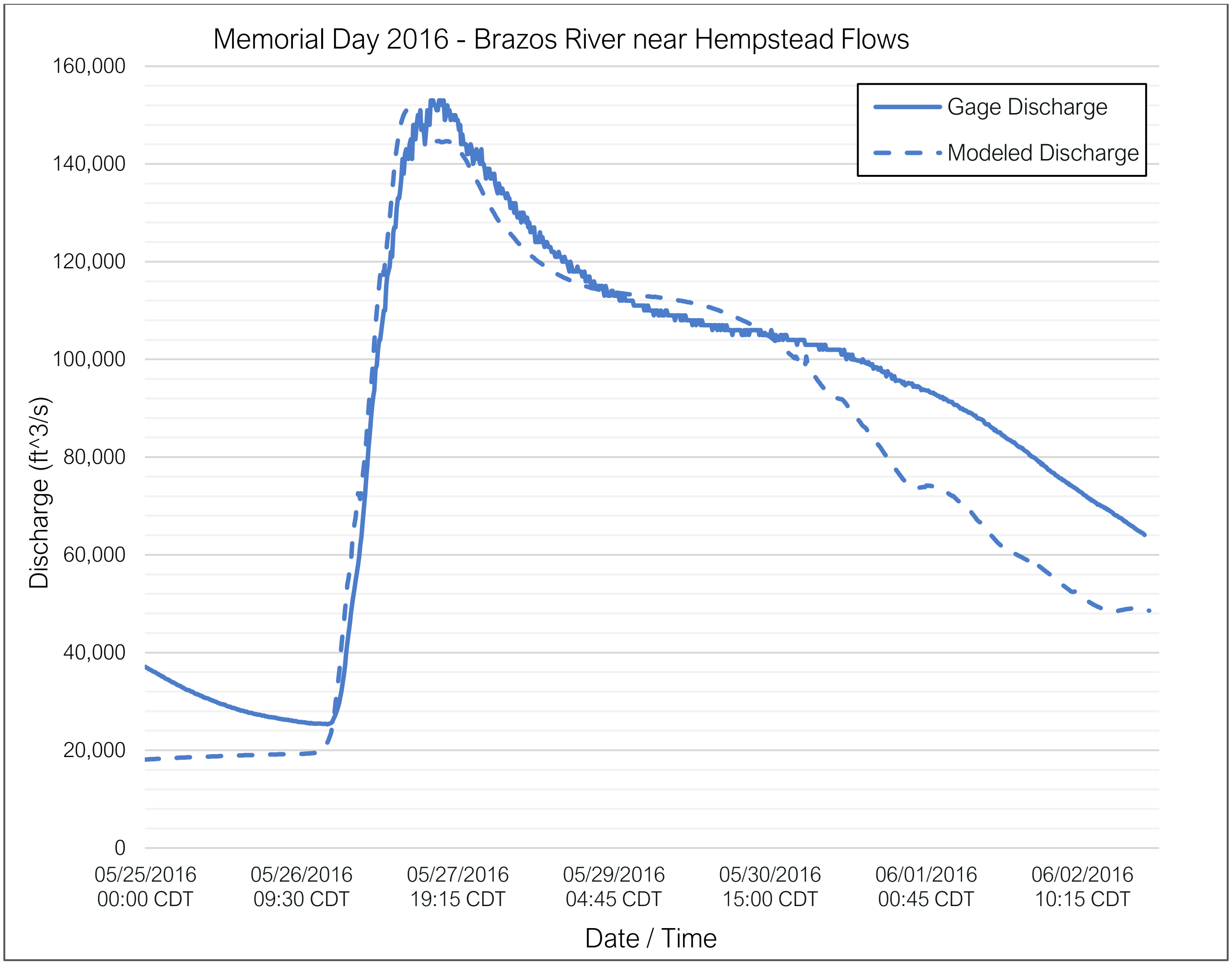


Figure 5-8. Memorial Day 2016 - Brazos River near Hempstead Flows

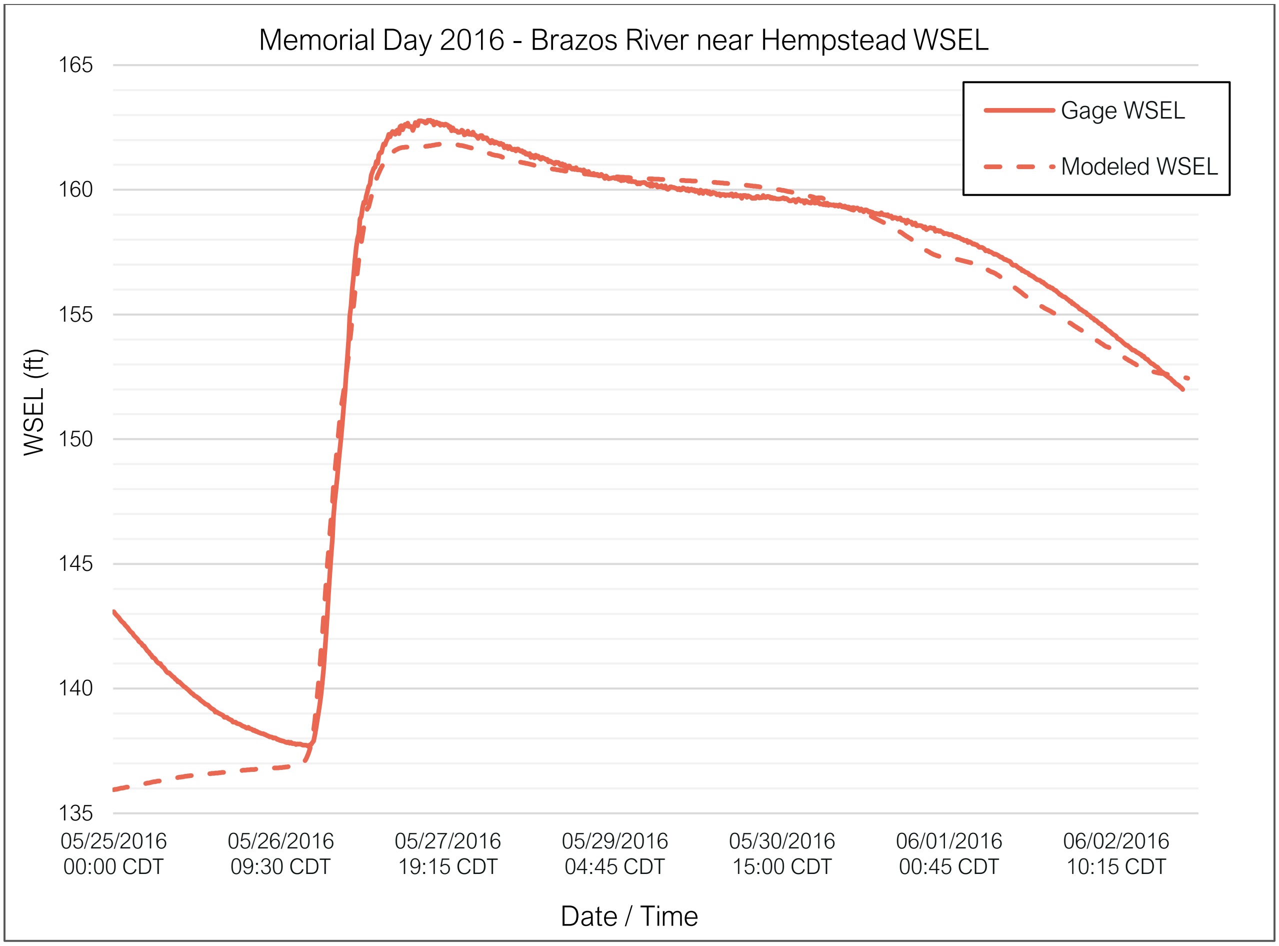


Figure 5-9. Memorial Day 2016 - Brazos River near Hempstead WSEL

5.3 Hurricane Harvey 2017

The same calibration process that was performed for the Memorial Day 2016 storm, was done for Hurricane Harvey 2017 data. Initial and constants losses were the main parameter adjusted for calibration since it is based on antecedent moisture conditions and can change significantly between storm events. In particular, the Memorial Day 2016 storm was preceded by another storm, of almost equal magnitude, less than a month before. The Tax Day 2016 storm was a significant storm for much of central Texas, including areas along the Navasota River down to Hempstead. This significant rainfall event happened less than one month before Memorial Day 2016, inhibiting the rate of infiltration during this second storm, and in-turn producing more runoff per capita of rainfall. Contrary to this, Hurricane Harvey was the first large storm of the season when it hit the same area over a year later. Significant infiltration was possible due to the drier conditions of the soil at the time of landfall.

5.3.1 Bryan / College Station gage

Hurricane Harvey 2017 calibration from the previous studies was implemented as the starting point for calibration at the Bryan / College Station Gage. Snyder Unit Hydrograph peaking coefficients were also adjusted to bring the water surface elevation peak closer to the early peak seen in historical data and align the parameters with Memorial Day 2016 calibration results. Only minor adjustments to initial and constant losses were needed due to the success of previous flow calibration at the gage.

- Snyder Unit Hydrograph peaking coefficients were increased from an average of 0.4 to 0.44 to increase the initial peak, while maintaining similar parameters to the Memorial Day 2016 calibration.
- Initial losses for contributing subbasins were decreased from an average of 6 inches to 5 inches, while constant losses were increased from an average of 0.13 inch/hour to 0.16 inch/hour. This shift in the timing of infiltration for the contributing subbasins helped shift the peak water surface elevation forward and increase the initial peak.
- Due to the position of the gage within the hydraulic model, the calibration at the Bryan / College Station Gage was not heavily influenced by changes to Manning's n values.

The calibrated model flow is within 1,000 acre-feet of the historical volume and the peak water surface elevation is within 0.10 feet of historical records. Figure 5-10 and Figure 5-11 show the calibration results for Hurricane Harvey 2017 at the Brazos River gage near Bryan / College Station, Texas.

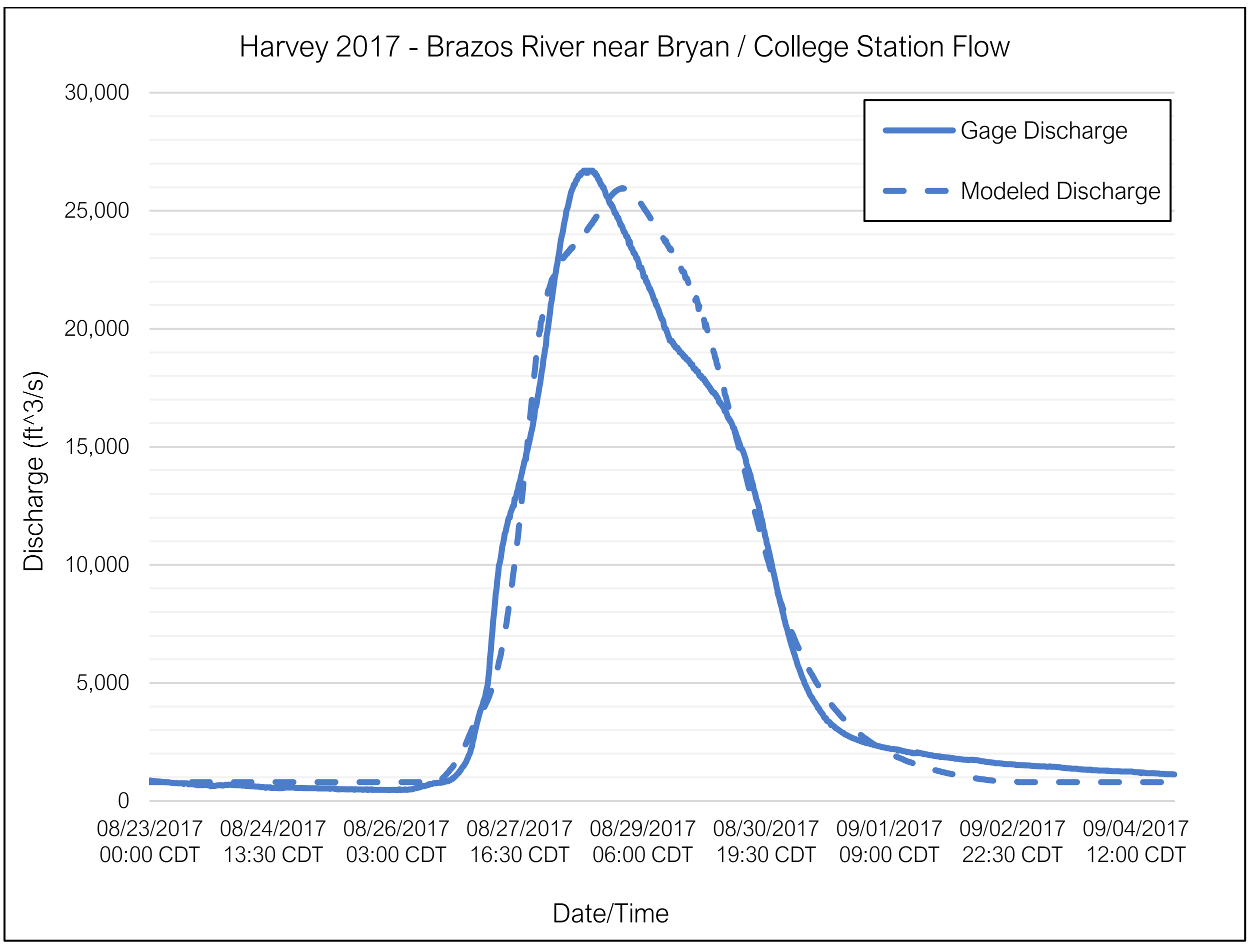


Figure 5-10. Harvey 2017 - Brazos River near Bryan / College Station Flow

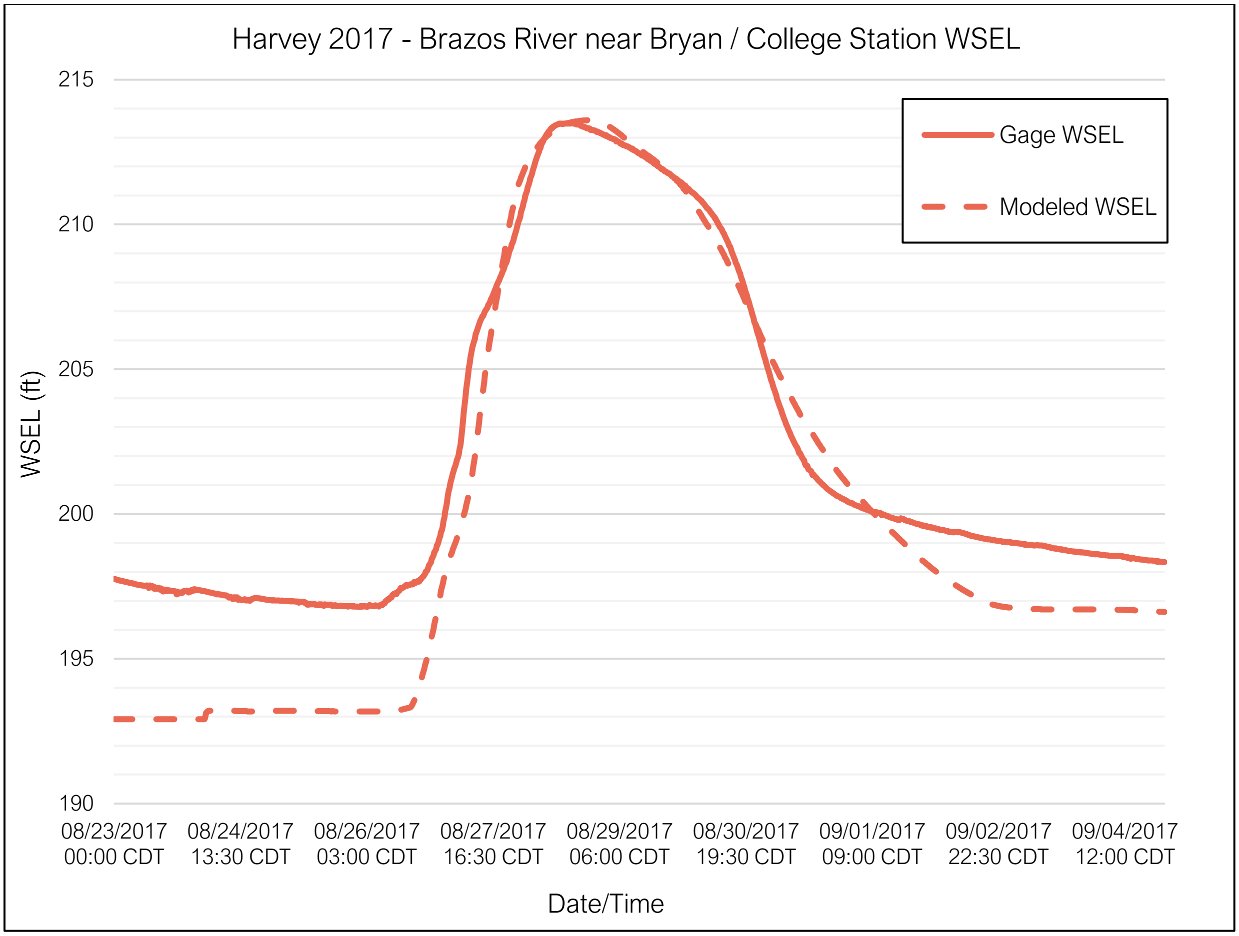


Figure 5-11. Harvey 2017 - Brazos River near Bryan / College Station WSEL

5.3.2 Navasota River gages

Two of the three gages along the Navasota River were used to inform the calibration of Hurricane Harvey 2017 at Hempstead, data for flows at Lake Limestone during Hurricane Harvey were unavailable. Unlike with the Memorial Day 2016 storm, Hurricane Harvey 2017 was not a significant event for the Navasota River watershed. This meant that adjustments to the hydrologic and hydraulic parameters to calibrate the storm for these gages, had little impact on the results or calibration at Hempstead.

