# Trinity River Authority

# Trinity River Mid-Basin Flood Infrastructure Funding Grant Study

Flood Infrastructure Fund Category 1 Project

Project ID #40010

Prepared by Halff Associates, Inc. for the Texas Water Development Board

# Acknowledgments and/or seal page

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They were prepared by, or under the supervision of:

STATE OF TEXAS
BRIAN W. DOWNING
133682
LICENSED
PROFESSIONAL ENGINEER

TBPELS
Firm #312

5/7/2024

Brian Downing, PE, CFM
Water Resources Team Leader
Halff Associates, Inc.

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# Acronyms

| | |
|---|---|
| 1-D | One Dimensional |
| ACE | Annual Chance Exceedance |
| AHPA | Archaeological and Historical Preservation Act of 1974 |
| ARPA | Archaeological Resources Protection Act of 1979 |
| A.U. | Assessment Unit |
| BFE | Base Flood Elevation |
| BCA | Benefit Cost Analysis |
| CDC | Corridor Development Certificate |
| CFS | Cubic Feet Per Second |
| CoCoRaHS | Community Collaborative Rain, Hail, and Snow Network |
| DFW | Dallas/Fort Worth |
| DFIRM | Digital Flood Insurance Rate Maps |
| ECOS | Environmental Conservation Online System |
| EHA | Espey, Huston, & Associates |
| EMST | Ecological Mapping System of Texas |
| EOR | Element Occurrence Record |
| EIS | Environmental Impact Statement |
| EPA | U.S. Environmental Protection Agency |
| ESA | Endangered Species Act |
| FAC | Facultative |
| FACU | Facultative Upland |
| FACW | Facultative Wetland |
| FDA | Flood Damage Reduction Analysis |
| FEMA | Federal Emergency Management Agency |
| FIF | Flood Infrastructure Funding |
| FIRM | Flood Insurance Rate Map |
| FIS | Flood Insurance Study |

| | |
|---|---|
| FPPA | Federal Farmland Protection Policy Act |
| GCD | Groundwater Conservation Districts |
| GIS | Geographic Information System |
| GMA | Groundwater Management Area |
| GPS | Global Positioning System |
| HEC | Hydrologic Engineering Center |
| HMA | Hazard Mitigation Assistance |
| HMAC | Hot Mix Asphalt Concrete |
| HMS | Hydrologic Modeling System |
| HMGP | Hazard Mitigation Grant Program |
| HWP | High Wetland Potential |
| IPaC | Information for Planning and Consultation |
| LESA | Land Evaluation and Site Assessment |
| LID | Levee Improvement District |
| LiDAR | Light Detection and Ranging Data |
| LWP | Low Wetland Potential |
| MWP | Moderate Wetland Potential |
| NAD83 | National American Datum of 1983 |
| NAVD88 | National American Vertical Datum of 1988 |
| NED | National Elevation Datasets |
| NEPA | National Environmental Policy Act |
| NHD | National Hydrography Dataset |
| NPS | National Park Service |
| NRCS | Natural Resources Conservation Service |
| NRHP | National Register of Historic Places |
| NWI | National Wetlands Inventory |
| NWS | National Weather Service |
| NWP | Nationwide Permit |
| OBL | Obligate |
| R.A. | River Authorities |

| | |
|---|---|
| RHA | Rivers and Harbors Act of 1899 |
| RAS | River Analysis System |
| ROW | Right-Of-Way |
| RWPA | Regional Water Planning Areas |
| SDR | Submitted Drillers Report |
| SGCN | Species of Greatest Conservation Need |
| SHPO | State Historic Preservation Office |
| SLD | Special Law Districts |
| SWCD | Soil and Water Conservation District |
| TASA | Texas Archaeological Sites Atlas |
| TCEQ | Texas Commission on Environmental Quality |
| THC | Texas Historical Commission |
| TNRC | Texas Natural Resources Code |
| TNRIS | Texas Natural Resources Information System |
| TPWD | Texas Parks and Wildlife Department |
| TSSWCB | Texas State Soil and Water Conservation Board |
| TWDB | Texas Water Development Board |
| TxDOT | Texas Department of Transportation |
| TXNDD | Texas Natural Diversity Database |
| TXRRC | Texas Railroad Commission |
| UPL | Upland |
| USACE | U.S. Army Corps of Engineers |
| USDA | U.S. Department of Agriculture |
| USFWS | U.S. Fish & Wildlife Service |
| USGS | U.S. Geologic Survey |