5.3.3 Hempstead gage

Finally, calibration was performed at for the Brazos River at Hempstead for Harvey 2017. Since the Navasota River had less of an impact on the final results at Hempstead than it did for Memorial Day 2016, calibration at Hempstead was more heavily reliant on the timing and overall volume of flow coming from the upstream portion of the Brazos River. Manning's n values within the Brazos River channel itself were heavily influential on the resulting water surface elevation peak and timing. Additional adjustments were made to Snyder Unit Hydrograph parameters to increase the steepness of the water surface elevation peak. Initial and constant loss parameters were increased to decrease the overall volume of flow to match historical records.

- Initial losses were increased from an average of to an average of 2.1 inches to 2.6 inches for subbasins contributing directly to Hempstead. Constant losses were increased from an average of 0.1 inches/hour to 0.14 inches/hour.
- Snyder Unit Hydrograph peaking coefficients were increased from an average of 0.54 to 0.57 for subbasins contributing directly to Hempstead.
- Manning's n values for the Brazos River channel downstream of Hempstead were increased from 0.04 to 0.06. Additional adjustments were made to bring manning's n values in alignment with the values determined during Memorial Day 2016 calibration.

The calibrated model resulted in a total storm volume within 4% of the gage data and a peak water surface elevation only 0.2 feet different than historical data. Figure 5-12 and Figure 5-13 show the calibration results for Hurricane Harvey 2017 at the Brazos River near Hempstead.

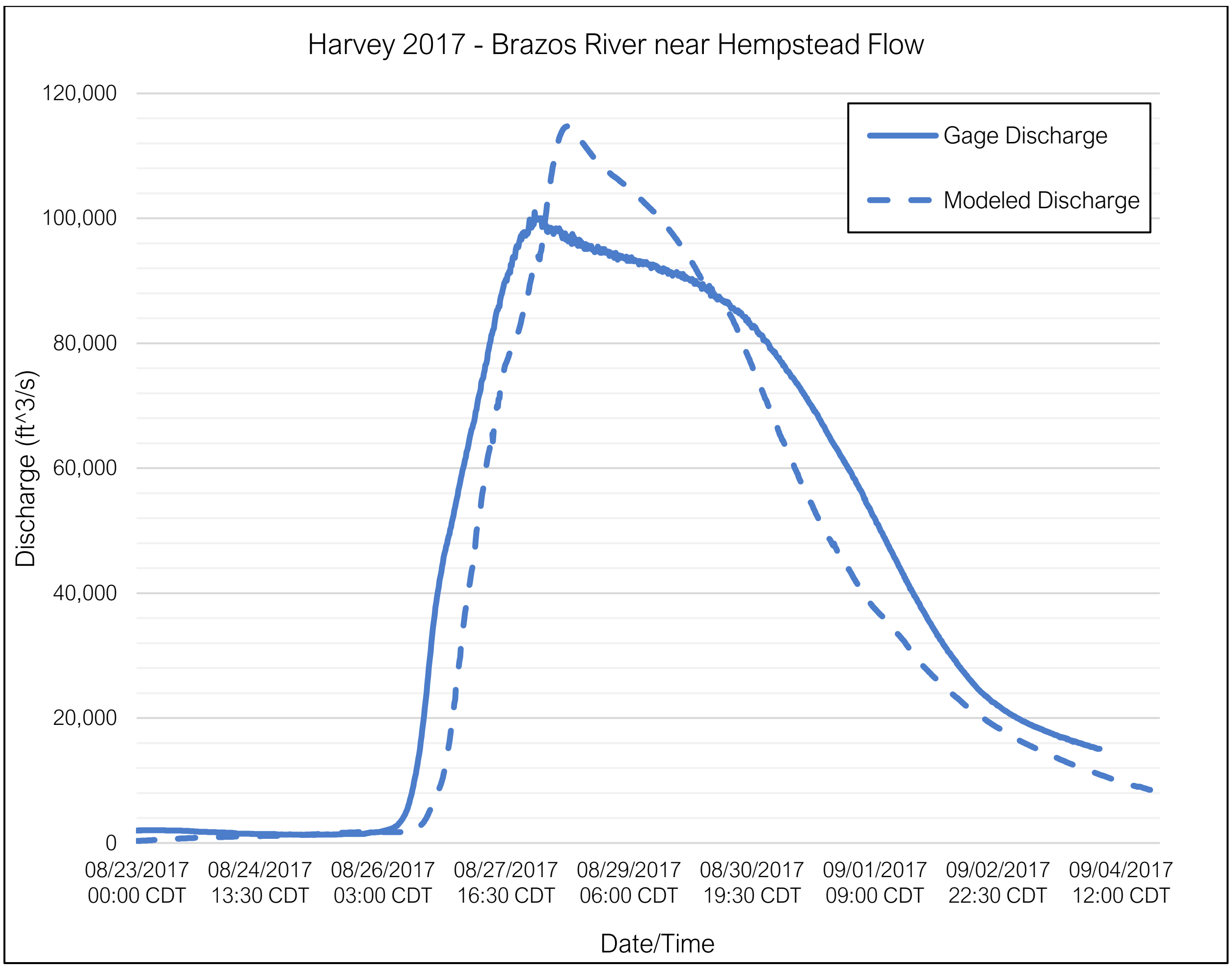


Figure 5-12. Harvey 2017 - Brazos River near Hempstead Flow

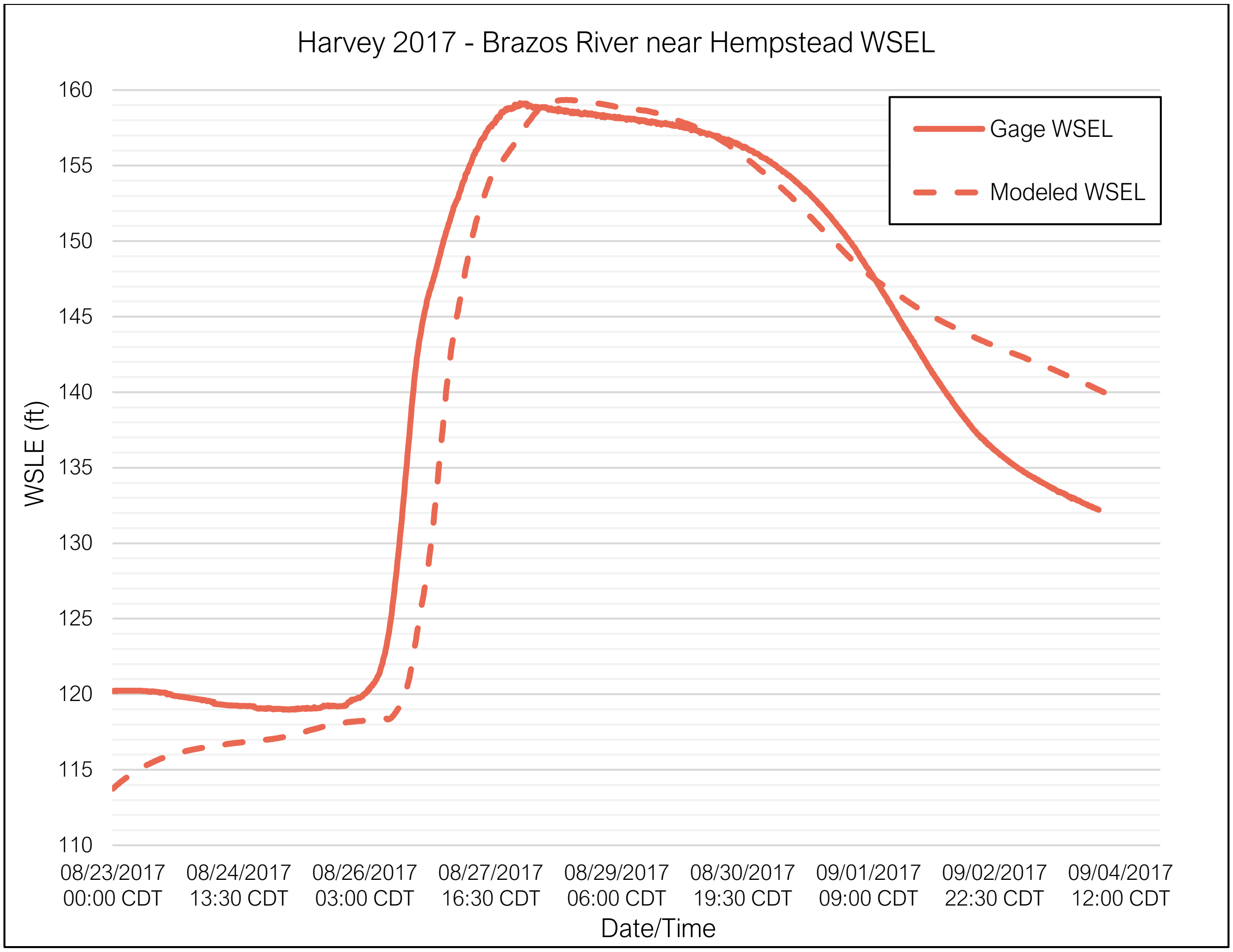


Figure 5-13. Harvey 2017 - Brazos River near Hempstead WSEL

6 Storm centering

A critically centered design storm approach was utilized to derive the storm placement and centering that generated the frequency flows developed for the Hempstead and Bryan/College Station USGS gages as discussed in Section 2.5. This approach to generating the frequency storm distribution was necessary due to the drainage area of the study area far exceeding 400 square miles, which is the upper limits of the areal-storm reduction methodology in TP-40 and the HEC-HMS technical reference manual.

The storm centering approach utilized in this study, and both previous Brazos River studies, moves an elliptically reduced storm around the basin to find the position and rotation that elicit the flood frequency peak flow volumes at the gages of interest.

6.1 Storm centering parameters

The application of the storm centering methodology required the selection of many parameters to ensure the storm is representative of historical conditions in the region.

6.1.1 Areal reduction factors

Areal reduction factors were applied to the point rainfall depths along the elliptical rings moving outwards from the storm center. For the 2021 Brazos Analysis, a curve was developed using a range of sources including: The Lower Colorado River (Texas) Flood Damage Evaluation Project, NOAA Technical Paper No. 40, NOAA Technical Paper No. 49, Hydrometeorological Report No. 51 (HMR-51), USACE SWF (Southwest Division – Fort Worth District) studies, and Areal Reduction Factors for Precipitation of the 1-Day Design Storm in Texas, published by the USGS in 1999. The areal reduction curve utilized the USACE SWF curve up to 20,000 square miles then followed a curve developed to mirror the characteristics of Hurricane Harvey (2017) up to 200,000 square miles. The application of these reduction factors to the elliptical storm shape can be seen in Figure 6-1 and the reduction factors are shown in Table 6-1. Both the areal reduction factors and storm shape were kept consistent with the parameters developed for the 2021 Brazos Analysis.

Table 6-1. Areal Reduction Factors

Ellipse	Area of Ellipse (square miles)	Areal Reduction Factors
A	10	1
B	100	0.96
C	400	0.92
D	1,000	0.85
E	2,000	0.82
F	3,000	0.80
G	4,000	0.77
H	5,000	0.74
I	10,000	0.68
J	20,000	0.51
K	60,000	0.17
L	100,000	0.09
M	200,000	0.03

6.1.2 Atlas 14 rainfall depths and duration

The durations of ten historical storms in the Brazos River basin were researched for the Brazos FPP. The average duration of rainfall at various gages within the region was determined to be just under four days. Based on this research, a five-day (120-hour) synthetic storm duration was selected for the frequency events. This duration is closely representative of both historical storms used for calibration, as discussed in Section 4.1, and was maintained during this storm centering process.

NOAA Atlas 14 point rainfall depths were used as the baseline precipitation depths. The data for the four-day and seven-day point rainfall depths were interpolated to determine a five-day baseline rainfall depth.

6.1.3 Hydrologic parameters

The hydrologic parameters resulting from historical storm calibration were used as the baseline for the frequency events. Transform and routing parameters upstream of the Hempstead gage were the same for both the Memorial Day and Harvey calibration events. However, the initial and constant losses had significantly different calibrated values for the two historical events.

Infiltration parameters, represented by initial and constant losses upstream of Hempstead in this study, are heavily reliant on soil type, land use, and antecedent moisture conditions. This causes these parameters to change significantly between storm events. In reflection of this, the initial and constant losses for the Memorial Day and Harvey calibrations are significantly different. However, since both storms most closely represent the flood frequency flows for the 1% ACE, they were both represented in the design storm frequency parameters. The calibrated initial and constant loss values for Harvey were much higher than those calibrated for Memorial Day. For the 1% ACE frequency event initial and constant losses that fall between these extremes were used to represent average conditions for the region.

Typical constant loss rates have also been found to vary across frequency events, as discussed in both the Brazos FPP and the 2021 Brazos Analysis. To reflect this variance, parameter adjustments were applied to all the frequency events to align them with the 1% ACE results at the optimum location. The factors used to adjust the 1% ACE loss rates for the other frequency events are shown in Table 6-2. The largest adjustments were to the 0.2% and 50% ACE. As more data is collected, or larger storm events are experienced along the Brazos River, the flood frequency analysis should be updated, and the associated design storms should be adjusted.

Table 6-2. Constant Loss Adjustments

Frequency Event	Constant Loss Multiplier
50% ACE	1.5
20% ACE	0.75
10% ACE	0.70
4% ACE	0.85
2% ACE	0.85
1% ACE	1.0 (Baseline)
0.2% ACE	2.0

6.2 Storm centering methodology

To determine the position and orientation of the storm that generated the flood frequency analysis peak flows at the gages, many iterations of the storm location were modeled.

The orientation of the storm in each iteration was generally aligned with the orientation of the Lower Brazos Basin; similarly, the position of the storm was kept upstream of the Hempstead gage and within the general bounds of the Lower Brazos Basin. These restrictions helped limit the number of iterations required to find the most accurate storm center.

For each position and location tested the following steps were performed:

1. Areal reduction factors were applied to the base Atlas 14 rainfall grids, adhering to the elliptical placement and rotation being tested.
2. The varying point rainfall depths were averaged for each subbasin to generate a 1-hour synthetic storm hyetograph for the reduced rainfall for the selected point.
3. The hyetographs were then run through both HEC-HMS and HEC-RAS.
4. Resulting peak flows at the Hempstead and Bryan/College Station gages were compared to target FFA flows.

A modified USACE storm centering script using global optimization automated this iterative process.

Since both the historical events used to calibrate the hydrologic and hydraulic models are most closely representative of the 1% ACE flows at Hempstead, the storm centering process was focused on this frequency event. Over 100 positional and rotational combinations were simulated to find optimal storm locations. At each optimum location for the 1% ACE storm, other frequency events (50%, 10%, and 0.2% ACE events) were modeled to see which optimum location was most representative across storm conditions.

Figure 6-1 shows the final storm center location. This storm center generated peak flows that closely resembled the results of the flood frequency analysis for all simulated storm events, as shown in Table 6-3.

Table 6-3. Storm Centering Flow Results at Hempstead

Frequency Event	FFA Results	Storm Centering Results	Percent Difference
0.2% ACE	195,230	196,010	0.4%
1% ACE	**161,060**	**160,700**	**0.2%**
2% ACE	144,820	142,770	1.4%
4% ACE	121,700	121,690	0.0%
10% ACE	102,680	99,020	3.6%
20% ACE	81,910	79,950	2.4%
50% ACE	49,830	53,680	7.7%

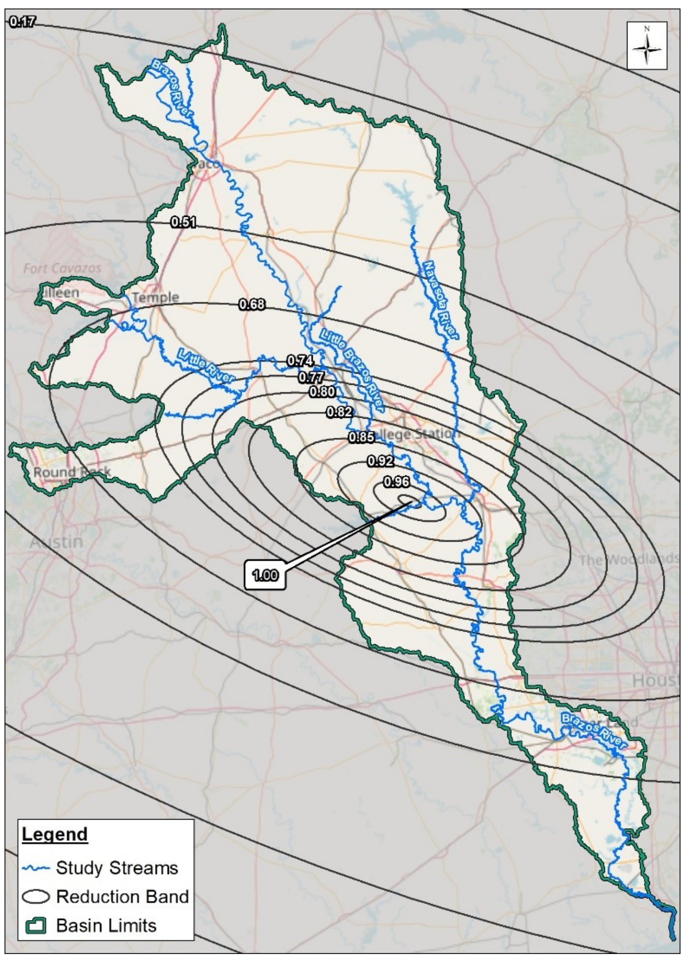


Figure 6-1. Storm Center Location

7 Existing conditions results

The hydraulic model developed as part of this study covers the Navasota River downstream of Lake Limestone, and the portion of the Brazos River between Hempstead and Bryan/College Station. This extension of more detailed routing analysis through 2D hydraulic modeling, and the calibration and storm centering of this model to ensure it reflects existing conditions, create more confidence in the results for the design storms in Waller County. The 1% and 0.2% ACE floodplains resulting from the updated modeling can be seen in Exhibit 2. Which streams were included in the detailed 2D hydraulic model are shown graphically within the Exhibit.

7.1 Frequency storm comparisons

Flows and water surface elevations for the 50%, 20%, 10%, 4%, 2%, 1%, and 0.2% ACE storm events were calculated by routing the flows from the 2D model through the previously created 2021 Brazos Analysis model. Comparisons between the Brazos FPP, 2021 Brazos Analysis, and published FIS flows and elevations were performed at significant locations.

7.1.1 Hempstead at HWY 290

The first point of comparison between FIS results, the previous studies, and existing conditions results was made at the Hempstead gage used for primary calibration. This gage is located in the northern portion of Waller County along US 290. Close to one of the most populous cities in Waller County, it is an important gage for informing the County of flood risk conditions along the Brazos River. A comparison of flow and water surface elevation results can be seen in Table 7-1 and Table 7-2, respectively. As shown in the tables, flow and water surface elevations from existing conditions modeling for the Hempstead gage is comparable to the results from the previous studies, with the most current data falling in between the Brazos FPP and Brazos Analysis results for most storm events. FIS flows and water surface elevations trend higher than any of the study results. However, FIS analysis is from 2009 and updated terrain, rainfall, and land use data likely contributes to the differences.

Table 7-1. Comparison of Flow Results at Hempstead

Frequency Storm	2009 FIS (cfs)	2019 Brazos FPP (cfs)	2021 Brazos Analysis (cfs)	Current Study Results (cfs)
10% ACE	110,000	98,000	108,000	**99,000**
2% ACE	182,000	142,000	144,000	**143,000**
1% ACE	207,000	161,000	158,000	**161,000**
0.2% ACE	260,000	227,000	188,000	**196,000**

Table 7-2. Comparison of WSEL Results at Hempstead

Frequency Storm	2009 FIS (ft)	2019 Brazos FPP (ft)	2021 Brazos Analysis (ft)	Current Study Results (ft)
10% ACE	163.00	158.62	159.54	**157.81**
2% ACE	167.80	162.05	163.50	**163.47**
1% ACE	169.20	162.92	164.76	**164.50**
0.2% ACE	171.70	165.66	165.27	**166.76**

7.1.2 San Felipe

The next major checkpoint is in the southern portion of Waller County. The crossing of FM 1458 in San Felipe has a newly installed USGS gage with 10 years of record. While this gage does not have enough historical data to perform a flood frequency analysis at, it does demarcate a checkpoint that may be used for analysis as the period of record grows. Currently, FIS flows are not available for this location. A comparison of flow and water surface elevation results can be seen in Table 7-3 and

Table 7-4, respectively. Existing conditions flow results trended a bit lower than the previous studies. Updated calibration at Hempstead accounting for routing along the Navasota and upstream portions of the Brazos River caused changes in the timing of upstream Brazos flows. This timing difference resulted in slightly lower peak flows, but very similar water surface elevation results.

Table 7-3. Comparison of Flow Results at San Felipe

Frequency Storm	2009 FIS (cfs)	2019 Brazos FPP (cfs)	2021 Brazos Analysis (cfs)	Current Study Results (cfs)
10% ACE	-	94,000	101,000	**94,000**
2% ACE	-	136,000	118,000	**115,000**
1% ACE	-	157,000	123,000	**119,000**
0.2% ACE	-	225,000	125,000	**126,000**

Table 7-4. Comparison of WSEL Results at San Felipe

Frequency Storm	2009 FIS (ft)	2019 Brazos FPP (ft)	2021 Brazos Analysis (ft)	Current Study Results (ft)
10% ACE	120.20	123.57	123.94	**122.76**
2% ACE	123.40	127.96	126.87	**126.68**
1% ACE	127.20	129.84	127.76	**127.86**
0.2% ACE	129.50	132.71	129.28	**129.70**

7.1.3 Richmond

Although this analysis is focused on flooding conditions through Waller County, impacts of the extension of the hydraulic modeling on the southern portions of the watershed were checked to verify that there were no significant changes. The USGS gage at US 90 in Richmond was used as the primary calibration point for both the Brazos FPP and Brazos Analysis, which were focused on flooding in Fort Bend County. A comparison of flow and water surface elevation results can be seen in Table 7-5 and

Table 7-6. Even with the updated hydraulics in the upstream portions of the watershed, existing condition results at Richmond were found to be very similar to the previous studies.

Table 7-5. Comparison of Flow Results at Richmond

Frequency Storm	2009 FIS (cfs)	2019 Brazos FPP (cfs)	2021 Brazos Analysis (cfs)	Current Study Results (cfs)
10% ACE	103,000	86,000	91,000	**85,000**
2% ACE	147,000	123,000	120,000	**124,000**
1% ACE	164,000	139,000	132,000	**139,000**
0.2% ACE	206,000	187,000	157,000	**157,000**

Table 7-6. Comparison of WSEL Results at Richmond

Frequency Storm	2009 FIS (ft)	2019 Brazos FPP (ft)	2021 Brazos Analysis (ft)	Current Study Results (ft)
10% ACE	76.65	77.04	77.11	**76.04**
2% ACE	81.34	82.76	81.51	**81.62**
1% ACE	82.81	84.43	82.85	**83.47**
0.2% ACE	85.20	87.66	84.92	**85.71**

7.1.4 Rosharon

The USGS gage at FM 1462 in Rosharon was used as the last checkpoint for flow comparison. This gage, located at the border of Fort Bend and Brazoria counties, was used for secondary calibration on both the previous studies. A comparison of flow and water surface elevation results can be seen in Table 7-7 and Table 7-8. Similar to the Richmond comparison, the existing condition results vary on slightly from the previous studies.

Table 7-7. Comparison of Flow Results at Rosharon

Frequency Storm	2009 FIS (cfs)	2019 Brazos FPP (cfs)	2021 Brazos Analysis (cfs)	Current Study Results (cfs)
10% ACE	103,000	86,000	85,000	**81,000**
2% ACE	105,000	126,000	113,000	**120,000**
1% ACE	107,000	145,000	126,000	**141,000**
0.2% ACE	114,000	202,000	150,000	**177,000**

Table 7-8. Comparison of WSEL Results at Rosharon

Frequency Storm	2009 FIS (ft)	2019 Brazos FPP (ft)	2021 Brazos Analysis (ft)	Current Study Results (ft)
10% ACE	52.05	50.73	49.10	**48.47**
2% ACE	52.53	51.17	50.71	**50.52**
1% ACE	52.59	51.29	51.10	**50.97**
0.2% ACE	52.91	51.62	51.75	**51.58**

7.2 Mapping comparisons

Extents of the 1% ACE floodplain from the modeling were compared to the published FEMA floodplains to identify locations with significant differences. A comparison of the floodplains throughout Waller County can be seen in Exhibit 3.

The FEMA floodplain was found to have a consistently smaller footprint than the results of the existing conditions analysis. This difference in extents is largely due to the incorporation of Atlas 14 rainfall statistics that were not available when the FEMA FIS for the Brazos River was completed. Additionally, this study incorporates several other updated datasets such as terrain, land use, and soils data. Beyond this general difference, some areas showed more drastic increases than others. Downstream of the crossing with US 159, the modeled Brazos River floodplain expands more drastically than the published FEMA floodplain, indicating the potential for many structures to have more significant flood risk than the published floodplain currently indicates. This area can be seen in Figure 7-1.

Another area of significant deviation is located just upstream of the I-10 and Brazos River crossing. Influenced by both Irons Creek and Brazos River floodplains, the modeling results show significant inundation of this natural low point during the 1% ACE event. The increased extents indicate that Robichaux Road is overtopped by Brazos River overflow during severe storm events, allowing flood waters to inundate several residents downstream. Figure 7-2 shows a comparison of the floodplains in this location.

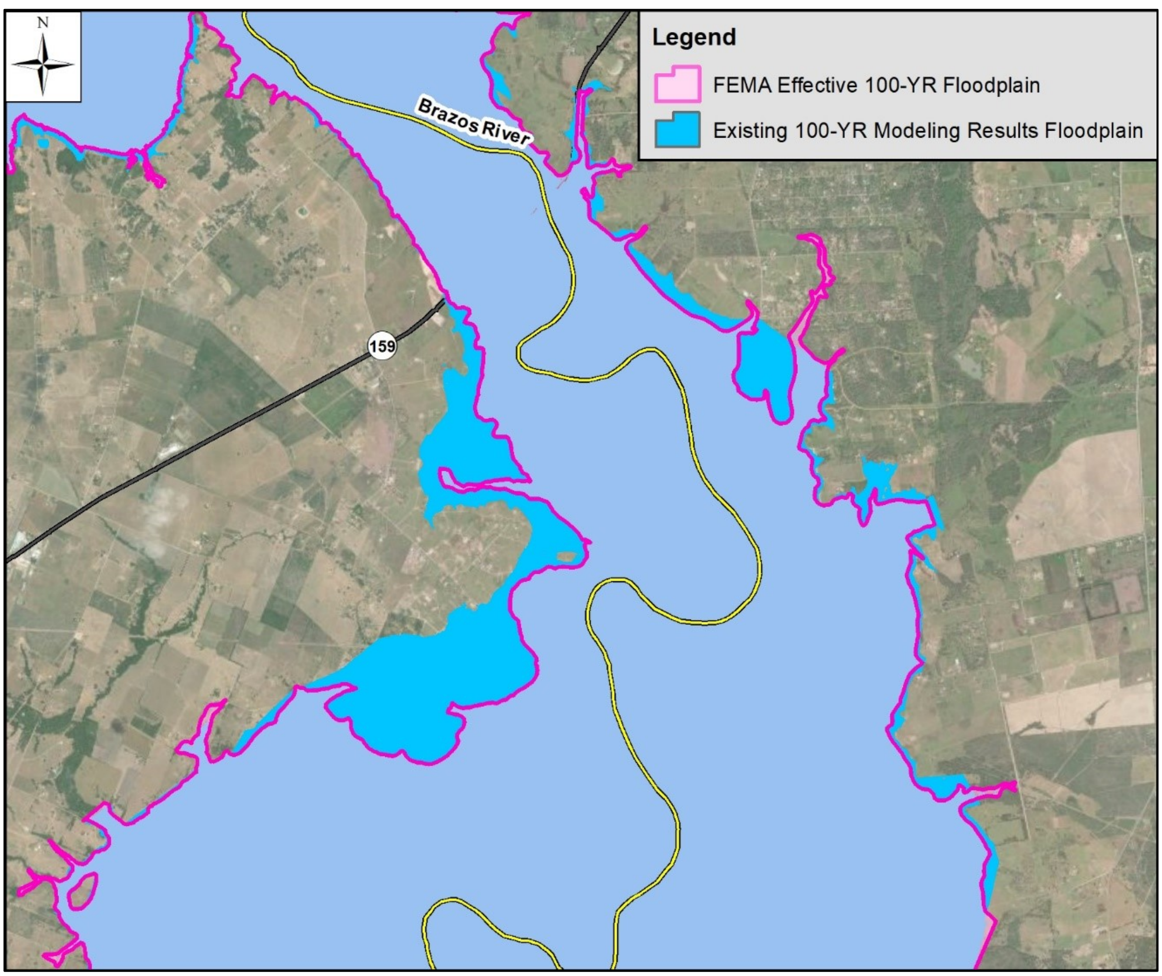


Figure 7-1. Floodplain Comparison Downstream of US 159

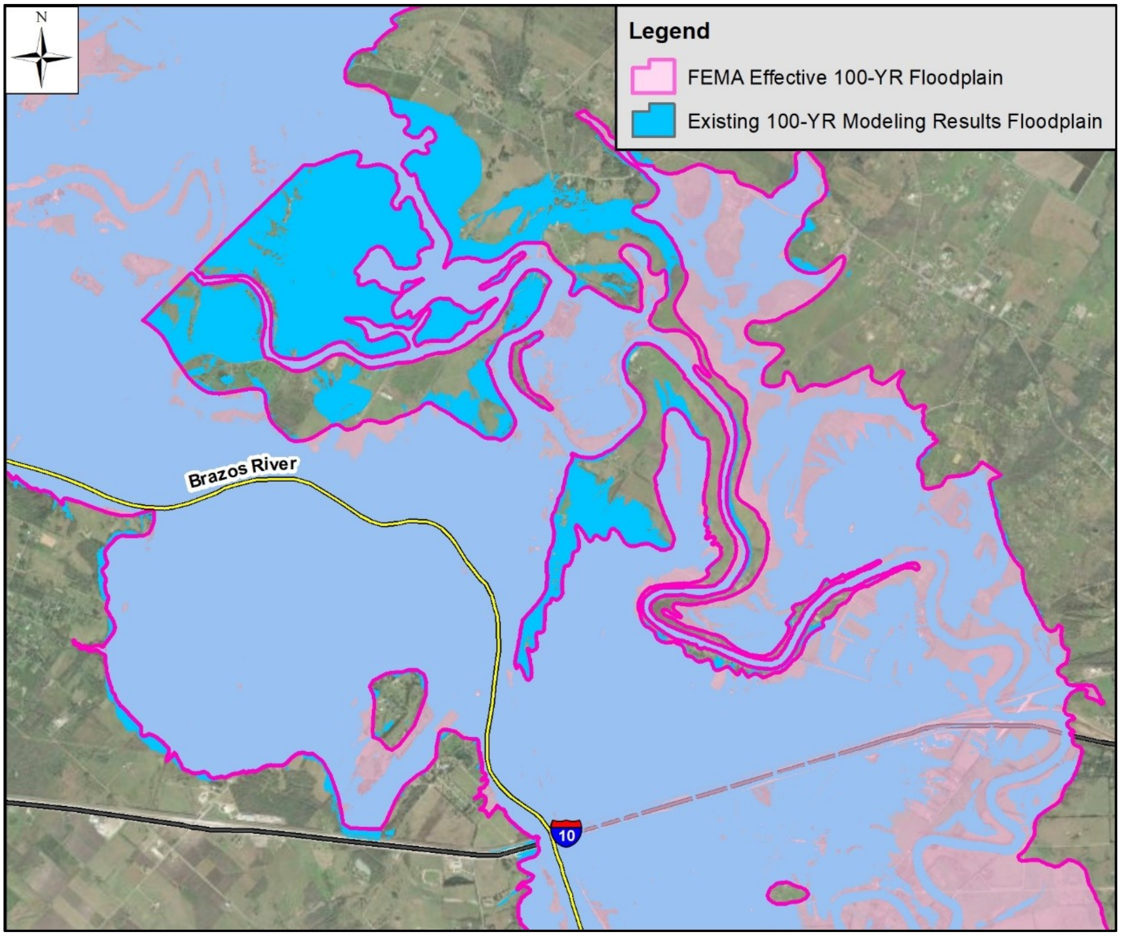


Figure 7-2. Floodplain Comparison Upstream of I-10

7.3 Existing conditions summary

A detailed analysis was performed to determine water surface elevations and flows along the Brazos River in Waller County. This analysis included updates to previously developed hydrology, development of additional hydraulic modeling, historical calibration of the models, a flood frequency analysis to calculate target design flows, and storm centering to generate the FFA flows at the desired locations. After developing this information, the results were compared to available existing information from the Flood Insurance Study and two previous analyses of the Brazos River to confirm the generated results are reasonable.

The developed existing conditions were then used to analyze flood risk exposure from the Brazos River floodplain throughout Waller County. Flood risk to structures, roads, agricultural areas, and critical facilities, among other metrics, were determined for Waller County. The results of this analysis for the 1% ACE can be seen in Table 7-9. Although the flood risk analysis was focused on this storm event, more frequent events are also shown to pose significant flood risk to infrastructure throughout Waller County. Table 7-10 summarizes the number of at-risk structures for each frequency event.

Table 7-9. Infrastructure at 1% ACE Flood Risk from Brazos River Floodplain in Waller County

Infrastructure Type	Quantity at Risk
Structures	623
Residential Structures	267
Estimated Population	289
Critical Facilities	1
Low Water Crossings	5
Length of Roads (mi)	41
Road Closures	44
Agricultural Areas (ac)	29,500

Table 7-10. Structures at Flood Risk from Brazos River Floodplain in Waller County

Annual Chance Event	Number of Structures at Flood Risk
50%	0
20%	2
10%	18
4%	190
2%	414
1%	623
0.2%	915

Much of the structural flooding in Waller County is located in the very southern portion, below I-10. This low-lying area has a more dense population than most of the rural county and is bounded on either side by the Brazos River and Bessie's Creek which both contribute to the flooding of the region. Other pockets of structural flooding are located north of I-10 near the community of Sunny Side which is in close proximity to the Brazos River. Similar to the southern portion of the County, this community experience overflow exchanges between the Brazos River and Irons Creek increasing the flood risk for the area.

8 Alternative analysis

Potential structural and non-structural flood mitigation alternatives were evaluated for locations with high flood risk in the Brazos River watershed within Waller County. Non-structural solutions were reviewed on a regional bases to be applied throughout the County to areas with high flood risk. Structural recommendations were developed through alternative analysis at identified flood prone locations.

8.1 Flood prone area identification

Flood prone areas were identified within the study area to characterize locations with high flood risk in the County that would most benefit from structural flood mitigation projects. Existing conditions flooding was the primary metric used to identify flood prone areas. However, information provided by the County was used to verify the existing conditions and narrow down evaluation to areas with historical flood risk.

As discussed in the previous sections, existing conditions modeling was performed for the Brazos River floodplain. Due to the size of the Brazos River, projects mitigating risk caused by riverine flood risk from the Brazos would be costly and take many years to implement. To provide more immediate flood risk solutions to Waller County, areas within the Brazos River watershed, but not the Brazos River floodplain, were also evaluated for flood risk. Data was gathered from many public sources including existing flood hazard identified in the Lower Brazos Regional Flood Plan, FEMA Flood Insurance Studies (FIS), and BLE and was leveraged for problem area identification.

Since the sources for existing conditions (1% ACE) flood risk varied for the analysis performed, historical and local data provided by the County was used to validate identification of flood prone areas. Table 8-1 and Figure 8-1 summarize the identified problem areas.

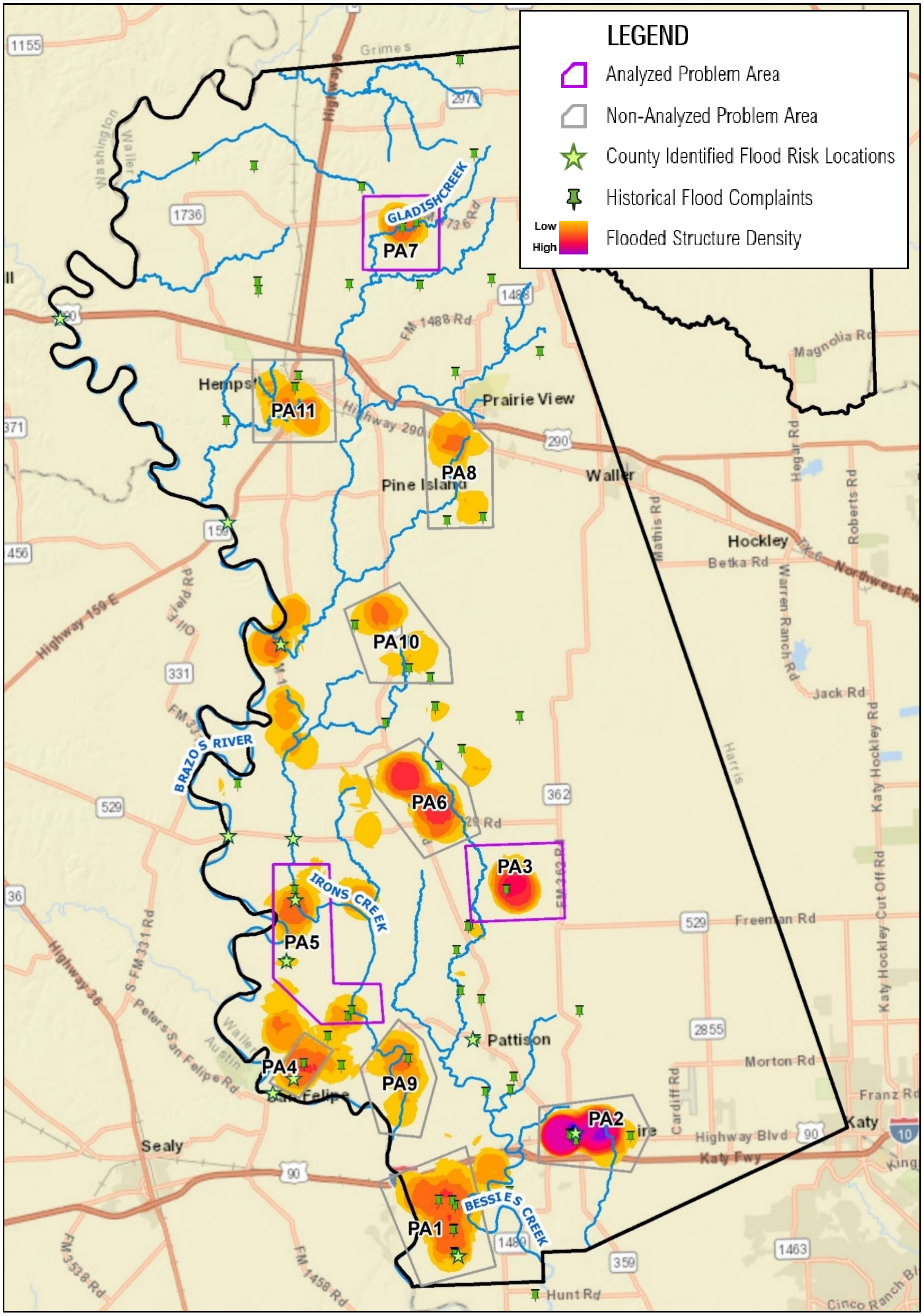


Figure 8-1. Problem Area Identification

Table 8-1 Problem Areas

	PA Name	Brief Description of Flooding	Analyzed Further?
1	Peach Ridge Road	Riverine flooding of neighborhood caused by Brazos River and Bessies Creek. Would require mitigation of Brazos River flows to provide substantial relief.	No
2	Brookshire	Riverine flooding caused by Bessies Creek and Bessies Creek tributaries. Existing project for area under development by GLO.	No
3	Adams Flat Road	Riverine flooding of neighborhood in frequent events, caused by two Bessies Creek tributaries.	Yes
4	Foots Wilson Road	Riverine flooding of neighborhood during extreme events, caused by Brazos River.	No
5	Irons Creek Crossings	Riverine flooding from Irons Creek that prevents resident mobility in frequent events.	Yes
6	FM 359	Localized flooding of residents near FM 359 caused by low-lying terrain preventing positive drainage.	No
7	Rolling Hills Lake	Riverine flooding of lake community, caused by Gladish Creek and Rolling Hills Lake.	Yes
8	South Prairie View	Combination of local and riverine flooding from Threemile Creek impacting neighborhood.	No
9	Beaver Creek Road	Riverine flooding caused by Irons Creek and Brazos River in extreme events. Would require mitigation of Brazos River flows.	No
10	Harris Headwaters	Localized flooding of residents caused by low-lying terrain preventing positive drainage.	No
11	Downtown Hempstead	Riverine and local flooding from multiple sources, including Clear and Lewisville Creeks.	No

Several areas with a high concentration of at-risk structures were identified. However, many of these were not selected for further analysis. Although this study did not model projects for all flood risk areas within the watershed, further study should be done to identify projects for other areas of high flood risk within Waller County. For this study, areas were prioritized for further analysis if they met the following criteria:

- Located outside of the Brazos River floodplain, or primary cause of flooding is not the Brazos River
- Had historical complaints or were County identified as areas of noted flood risk
- Do not have flood risk projects developed for the area

After evaluating the available existing conditions data, three locations were chosen for further analysis:

1. **PA 7 – Rolling Hills Lake**: This problem area contains a neighborhood centered around Rolling Hills Lake. Historical flood complaints and a high concentration of structures with flood-risk indicate that this area experiences extensive flooding due to the limited lake and channel capacity through the neighborhood. Overtopping of this drainage infrastructure causes structural inundation, and historically structural damage, throughout the neighborhood.

2. **PA 3 – Adams Flat Road**: This problem area is located just east of Bessie's Creek. Two tributaries run through a small neighborhood along Adams Flat Road. As indicated by historical flood complaints and existing conditions flood risk, a combination of riverine flooding from these tributaries, and localized sheet flow, cause extensive inundation throughout the neighborhood and surrounding properties.
3. **PA 5 – Irons Creek Crossings**: This problem area, located between FM 529 and FM 1458 near the Brazos River, is a location that Waller County has identified as high flood risk. Although structural inundation is not as significant of an issue at this location, road inundation causes residents living along Diemer Road, and other surrounding communities, to become trapped during severe storm events. Historical flood complaints concerning lack of mobility support the County's concerns.

8.2 Model development and results

Since the locations selected for further analysis are not within the bounds of the current existing conditions model for the Brazos River floodplain, new models were developed to perform alternative analysis for the identified problem areas.

Two different types of modeling were used: 2D rain-on-grid (ROG) modeling and 1D steady-state modeling.

2D ROG modeling was used to evaluate Rolling Hills Lake (PA 7) and Adams Flat Road (PA 3). Both areas experience a combination of local and riverine flooding. ROG modeling allows for both creek flows, and overbank flows to be evaluated together, providing a more comprehensive overview of the cause and extents of flood risk.

1D steady-state modeling was used to evaluate Irons Creek Crossings (PA 5). 1D models allow for detailed analysis of flooding conditions along an identified channel and its overbanks. Since this area has been studied and evaluated by Waller County in the past, the source of flooding and approach for mitigation, were already known and a 1D model was deemed sufficient for alternative analysis.

8.2.1 2D models

The 2D rain-on-grid models were developed using the following data:

- Atlas 14 rainfall data
- Terrain data sourced from Texas Natural Resources Information System (TNRIS)
- National Land Cover Database (NLCD) land cover raster
- Field measurements for critical drainage structures

HEC-HMS version 4.10 models were developed to create rainfall rasters from the Atlas 14 point precipitation frequency data. Green and Ampt parameters were used to define losses for the basins.

The rainfall data generated from the HEC-HMS models was evaluated hydraulically using HEC-RAS version 6.3. The HEC-RAS models were constructed similarly to the 2D model generated for the detailed analysis of Navasota River and upstream Brazos River flows, discussed in Section 3.3 - Model development.

TNRIS terrain data was used to delineate breaklines along critical features. Roads, berms, and other high points were delineated to ensure the 2D mesh aligned with the high points and flow did not pass over until overtopping these peak elevations. Stream banks for the major channels being evaluated were also delineated to align the 2D cells perpendicular to flow. Critical crossings were modeled using 2D connectors with dimensions gathered from field measurements, while minor crossings were modeled using "leaks" that allow flow to pass through the breaklines.

NLCD land use was used to define manning's n values for the problem areas. Varied values were used for each land use type to represent flow characteristics at different depths. Three different depth conditions were considered for each NLCD land use type:

- Channel: Within stream banks
- Overbank: Greater than 6 inches of flooding depth
- Rain-on-mesh: Less than 6 inches of flooding depth

Typical manning's n values were sourced from the HEC-RAS manual and Open-Channel Hydraulics by Ven Te Chow, 1959.

The models were evaluated for three frequency events, 1% ACE, 10% ACE, and 50% ACE, to determine existing conditions and perform alternative analysis. Modeling results for each project are discussed in the following sections.

8.2.2 1D steady-state model

The 1D steady-state models were developed using the following data:

- Atlas 14 rainfall data
- Terrain data sourced from Texas Natural Resources Information System (TNRIS)
- National Land Cover Database (NLCD) land cover raster

A HEC-HMS version 4.10 model was developed to determine flows for Irons Creek. Green and Ampt parameters were used to defined losses for the basin, and the Basin Development Factor (BDF) method was used to determine Clark Unit Hydrograph transform parameters.

Resulting flows were evaluated hydraulically using HEC-RAS version 6.3. Cross-sections were developed to characterize Irons Creek directly upstream and downstream Mt Zion Road and Garret Road bridge crossings. Structures were added in to characterize the existing bridge crossings and perform alternative analysis on bridge improvements.

TNRIS terrain was used to model channel elevations along the cross-sections and NLCD land use data was used to determine manning's n values for the innerbanks and overbanks.

8.3 Concept development

Conceptual flood mitigation projects were developed and evaluated to reduce flood risk for structures and roadways at flood prone areas within the watershed. Mitigation was focused on addressing frequent flooding. Each alternative was evaluated based on the following criteria:

- Ability to reduce the number of impacted structures

- Ability to be funded and constructed
- Improvements to mobility during storm events

Conceptual alternatives were first explored to identify the viability of different types of solutions at each location. Viable conceptual solutions were then analyzed in detail to create project recommendations. Structural solutions were the primary focus for the conceptual alternatives developed for the identified locations. The areas were specifically selected due to their being characterized by easily identifiable sources of flooding with the potential for concise structural solutions. Non-structural alternatives were evaluated for flood prone areas not easily mitigated by structural solutions, as discussed in Section 8.7: Non-structural. The concepts explored for the identified problem areas include:

- Selective Clearing
- Lake Lowering
- Weir Improvements
- Culvert and/or Bridge Enhancements
- Conveyance Improvements
- Detention
- Diversion Channels

From these conceptual alternatives, four structural projects were identified, evaluated, and recommended for implementation. These projects are:

- **FMP 1 in PA 3**: Diversion channel rerouting water from Bessie's Creek Tributary 1 to Bessie's Creek mainstem to the west, initiating north of the Adams Flat Road neighborhood.
- **FMP 2 in PA 3**: Diversion channel rerouting water from Bessie's Creek Tributary 2 to Bessie's Creek Tributary 1 along eastern portion of the Adams Flat Road neighborhood.
- **FMP 3 in PA 7**: Expansion of outflow structure for Rolling Hills Lake.
- **FMP 4 in PA 5**: Upsizing of crossing structure at Irons Creek and Mt Zion Road.

A summary of the flood risk benefits provided by the recommended projects is provided in Table 8-2. The projects were developed in accordance with TWDB requirements to qualify them as Flood Mitigation Projects (FMPs) within the regional and state flood plans. Projects identified within this study were screened for feasibility using information available at the time of the study. Based on initial screening, the projects were determined to be implementable (in terms of permitting and construction) in the same manner as similar projects throughout the region.

Table 8-2. Recommended Project Flood Risk Benefits

Mitigation Measurement	FMP 1 West Diversion Channel	FMP 2 East Diversion Channel	FMP 3 Gladish Weir Improvement	FMP 4 Mt Zion Bridge Improvement
Structures with reduced 1% ACE flood risk	67	62	15	-
Structure removed from 1% ACE flood risk	2	3	1	-
Structures removed from 0.2% ACE flood risk				-
Residential structures removed from 1% ACE	0	1	1	-
Population removed from 1% ACE flood risk	2	3	1	-
Critical facilities removed from 1% ACE flood risk	0	0	0	-
Low water crossings removed from 1% ACE	0	0	0	1
Reduction in road closure occurrences in 1% ACE	0	0	0	1
Length of road removed from 1% ACE (mi)	0	0	0	0.5
Farm & ranch land removed from 1% ACE	0	0	0	-
Estimated reduction in fatalities	0	0	0	0
Estimated reduction in injury	0	0	0	0
Pre-Project Level of Service	< 50% ACE	< 50% ACE	< 50% ACE	4% ACE
Post-Project Level of Service	10% ACE	4% ACE	20% ACE	2% ACE
Cost/Structure Removed	$4,738,550	$1,059,930	$9,654,300	-
Percent Natured-Based Solution	0%	0%	0%	0%
Negative Impact?	No	No	No	No
Negative Impact Mitigation?	-	-	-	-
Social Vulnerability Index	0.77	0.76	0.78	0.80
Water Supply Benefits?	No	No	No	No
Traffic Count for Low Water Crossings	-	-	-	227

8.4 Adams Flat Road (PA 3)

8.4.1 Existing conditions

The Adams Flat Road problem area (PA 3) is located east of Bessie's Creek; two small tributaries (Bessie's Creek Tributary 1 on the west side and Bessie's Creek Tributary 2 on the east side) cross several neighborhood streets, potentially inundating many homes during storm events. PA 3 contains 111 structures preliminary identified as being prone to flooding within the 1% ACE as well as inundated roadways. Additionally, Waller County has records of flooding complaints for the neighborhood. Figure 8-2 shows the existing conditions within PA 3

Preliminary analysis indicated that flooding within PA 3 is due to a combination of localized sheet flow and riverine flooding from both Bessie's Creek Tributaries. Improvements to undersized drainage infrastructure within the neighborhood, such as driveway culverts, roadside ditches, and road crossing structures, was explored for the area. However, since the floodplain for the tributaries are expansive, there were minimal benefits provided by the additional conveyance capacity at the crossings.

Selective clearing was explored to provide additional capacity to the channels. The benefits provided by selective clearing were largely localized to land directly adjacent to the channel.

Diversion channels were the final conceptual alternative explored for PA 3. This solution was found to be especially viable due to the reach of the improvements, gathering both riverine overflow and sheet flow, and providing flood relief to the neighborhood and surround residential structures. Two diversion channel projects, West Diversion Channel (FMP 1) and East Diversion Channel (FMP 2), were developed to mitigate flooding within PA 3. They are described in Sections 8.4.2 and 8.4.3, respectively.

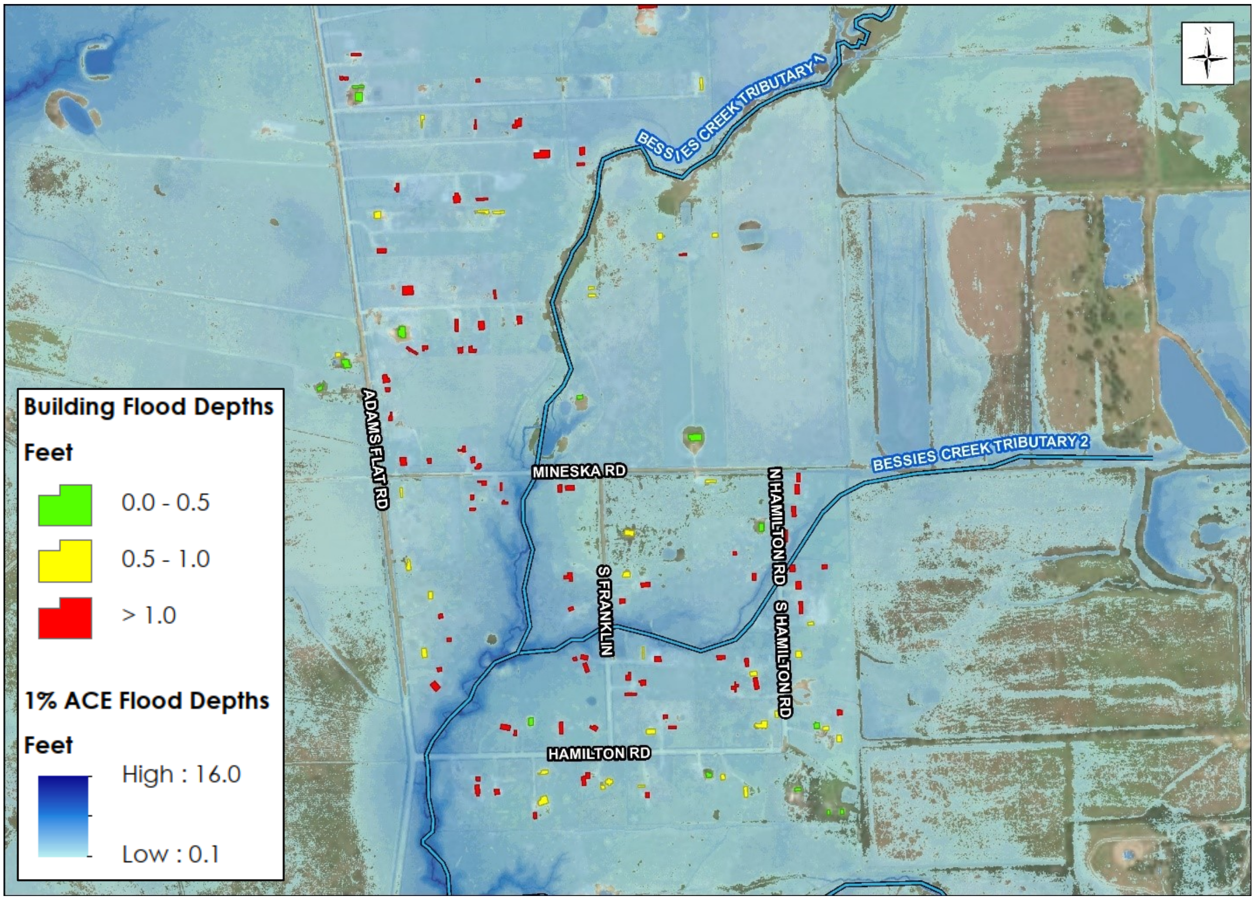


Figure 8-2. Adams Flat Road Problem Area (PA 3) Existing Conditions

8.4.2 West diversion channel (FMP 1)

The West Diversion Channel project (FMP 1) includes the construction of a 1 mile long, 70-feet wide, 8 feet deep channel north of the neighborhood that would convey flow west towards Bessie's Creek. FMP 1 would include a channel starting at from the Bessie's Creek Tributary 1, north of Mikeska Road, to the Bessie's Creek mainstem to the west. Five 8 by 7-foot culverts would also be necessary to allow the diversion channel to cross Adams Flat Road. An 80 acre-foot detention pond is also proposed at the confluence with Bessie's Creek to mitigate increases in discharges. The project geometries can be seen in Exhibit 7.

Modeling results

This diversion channel would capture a significant portion of the flow inundating the problem area and reroute it to a less developed region. 1,440 and 280 cubic feet per second is shown to be rerouted from Bessie's Creek Tributary 1 during the 1% and 50% ACE, respectively. Water surface elevations within the neighborhood are lowered by an average of 6 inches for the 1% ACE and 9 inches for the 10% ACE.

Benefits

The diversion channel provides benefits to the western portion of the neighborhood along Adams Flat Road as well as to several structures north of the area by reducing flows and ponding depths.

Benefits are primarily seen in frequent storm events such as the 50% and 10% ACE with minor benefits in the larger events. Table 8-3 summarizes the benefits provided the proposed project, FMP 1 – West Diversion Channel. Figure 8-3 and Exhibit 11 show the benefits provided.

Table 8-3. West Diversion Channel (FMP 1) Benefits

Frequency Storm	Structures Benefitted	Structures Removed	Population Benefitted	Roads Benefitted
1% ACE	67	2	46	0
10% ACE	45	1	24	0
50% ACE	27	1	12	0

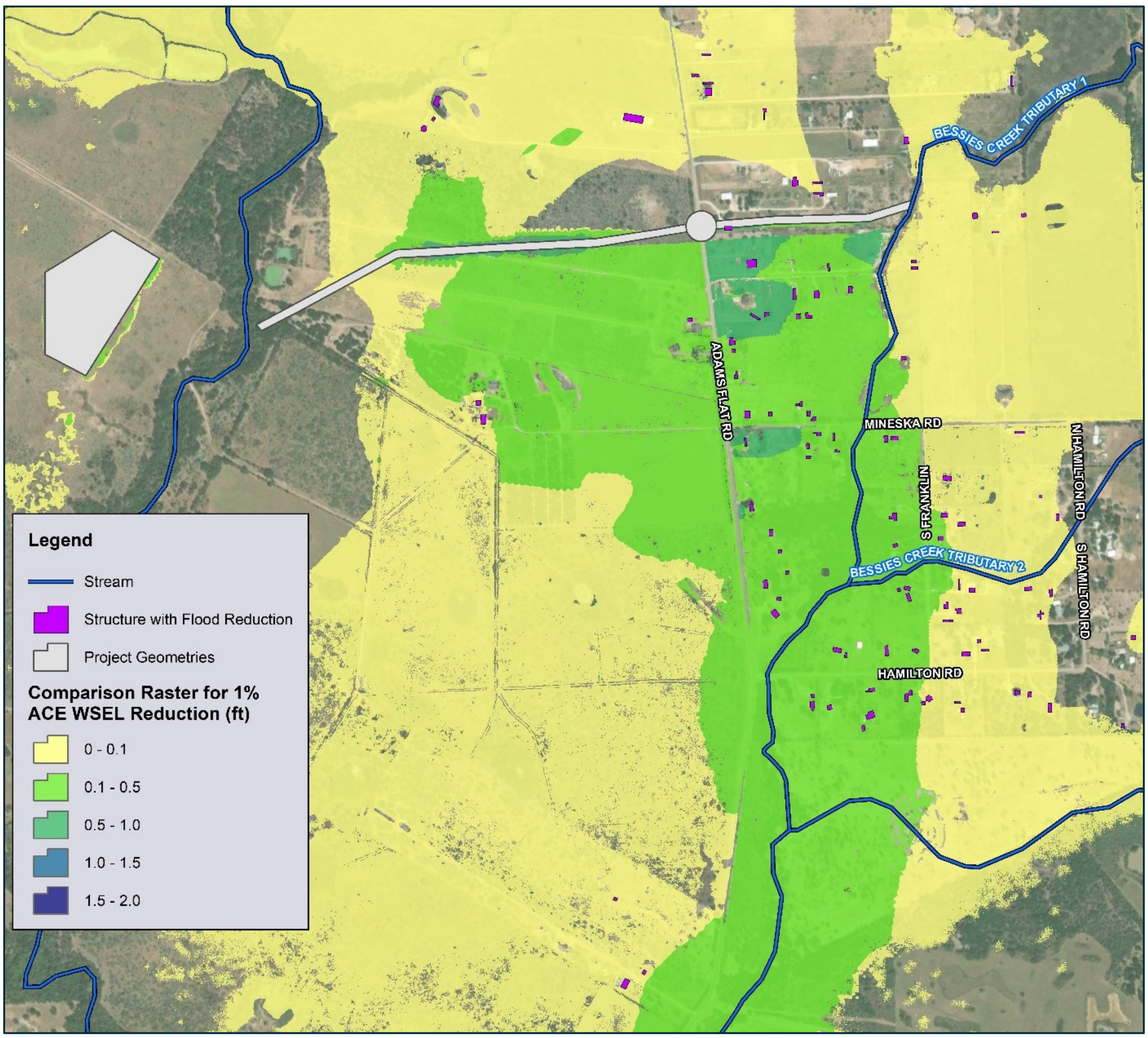


Figure 8-3. West Diversion Channel (FMP 1) Benefits

No negative impact statement

There are no negative impacts shown in the modeling of the proposed project which includes the diversion channel, crossing structures, and detention pond.

Estimate of probable project cost

The proposed project costs are primarily associated with the need for extensive excavation and property acquisition needed for both the diversion channel and detention mitigation. Additional costs associated with the implementation of the crossing structure at Adams Flat Road, as well as final design and contingency costs were also estimated for the project. The estimated probable project cost was determined to be $9.5 million and is summarized in Table 8-4. A detailed cost estimate can be found in Appendix C.

Table 8-4. West Diversion Channel (FMP 1) Costs

Category	Cost
Structural Improvements	$5,136,300
Right-of-Way Acquisition	$1,399,600
Design/Engineering Costs	$2,941,200
Total	**$9,477,100**

Benefit cost analysis

An analysis was performed to determine the benefit cost ratio for FMP 1 using the BCR spreadsheet provided by the TWDB. Structural benefits were calculated using the structure size, structure type, and pre- and post-project conditions flooding depths. Benefits to mobility were also estimated using depths and durations of flooding across effected roadways in pre- and post-project conditions. The BCR for FMP 1, West Diversion Channel, is 1.2. Benefit-cost analysis details can be seen in Appendix D.

8.4.3 East diversion channel (FMP 2)

Similar in concept and purpose to the previously described project, the East Diversion Channel Project (FMP 2) consists of the development of a diversion channel to carry flows draining towards Bessie’s Creek Tributary 2. This diversion channel would travel along the eastern side of the neighborhood, wrapping around the south edge, then release flows back into Bessie’s Creek Tributary 1, south of its confluence with Bessie’s Creek Tributary 2.

Modeling indicated a 1 mile long, 60ft wide, 8ft deep channel would provide adequate capacity to relieve flooding within the neighborhood, while meeting slope constraints caused by the depth of Bessie’s Creek Tributary 1. The project geometries can be seen in Exhibit 13.

Modeling results

This diversion channel would capture a significant portion of the flow inundating the problem area and reroute it to a less developed region. 990 and 290 cubic feet per second is shown to be rerouted around the neighborhood during the 1% and 50% ACE, respectively. Water surface elevations within the neighborhood are lowered by an average of 5 inches for the 1% ACE and 7 inches for the 10% ACE.

Benefits

The diversion channel provides structural benefits to residents in the eastern portion of the Adams Flat Neighborhood, located near Bessie's Creek Tributary. Benefits are primarily seen in frequent storm events such as the 50% And 10% ACE with minor benefits in the larger events. Table 8-5 summarizes the benefits provided by proposed FMP 2. Figure 8-4 and Exhibit 12 show the benefits provided.

Table 8-5. East Diversion Channel (FMP 2) Benefits

Frequency Storm	Structures Benefitted	Structures Removed	Population Benefitted	Roads Benefitted
1% ACE	62	3	65	0
10% ACE	52	3	57	0
50% ACE	41	3	45	0

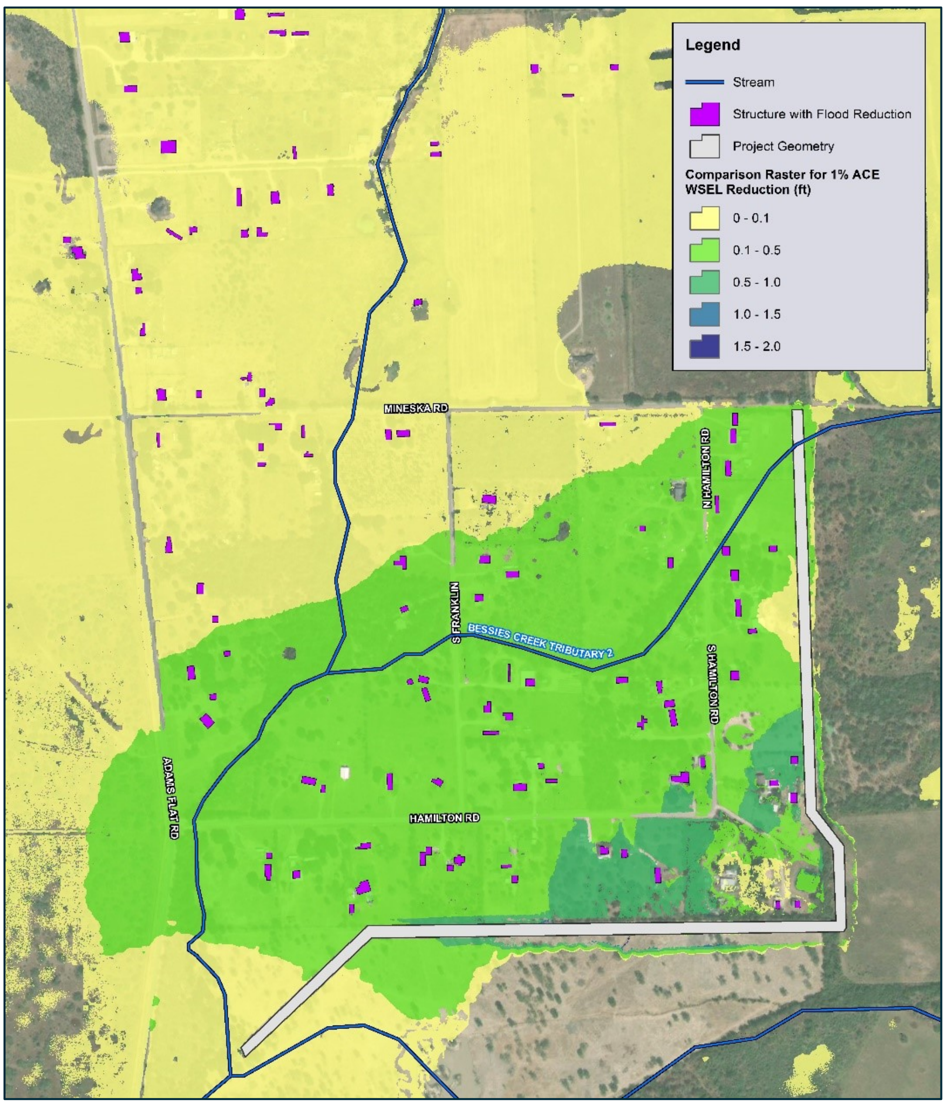


Figure 8-4 East Diversion Channel (FMP 2) Benefits

No negative impact statement

Since the diversion channel disperses into Bessie's Creek Tributary 1, just south of its conjunction with Bessie's Creek Tributary 2, there is no change in flows or water surface within the studied area.

Estimate of probable project cost

The proposed project costs are primarily associated with the need for extensive excavation and property acquisition needed for both the diversion channel and detention mitigation. Additional costs associated with final design and contingency costs were also estimated for the project. The estimated probable project cost was determined to be $3.2 million and is summarized in Table 8-6. A detailed cost estimate can be found in Appendix C.

Table 8-6. East Diversion Channel (FMP 2) Costs

Category	Cost
Structural Improvements	$1,841,400
Right-of-Way Acquisition	$351,600
Design/Engineering Costs	$986,800
Total	**$3,179,800**

Benefit cost analysis

An analysis was performed to determine the benefit cost ratio for FMP 2using the BCR spreadsheet provided by the TWDB. Structural benefits were calculated using the structure size, structure type, and pre- and post-project conditions flooding depths. Benefits to mobility were also estimated using depths and durations of flooding across effected roadways in pre- and post-project conditions. The BCR for FMP 2, East Diversion Channel, is 2.1. Benefit-cost analysis details can be seen in Appendix D.

8.5 Rolling Hills Lake (PA 7)

8.5.1 Existing conditions

The Rolling Hills Lake problem area (PA 7) contains 53 structures preliminary identified as being prone to flooding. The structures in this area are primarily residential, with a few agricultural and commercial structure interspersed. Additionally, Waller County has records of flooding complaints for the neighborhood. This area sits along Gladish Creek and contains Rolling Hills Lake, a neighborhood lake created by a dam directly along the Gladish Creek mainstem. Preliminary analysis of PA 7 indicated that flooding is caused by the lake overtopping and inundating nearby structures. Upstream of the lake, and downstream from the dam, additional structures and roads are inundated by riverine flooding caused by Gladish Creek. Existing conditions can be seen in Figure 8-5.

The first conceptual alternative explored for PA 7 was lowering the lake level. The lake outflow is controlled by a combination of a low flow weir and a high flow spillway that is only activated during severe storm events. By lowering the release elevations for these drainage infrastructure by 2 feet, the lake level was lowered correspondingly. Although this alternative provides substantial flood relief to many of the affected structures and roads, it impacts recreation and neighborhood aesthetics, which would likely not be well received by the community. The drawbacks to the alternative make it unlikely to receive public support.

Selective clearing downstream of the dam was the next conceptual alternative explored for PA 7. The channel overbanks are heavily wooded, constricting flow capacity. Selective clearing modeled the effects of removing brush and trees for areas of the overbanks that convey deep flow. Benefits from this conceptual alternative were found to be localized to properties adjacent to the channel, with no benefits being seen upstream of the dam.

Finally, improvements to the outflow weir and spillway were explored. To avoid lowering the constant elevation of the lake, the outflow structures were expanded into one widened weir at the same elevation as the existing weir. This solution preserves the constant lake elevation, while allowing peak flow events to drain more quickly resulting in less overtopping along the lake perimeter.

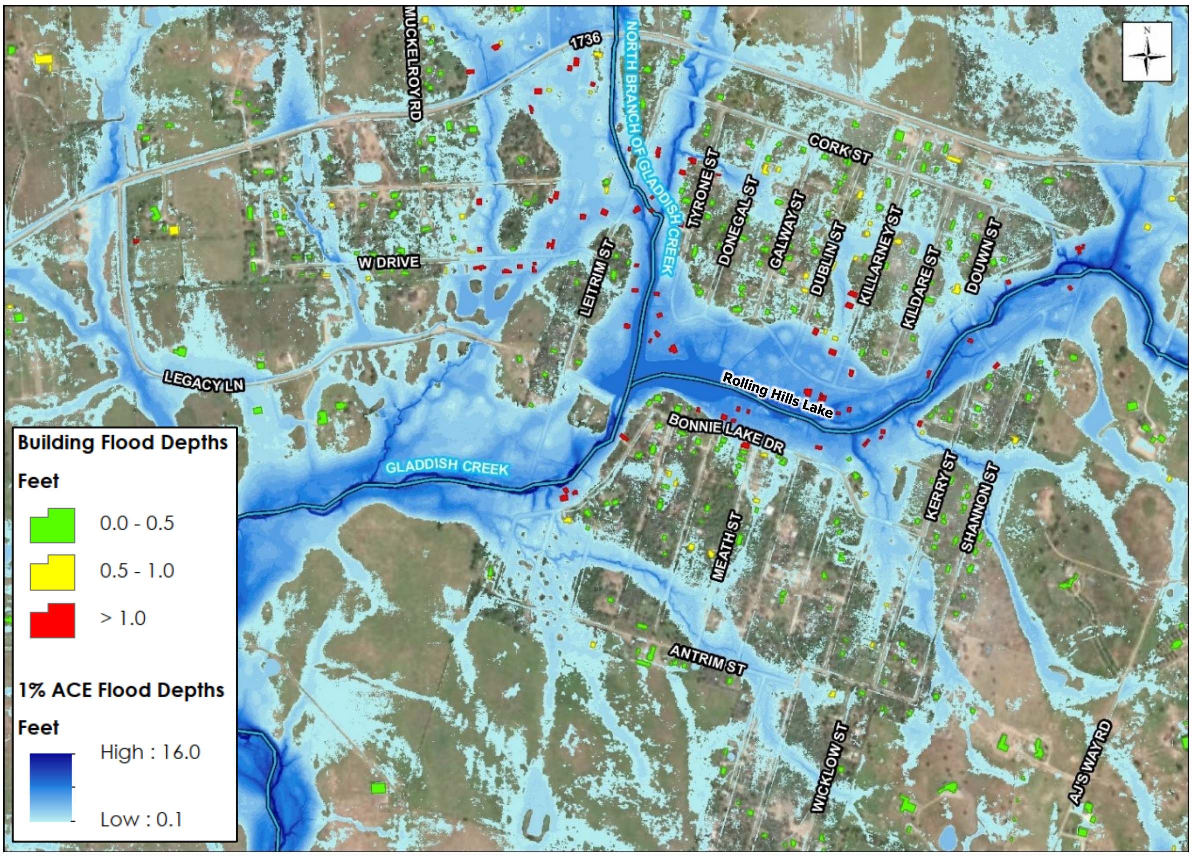


Figure 8-5. Rolling Hills Lake Problem Area (PA 7) Existing Conditions

8.5.2 Gladish weir improvement (FMP 3)

As indicated by preliminary analysis, widening the weir is the most effective alternative for PA 7 that preserves the benefits provided by the current constant lake elevation. Modeling results indicated widening the current weir 70 feet to the west and removing the current median between weirs provided increased capacity to drain the peak flows of severe flood events. The weir was widened as far as possible without requiring property acquisition.

Channel benching downstream of the weir was determined to be required to mitigate the increase in peak flow rates. Widening Gladish Creek by 5 to 6 feet for 900 feet downstream of the weir was found to mitigate the increase in flows and ensure there are no increases in water surface elevation. The project geometries can be seen in Exhibit 9.

Modeling results

The widening of the weir structure allows for an increase in flow rates from the lake of 700 cubic feet per second. For a 1% ACE storm this allows for an additional 200 acre-feet of water to be drained in the 3-hour peak of the storm event.

Benefits

The weir improvements provide structural benefits to residents along the western and southern portions of Rolling Hills Lake, as well as residents just south of the dam. Although benefits can be seen in the 1% ACE, there is still significant inundation during larger frequency events. Benefits are primarily seen in frequent storm events with some benefits in the larger events. Table 8-7 summarizes the benefits provided by FMP 3. Figure 8-6 and Exhibit 12 show the benefits provided.

Table 8-7. Gladish Weir Improvement (FMP 3) Benefits

Frequency Storm	Structures Benefitted	Structures Removed	Population Benefitted	Roads Benefitted
1% ACE	15	1	5	0
10% ACE	2	0	4	0
50% ACE	2	0	4	0

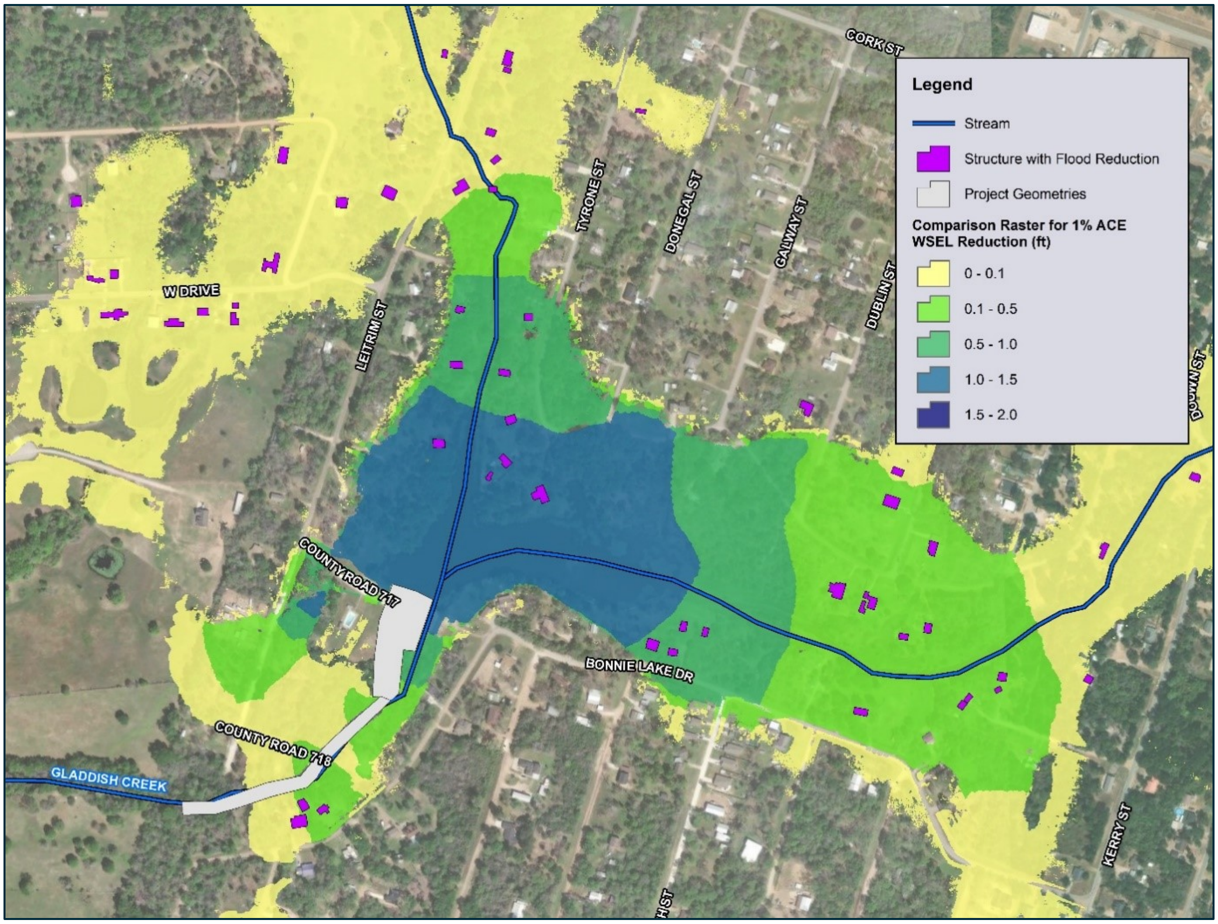


Figure 8-6 Gladish Weir Improvements (FMP 3) Benefits

No negative impact statement

There are no negative impacts shown in the modeling of FMP 3 which includes the weir improvements and channel benching downstream of the dam.

Estimate of probable project cost

The proposed project costs are primarily associated with the regrading and construction of the extended weir. Additional costs associated with excavation, right-of-way access, and final design and contingency costs were also estimated for the project. The estimated probable project cost was determined to be $9.7 million and is summarized in Table 8-8. A detailed cost estimate can be found in Appendix C.

Table 8-8. Gladish Wier Improvement (FMP 3) Costs

Category	Cost
Structural Improvements	$5,372,000
Right-of-Way Acquisition	$1,286,100
Design/Engineering Costs	$2,996,200
Total	**$9,654,300**

Benefit cost analysis

An analysis was performed to determine the benefit cost ratio for FMP 3 using the BCR spreadsheet provided by the TWDB. Structural benefits were calculated using the structure size, structure type, and pre- and post-project conditions flooding depths. Benefits to mobility were also estimated using depths and durations of flooding across effected roadways in pre- and post-project conditions. The BCR for FMP 3, Gladish Weir Improvement, is 0.5. Benefit-cost analysis details can be seen in Appendix D.

8.6 Irons Creek crossings (PA 5)

Diemer Road runs north to south between Irons Creek and the Brazos River south of FM 529. Near the center of the road, erosion of the Brazos River banks and several severe storm events, have contributed to washing out roughly 0.5 miles of the road. Waller County is working to reconstruct the road and reroute it to the east to prevent it from being washed out again. This reconstruction will increase resident mobility during storm events, providing access to multiple roads leading west and away from Brazos River flooding.

However, as discussed by the County, and confirmed by existing conditions modeling, Irons Creek crossings on roads leading west from Diemer Road on both its north and south side are subject to heavy inundation and often become impassible. While the reconstruction of Diemer Road will provide residents with increased north/south mobility, these crossings may still inhibit residents' ability to evacuate towards the east, away from the Brazos River.

Modeling of both crossings was performed to determine the current level of service provided. Results indicated that both crossings are inundated during the 4% ACE event on the Brazos River. Significant overflow from the Brazos River into Irons Creek causes severe flooding of the crossings and adjacent roads and structures. However, due to how widespread this flooding is and the influence of the Brazos River, improving the crossings to provide an increased level of service for Brazos River flooding is not feasible. Instead, improvement efforts were focused on providing increased mobility in an event focused on Iron Creek flows. Using 1D models to analyze the crossings, it was determined that the southern crossing at Garrett Road provides an Irons Creek 1% ACE level of service. However, the northern crossing at Mt Zion road provides less than an Irons Creek 4% ACE level of service. To address this concern, alternative analysis on the bridge capacity was performed.

8.6.1 Existing conditions

The current bridge at the crossing of Mt Zion Road and Irons Creek is about 100 feet wide with the bridge deck being 10 feet above Irons Creek channel elevation. Modeling results show the road to be overtopped by more than 3 feet during the Irons Creek 1% ACE, with some water still on the road during events as frequent at the Irons Creek 4% ACE.

Alternative analysis was performed to determine what improvements would be needed to provide a high level of service at the bridge and decrease mobility restrictions for residents during rainfall events.

8.6.2 Mt Zion bridge improvements (FMP 4)

Since it was determined improving the bridge to convey overflow from the Brazos River would not be practical, the improvements needed to allow Irons Creek flows were modeled. In existing conditions, the Irons Creek 1% ACE not only floods the road at the crossing, but also several hundred feet in either direction from the crossing. To mitigate this, the roadway adjacent to the crossing would have to be elevated along with the crossing. This type of improvement could cause visibility issues when approaching the Mt Zion and Diemer Road intersection. Alternatively, to provide an Irons Creek 2% ACE level of service, only the bridge deck would need to be raised to allow for flow to be conveyed under the road. While small amounts of overflow would potentially still cross adjacent roadway, modeling results showed these depths to be less than 0.5 feet at all locations, which is passible by vehicles. Based on these results, it was determined that the bridge should be expanded to be 300 feet wide and raised by 3 feet. The project geometries can be seen in Exhibit 6.

Modeling results

The improvements to the crossing structure reduce the depth of flooding across the roadway from 3.9 feet to 1 foot for the 1% ACE and from 2.5 feet to 0.25 feet in the 2% ACE.

Benefits

The implementation of proposed FMP 4 would reduce flood risk at the Mt Zion Road and Irons Creek crossing. This crossing is only one of two east to west roads connecting Diemer Road to the eastern portion of Waller County. Although the recommended project does not completely mitigate flooding at the crossing for the 1% ACE, the improvements would allow for greater resident mobility in more frequent storm events and reduce the risk of residents becoming trapped between the Brazos River and Irons Creek. Figure 8-7 and Exhibit 13 show the benefits provided.

Table 8-9. Mt Zion Bridge Improvements Project (FMP 4) Benefits

Frequency Storm	Depth Reduction at Crossing (ft)
1% ACE	2.90
2% ACE	2.25
4% ACE	1.60

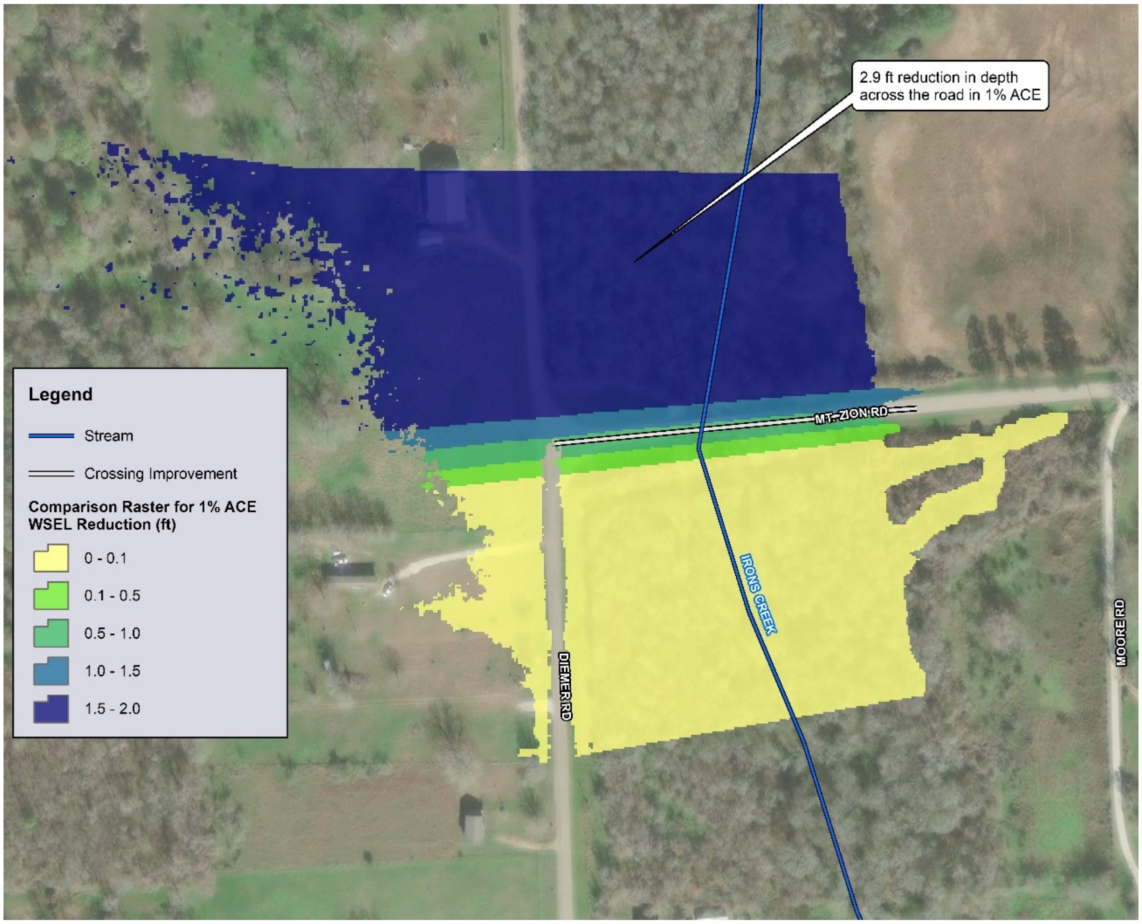


Figure 8-7 Mt Zion Bridge Improvements (FMP 4) Benefits

No negative impact statement

The improvement of the bridge structure does not cause downstream impacts. The increase in bridge width and depth allows for flow to pass under the road, instead of flowing over the road, in severe storm events. However, this does not increase the amount of flow that ultimately moves from the north side of the crossing to the south side. Additionally, the area downstream of the crossing is largely agricultural for several miles, allowing for any minor increases in flow or water surface elevation to dissipate before reaching structures or other roads.

Estimate of probable project cost

The proposed project costs for the removal of the current bridge structure and construction of the improved crossing structure. No right-of way acquisition would be required for the project, contributing to a lower cost estimate than the other alternatives. The cost engineering opinion of probable cost for FMP 4 can be seen in Table 8-10. A detailed cost estimate can be found in Appendix C.

Table 8-10. Mt Zion Bridge Improvements Project (FMP 4) Costs

Category	Cost
Structural Improvements	1,038,700
Design/Engineering Costs	467,400
Total	**1,506,100**

Benefit cost analysis

An analysis was performed to determine the benefit cost ratio for FMP 4 using the BCR spreadsheet provided by the TWDB. Benefits to mobility were estimated using depths and durations of flooding across effected roadways in pre- and post-project conditions. Due to the availability of another route, the mobility benefits calculated using the TWDB tool were found to be extremely low. The BCR for FMP 4, Mt Zion Crossing Improvements, is 0.02. Benefit-cost analysis details can be seen in Appendix D.

8.7 Non-structural

8.7.1 Structural buyouts

Although the recommended alternatives provide flood risk mitigation for structures within the Brazos River watershed in Waller County, they do not actively mitigate flooding caused by the Brazos River itself. Due to its size, existing discharges, and extensive floodplain, mitigating riverine flooding caused by a source as large as the Brazos River is challenging. Water rights, extensive right-of-way acquisition, and potential environmental impacts are just a few of the barriers that make mitigating flood risk from the Brazos River costly and difficult to implement.

One of the most cost-effective approaches to mitigating flood risk for structures that experience frequent flooding from the Brazos River is property buyouts and land preservation. The inundation extent results obtained from existing conditions modeling were used to identify structures buyout costs for each modeled event. FEMA buyout programs could be leveraged to help fund and prioritize the buyout of residential structures, especially those inundated in the more frequent events such as the 10% and 4% ACE. As funding becomes available, buyouts for structures at lower flood risk could be approached.

Although the 50% ACE event was modeled, no structures were found to be within these inundation extents. The presumed cost of acquiring and removing a structure was assumed to be 2.5 times the property's market value. Property acquisition is assumed to have a benefit cost ratio of 1.0 due to the complete removal of flood risk through removing the structure. Table 8-11 below shows the estimated number of buyout candidates as well as the estimated costs.

Table 8-11. Waller County Buyout Candidates

Annual Chance Event	Structure Type	Number of Buyout Candidates	Buyout Cost
20% ACE	Residential	0	$0
	Other	2	$5,353,000
10% ACE	Residential	2	$2,472,000
	Other	16	$56,136,000
4% ACE	Residential	76	$60,065,000
	Other	114	$159,084,000
2% ACE	Residential	169	$164,584,000
	Other	245	$371,929,000
1% ACE	Residential	267	$250,052,000
	Other	356	$526,360,000
0.2% ACE	Residential	402	$356,844,000
	Other	513	$1,000,333,000

8.7.2 Criteria updates

Drainage policy also has a significant impact on mitigating current flood damages and preventing future damages as Waller County continues to develop. Policy considerations for the County were not evaluated using detailed hydrologic and hydraulic modeling like the previous mitigation recommendations; instead, they are more general ideas based on team experience and historical trends indicating the importance of drainage criteria.

The Waller County Drainage Criteria Manual specifies guidance for developers and engineers including discharge rate calculation, minimum detention requirements, and open channel calculations. However, expanding the manual to include items below would provide a more comprehensive approach to minimizing the impacts of development. Updates should include:

- Requiring detention outflow calculations for the 2-year storm event. Many of the outfalls in the County are roadside ditches that have a 2-year capacity. Requiring the detention ponds to include a 2-year outfall would limit the outflows during this event and reduce the impacts on roadside ditches.
- Adopting site runoff curves for calculating discharge rates for areas 100 acres to 640 acres. The manual currently uses the rational method which can be inaccurate for these larger developments.
- Establishing a hydrologic methodology for areas greater than 640 acres. Many jurisdictions in the area have adopted the Basin Development Factor method which would be applicable for Waller County.
- Adopting criteria for pumped detention which occurs frequently due to the limited outfalls throughout the County.
- Adopting general computing software requirements to standardize approaches for channel and detention calculations

- Including requirements for storm sewer design such as calculation requirements, manhole and inlet spacing, and maximum ponding elevations.
- Standardizing drainage report submittals by establishing a typical report outline

8.8 Implementation and phasing

Once implemented, the projects and strategies identified will reduce flood risk within the Brazos River Watershed. Implementation of the structural projects, buyouts, and criteria will occur over time and include both short-term and long-term actions to complete.

In general, the project lifecycle follows the flow path shown in Figure 8-8. The Brazos Flood Update Study completed the planning portion of the project. Short term actions are those than can be implemented over the next few years and will be steppingstones to completing the larger projects. Phase I includes those short-term targets. Longer-term actions will likely take more than five years due to funding, construction time, and project constraints. Phase II includes the longer-term actions.

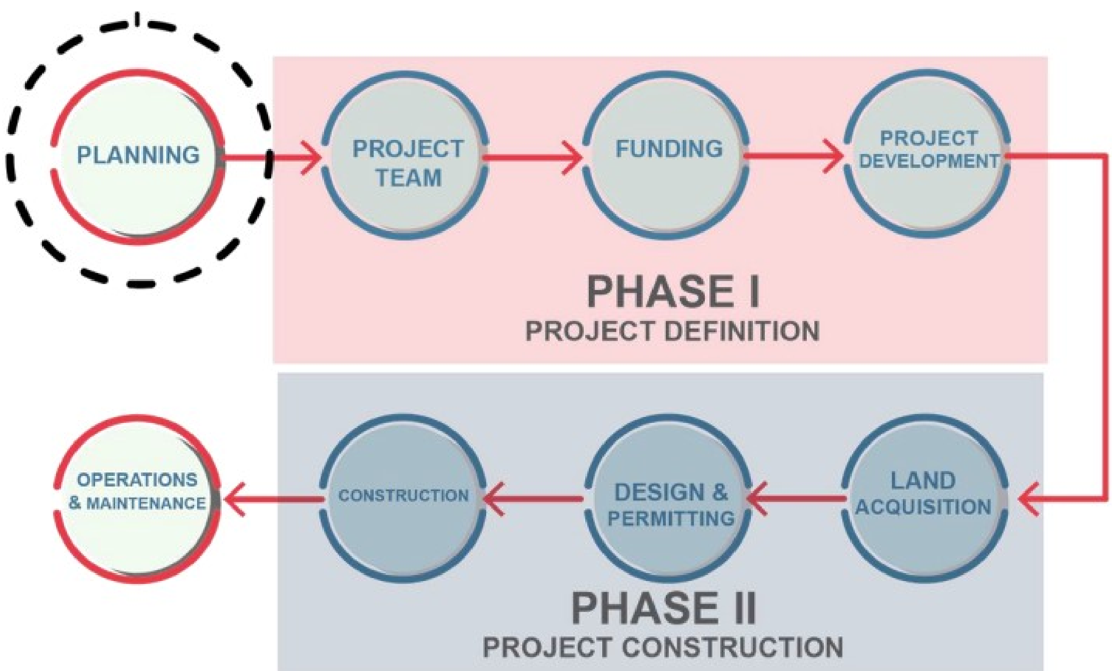
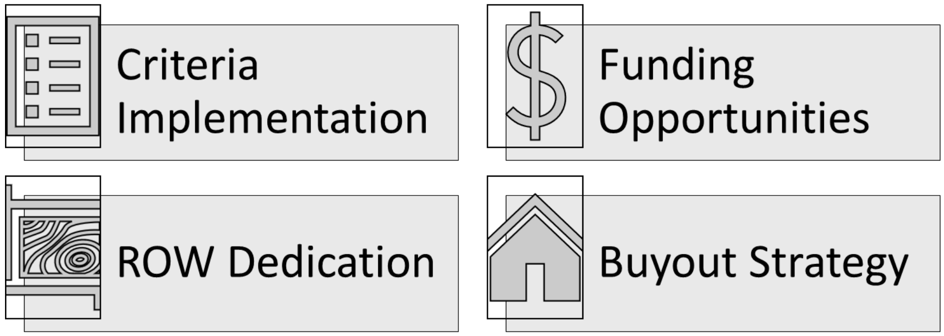


Figure 8-8. Drainage Project Lifecycle

8.8.1 Short term actions

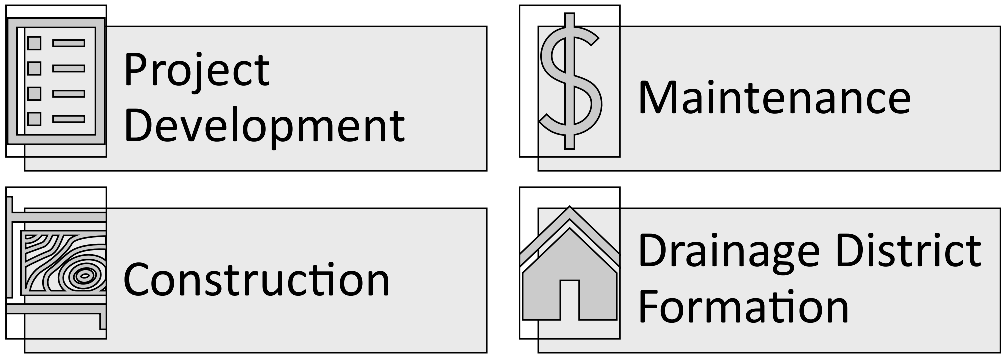
Waller County has limited funding for drainage project implementation and therefore short-term actions are those that can be implemented with limited funding.



- **Criteria Implementation** – Updating drainage and development criteria is one of the most effective was to reduce flood risk within a growing County. An updated criteria would assist in reducing flood risk for future residents as well as mitigate the impacts of development on existing ones. Criteria could be implemented over a two-year budget cycle to reduce yearly costs. Brazoria, Fort Bend, Harris, and Montgomery Counties have recently developed and/or adopted criteria which could be used as a basis for Waller County. There are also multiple funding mechanisms to assist in criteria updates.
- **Right of Way Dedication** – Each of the project identified requires right of way to implement the project. As tracts in these areas begin to develop, the County should require dedication of these areas to the County so that the right of way is available for future use. This could include dedication in fee to the County, dedicated to the public, or as a drainage easement. The County should work with developers and landowners as available.
- **Funding Opportunities** – With the limited available County budget, Waller should continue to investigate other funding strategies for implementation. The TWDB Flood Infrastructure Fund is a first choice due to the current project being FIF funded; however, other funding opportunities exist in both local, state, and federal sources. Some of these are included in Section 7.3.3.
- **Buyout Strategy** – Buyouts within the Brazos River floodplain are the most efficient strategy to reducing flood risk along Texas' longest river. The County should work alongside FEMA to advocate for voluntary buyouts along the river for the repetitive and frequently flooded structures. The County should also investigate land acquisition in these areas to reduce future development within the floodplain.

8.8.2 Long term actions

As the short-term actions are completed, funding and other strategies will become available for the recommended projects. At this point, the long-term actions will commence.



- **Project Development –** Further development and design of the project will be needed before construction. The development will include a preliminary engineering report which will include survey, geotechnical analysis, environmental study, utility coordination and land acquisition. The Design will include the development of engineering drawings and permitting needed to completely implement the project.
- **Construction –** Construction of the weir and channel projects will likely take 12-18 months each. Construction will include mobilization of the project, acquisition of construction easements, and the excavation of the channel or pouring of cement for the weir.
- **Maintenance –** Once constructed, the projects will require regular maintenance to remain functional for their life span. The channel projects will require regular mowing, regular inspections, and repair throughout the project life. The weir will require inspection and maintenance as needed and should be maintained by the HOA that maintains the existing structure.
- **Drainage District Formation –** Identifying a local and consistent funding source would be beneficial to implementing the recommended projects, buyouts, and land purchase. The County should continue explore a drainage district which would provide both a revenue source for implementation of the projects as well as a dedicated entity for maintaining ditches and channels throughout the County.

8.8.3 Funding sources

The potential funding sources of the recommended projects and strategies will depend on the project type and readiness for construction. Funding sources are available from both local, state, and federal entities and each program identified may have differing procurement, administrative, and environmental requirements, impacting the cost and schedule of the projects. The funding sources below should be considered for the projects identified in the Brazos River Watershed.

Federal funding sources

- Community Development Block Grant Disaster Relief (CDBG-DR) - The CDBG-DR is based on response to Federally declared disaster and includes a variety of potential activities, including detention and conveyance improvements. The grant does have an LMI emphasis that may limit the applicability of this source in the watershed. The cost-share is typically 100% Federal to 0% Local. More information is at https://recovery.texas.gov/local-government/resources/overview/index.html.

- Community Development Block Grant Mitigation (CDBG-MIT) - The CDBG-MIT funds are also related to disaster declarations and are a little bit more flexible in that it has a lower threshold for the LMI component, which opens it to more of the watershed than the DR funding. Given the reduced requirement on Low to Moderate Income (LMI), the CDBG-MIT may be a viable funding source for several of the proposed flood mitigation projects in the watershed. As with the -DR funds, the cost-share is 100% Federal to 0% Local. Recommended future watershed protection studies could be partially funded through this grant program. For more information, visit https://recovery.texas.gov/action-plans/mitigation-funding/index.html.

State funding sources

- TWDB Development Fund (DFund) - The Dfund is a State of Texas loan program, that is relatively simple and has minimal red tape. Flood control projects are eligible; however, the fund is primarily loan based.
- TWDB Flood Infrastructure Fund (FIF) - The Flood Infrastructure Fund (FIF) is administered by the TWDB. The FIF allows for loans at or below market rates for a variety of actions, including flood planning, grant application, and engineering for structural and non-structural solutions. In addition, the FIF offers grants that can be used as the local entities matching funds for other federal funding programs. The state is currently allocating additional budget for the fund and will be accepting applications in 2024.

Local funding

- Bonds - Bond funding can be used for flood protection and management. Bonds typically provide project specific financing that requires proposed improvements to be ready for construction and meet the priorities set by the funder. Although repayment terms can offer low or no interest financing, these sources do require full repayment.
- Fees and Ad Valorem Taxes - A development impact mitigation fee is a tax that is imposed as a precondition for the privilege of developing land. Since the proposed projects address existing conditions are not meant for mitigating developing land, imposing a fee on new development to address pre-existing flooding conditions may be difficult to implement. Ad valorem taxes are based on the value of a transaction of a property. Sales taxes or property taxes are ad valorem taxes that could be considered for funding the projects.
- Public Private Partnerships - While there is not an identified stream of funding available for private investment, it may be considered as an option if the opportunity is presented. The watershed includes several different industrial and commercial developments that were significantly damaged in recent flood events and whose owners may be looking for opportunities to reduce flood risk in the area.

8.8.4 State Flood Planning

The projects developed as part of this study have been developed in accordance with the requirements of the Regional and State Flood Planning process to ensure their eligibility for FIF funding. Requirements for inclusion in the State Flood Plan have been set forth by the TWDB, with additional requirements for inclusion in the Regional Flood Plan being set forth by the relevant Regional Flood Planning Group (RFPG). For the area being analyzed within this study, the Lower Brazos RFPG was identified as the encompassing region.

The Lower Brazos RFPG limited the collection of eligible flood mitigation projects (FMPs), flood management evaluations (FMEs), and flood mitigation strategies (FMSs) for inclusion within the first Lower Brazos Regional Flood Plan, to submittals received before March 23, 2023. The projects developed as part of this study were not fully evaluated at this time, and thus, were not able to be brought forth for inclusion within the first cycle of Regional and State Flood Planning. As the second planning cycle initiates in 2024, it is expected that the Lower Brazos RFPG will begin allowing for additional FMPs, FMEs, and FMSs to be submitted for consideration. When this happens, the FMPs and all supporting data developed as part of this plan will be provided to the RFPG for consideration.

9 Flood response plan

The reduction of flood risk through structural and non-structural projects is a critical component to lessen the impacts of severe storm events and preserve the safety of life and property. However, the implementation of these projects can take years to fund, permit, and construct. By improving flood response through planning hazard mitigation actions, communities can lessen the impact of flooding and ensure the safety of residents is preserved.

The focus of this flood response plan is to identify existing flood prone areas, roading crossings, and critical structures and recommend public safety features to warn resident and visitors of flood risk.

9.1 At-risk infrastructure mapping

Using the updated existing conditions modeling developed for the Brazos River through Waller County, at-risk infrastructure for different severities of discharges within the river were identified. Live discharge data and discharge predictions can be accessed via the West Gulf Coast River Forecast Center during major storm events. The corresponding analysis can be referenced to determine what infrastructure may be at risk for the current and predicted storm events. The maps should be used by Waller County to locate potential overtopped roads and impacted structures for various discharge rates.

Exhibits 14 through 20 show the identified at risk infrastructure for each simulated flow condition.

9.1.1 Critical facilities

A database of critical facilities within the watershed was developed to identify if any of these structures may be at flood risk during the simulated conditions. Critical facilities are community assets that provide services vital to community survival such as medical centers or water supply. The following categories were included as critical infrastructure within the database:

- Hospitals
- Fire Stations
- Police Stations
- Government or cultural buildings storing critical records
- Energy-producing facilities
- Water and wastewater treatment plants

The dataset was primarily sourced from open-source GIS libraries associated with Homeland Infrastructure Foundation Level Data and the Texas Education Agency. This data was then supplemented with local knowledge provided by the study team, county staff, and the public. Once complete, the database identified 75 critical facilities within the Brazos River watershed in Waller County.

The critical facilities dataset was intersected with the inundation bounds associated with the different flow conditions at Hempstead to identify potential at-risk structures. Although many critical facilities were collected, only one of these were identified to be at risk from riverine flooding caused by the Brazos River during any of the simulated events. This facility, located near on Diemer Road, just south of Garret Road, is a center for disabled adults. This center provides housing and other support for adults who cannot live unassisted. Current results indicate several of the on-campus housing apartments are flooded in the 1% and 0.2% ACE storms. Additionally, nearby roads are flooded in events as frequent as the 4% ACE, restricting the mobility of the residents that live in identified the critical facility.

9.1.2 Road crossings

A similar analysis was performed for major roadway crossings. The Brazos River crosses 4 public roads within Waller County. Additionally, there are several major thoroughfares within the Brazos River floodplain, that do not directly cross the river. Roadway flooding poses many threats to a community. Cars being swept off roadways during storm events is one of the leading causes of death and injuries due to flooding. Roadways becoming impassible due to flooding can also restrict residents' access to emergency medical care during emergencies.

The identified roadways were evaluated to determine their potential for being overtopped during the different simulated events. Terrain data was used to identify road heights and determine what depths would overtop them, and by how much. During this analysis it was found that none of the bridges overtop in any of the modeled events. However, for several of the crossings the approaching roadway is inundated in some of the modeled events, which would effectively make the crossing impassable. The level of service associated with the crossings and access to the crossings are summarized in Table 9-1.

Table 9-1. Brazos River Crossings Level of Service

Crossing	LOS
US 290	0.2% ACE
FM 159	2% ACE
FM 529	4% ACE
FM 1458	10% ACE
I10	0.2% ACE

9.1.3 Structures

The number of structures potentially at risk for inundation from the Brazos River during different simulated events was analyzed next. To account for the difference between the terrain elevation, and the finished floor elevations of structures, a 6-inch adjustment was made to the depths at the structures. Some structures, especially mobile homes and stilted structures may have finished floor elevations even higher than 6-inches above the ground. However, the flooding depths may still inhibit residents' ability to leave during a flooding event or otherwise damage possessions adjacent to the structures, so the adjustment was applied uniformly.

The number and types of structures identified as prone to flooding during the different simulated events are summarized in Table 9-2.

Table 9-2. Structures At-Risk

Flow at Hempstead (cfs)	Residential Structures At-Risk	Other Structures At-Risk
54,000	0	0
80,000	0	2
99,000	2	16
122,000	76	114
143,000	169	245
161,000	267	356
196,000	402	513

9.2 Public safety features

Being able to notify the public of imminent flood risk is extremely important during storm events. By having infrastructure in place to help County officials to assess flood risk and communicate that to residents, the risk of loss of life due to the hazards associated with flooding can be decreased. Informational infrastructure such as gages and flood warning signs and systems can provide live flood data to County officials to assist them in making the best flood response decisions. Systems such as emergency notifications, sirens, and public facing websites with live flood risk information can ensure that County officials can inform residents of their flood response decisions in a timely manner.

9.2.1 Flood warning

The primary focus of flood warning infrastructure is to transmit live rainfall, lake, stream, or river data for use by public and government officials to make informed flood response decisions. The information collected by gages can also be used to develop post-flood reports and perform engineering analysis to determine the probability flooding events at gaged locations.

Flood warning infrastructure is primarily based on the information provided by gages. Gages can record and transmit river or stream water surface elevations, flows, and/or precipitation data. These gages can be linked together through a flood warning system to provide comprehensive coverage for an entity, or part of regional systems that provide coverage throughout the United States.

Gages

The USGS gage system provides lake, riverine, and precipitation data coverage nationwide. Due to its easily accessible public interface, this system is often leveraged by entities for live flood risk information used to inform flood response actions. In Waller County, there are currently two USGS gages along the Brazos River in Waller County. As discussed previously in this report, the Hempstead gage in the northern portion of the County was used heavily for historical calibration and the development of the design storms. Similarly, the Brazos River gage at San Felipe provides valuable historical information that can be leveraged for the development of flood studies, as well as live flood risk data.

Additional gages along other streams, creeks, and rivers that cause significant flooding in the County could help supplement this data and provide more complete flood risk coverage in the event of severe weather. Three potential gage locations in Waller County were identified in the

Lower Brazos Regional Flood Plan. These locations are along critical creeks that contribute to flooding within the County and cross major thoroughfares important for resident mobility during storm events. Table 9-3 and Figure 9-1 summarize these locations. Further analysis would be needed to evaluate the locations for constructability and maintenance access.

The addition of these gages, or others throughout the County, could increase the available live flood-risk data County officials could leverage during storm events. If incorporated into the USGS system, these gages would likely be leveraged by the National Weather Service (NWS) as part of their National Water Model. This tool simulates and forecasts how water moves throughout streams and rivers across the nation by utilizing real time data points as simulation checkpoints. The results of this analysis are available to the public in the form of short (18-hour), medium (10-day), and long (30-day) range flow forecasts that show the projected extents of flooding along streams. Areas with higher concentrations of gages to be leveraged within this system, are likely to have more accurate predictive and mapping information available.

USGS maintained stream flow gages require regular maintenance for updating the stage-flow rating curves. Gage installation costs approximately $30,000 per gage with roughly $160,00 yearly maintenance. Partnerships between the USGS and state, local, non-profit, and private entities is common to spread the costs across multiple agencies.

Table 9-3. Potential Gage Locations in Waller County

Gage Location	Critical Features
I10 and Bessie’s Creek	Along TxDOT evacuation route. Thousands of nearby at-risk structures. Shares flow with Brazos River.
FM 1887 and Irons Creek	Hundreds of nearby at-risk structures. Downstream of confluence of three creeks central to County. Shares flow with Brazos River.
US 290 and Clear Creek	Along TxDOT evacuation route. Local to several at-risk major road crossings.

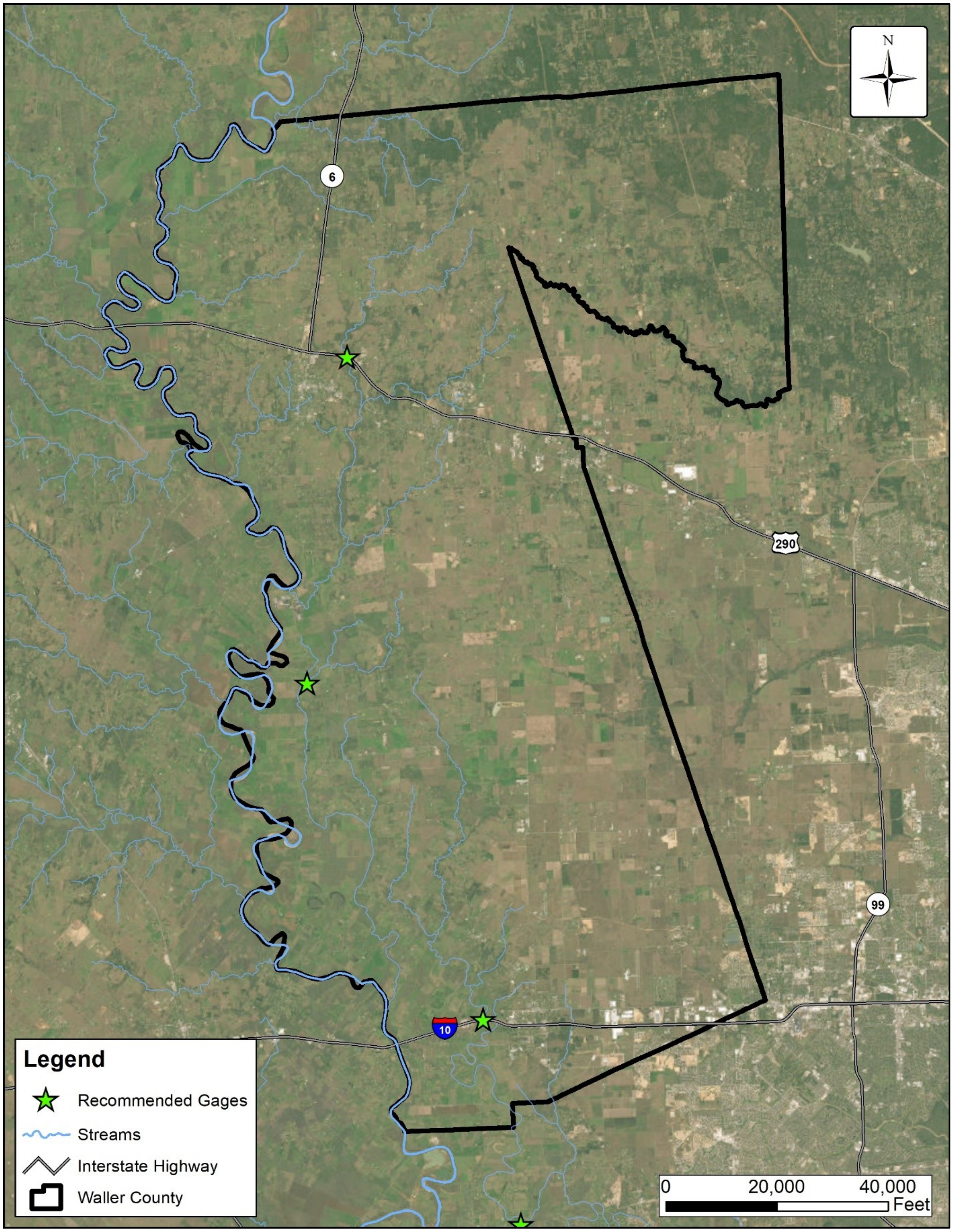


Figure 9-1. Recommended Gauges

10 Conclusion

The Brazos River Flood Update Study, sponsored by Waller County and funded through the TWDB's FIF program, focused on a detailed evaluation of existing flood risk within the County and the development of structural and non-structural mitigation solutions to address this risk.

Existing conditions data was developed by updating modeling previously completed for the Brazos River watershed. A new 2D hydraulic model covering the Navasota River, Yegua Creek, and the Brazos River between Bryan/College Station and Hempstead, Texas, was developed to better characterize the flow patterns coming in to Waller County. The existing HEC-HMS model, covering the entirety of the Lower Brazos basin, was updated to include hydrology focused and centered on the Brazos River gage in Hempstead. These flows were then routed through both the newly developed 2D HEC-RAS model and the 1D/2D HEC-RAS model previously developed for the lower half of the Lower Brazos basin to generate existing conditions flood risk modeling and mapping for Waller County.

Using the updated depth and flow information, flood risk was evaluated for the portion of Waller County within the Brazos River floodplain. At-risk structures, crossings, and critical facilities were identified for several flow conditions at the Hempstead Brazos River gage for the County to use in flood response and preparation. Exhibits 14 through 20 show the estimated inundation extents for each of the modeled flow conditions.

After analyzing existing flood risk within the County, problem areas with particularly high flood risk were identified. Historical claims data, County official identification, and flood risk data were used to initially identify 11 problem areas. These areas were then vetted for flood risk source, proposed or ongoing projects, and viability for structural mitigation. Three problem areas were selected for additional study:

1. Rolling Hills Lake (PA 7)
2. Adams Flat Road (PA 3)
3. Irons Creek Crossings (PA 5)

Detailed models were built for the three selected problem areas to perform alternative analysis. Projects were developed to be feasible for both funding and construction; however, as the projects are fully vetted in design, construction and permitting needs will need to be revisited. The recommended projects developed for these selected problem areas are summarized in Table 10-1.

Table 10-1 Summary of Recommended Projects (FMPs)

Project		Brief Description	Summary of Benefits	Estimated Costs	BCR
FMP 1	West Diversion Channel	Construction of a channel to divert flows around neighborhood with significant flood risk.	Flood risk reduction to 67 structures in 1% ACE.	$9,500,000	1.2
FMP 2	East Diversion Channel	Construction of a channel to divert flows around neighborhood with significant flood risk.	Flood risk reduction to 62 structures in 1% ACE.	$3,200,000	2.1
FMP 3	Weir Improvements	Widening of existing weir to allow Rolling Hills Lake to drain more quickly during flood events.	Flood risk reduction to 15 structures in 1% ACE.	$9,700,000	0.5
FMP 4	Irons Creek Crossing	Improvements to crossing at Mt Zion Rd and Irons Creek to convey 2% ACE.	1 ft reduction in depth across roadway in 2% ACE.	$1,500,000	0.0*

In addition to the structural projects recommended for the identified problem areas, non-structural mitigation approaches for the County were analyzed and recommended. Property buyouts, implementation of additional flood warning infrastructure, and updates to drainage criteria would allow the County to mitigate and prevent flood risk within the Brazos River floodplain.

The results of this study, including the flood risk modeling and mapping, are available to Waller County to provide them with a database of current flood risk within their communities and provide context and guidance to inform decisions regarding the mitigation of flood risk. The recommended flood mitigation solutions, both structural and non-structural, were developed to assist Waller County with the reduction of flood risk.

Immediate actions can be taken to begin the process of implementing the recommendations outlined within this study. While searching for and applying to funding opportunities to support the implementation of the recommended flood risk mitigation projects, short-term actions such as the initiation of a voluntary buyout program and the development of criteria updates can help ensure flood risk does not increase in the future.