# 1 Executive summary

Communities within the Trinity River Mid-Basin have experienced significant floods over the last 40 years. The Trinity River Mid-Basin Flood Infrastructure Funding (FIF) Grant Study ("Trinity River Mid-Basin Study") is a comprehensive drainage plan for an approximately 3,200 square mile watershed in Central Texas. This Trinity River Mid-Basin Study will identify flood risks and options for flood risk mitigation. The Trinity River Mid-Basin is an integrated system in which the entire basin must be considered, including the interaction of reservoirs, overflows, diversions, bridges, etc., to accurately assess flood impacts and the complex interaction of these elements. The Trinity River Authority of Texas (Authority) obtained a Texas Water Development Board (TWDB) FIF Grant for the Trinity River Mid-Basin Study. Category 1 studies are focused on identifying flooding issues, developing conceptual solutions to flooding issues, and estimating the benefits and costs of these potential solutions.

The study leveraged the existing InFRM Trinity River Watershed Hydrologic Assessment (WHA) hydrologic model to develop a basin-wide calibrated hydrologic model of the area. The Trinity River Mid-Basin area encompasses all or portions of Anderson, Freestone, Grimes, Houston, Leon, Madison, Polk, San Jacinto, Trinity, and Walker Counties. The updated hydrologic model was validated with three historical events (June-July 2007, May-June 2015, and October-November 2015) at USGS Gage 08065350 (Trinity River Near Crockett, Texas). The frequency storms modeled are the 10%, 4%, 2%, 1%, and 0.2% ACE events.

Detailed 1D unsteady hydraulic models were prepared to produce water surface elevations for the Trinity River, Gail Creek, Hurricane Bayou, Spring Creek 1, Spring Creek 2, Tantabogue Creek, and White Rock Creek. The Trinity River analysis extends from near the tripoint of Anderson, Houston and Leon Counties downstream to US-190 along the Polk and San Jacinto Counties shared boundary. The hydraulic modeling was used to establish floodplain extents and identify areas that could benefit from flood mitigation.

Several conceptual flood reduction alternatives were identified, including a levee along the Trinity River mainstem, a levee along both banks of Spring Creek 2, channelization of Spring Creek 2, large-scale regional detention, distributed regional detention, and flood warning service. The conceptual flood mitigation alternatives in this report are presented as projects that local sponsors may consider and evaluate further to help reduce flood risk. As such, the conceptual flood mitigation alternatives presented do not reflect the position of the Trinity River Authority or study partners as to whether these alternatives should be implemented or how they should be prioritized.

A Benefit-Cost Analysis (BCA) was performed for the flood mitigation alternatives. The minimum criteria for state and federal funding is a Benefit-Cost Ratio (BCR) of 1.0 or greater, meaning that the benefit(s) of the proposed project would equal or exceed the cost of the project. The calculated BCR for each flood mitigation alternative is approximately 0.01.

The flood mitigation alternatives developed for the Trinity River Mid-Basin Watershed Study are high-level feasibility studies. The alternatives, damages, and costs were analyzed at a preliminary level. Any results from this study, including post-project flood risk and estimated project costs, must be refined if selected for further evaluation. A no negative impact analysis will be required in order to meet criteria to classify the alternative as a flood mitigation project.

Based on local feedback, the losses due to flooding are primarily crops and cattle. Landowners could benefit greatly through the implementation of a flood warning system. The flood warning system could alert landowners before flooding, allowing them to move cattle, harvest crops, or implement emergency flood protection measures before flood waters inundate their land. The modeling provided with this study provides timing, severity of inundation, and length of inundation for multiple events and can be used as a basis for designing a flood warning system. Additional streamflow gages along the major tributaries, Upper and Lower Keechi, Boggy Creek, and Bedias Creek, would help strengthen the flood warning system and future modeling within the area. A flood warning system would need to be analyzed further to be implemented. However, no structural flood mitigation alternative is recommended based on the findings of this study. See Table 1-1 below for a summary of recommended alternatives and Table 1-2 for a table of alternatives that were analyzed but are not being recommended.

**Table 1-1 Recommended Alternatives Summary**

| Alternative | Description | Recommended for Consideration | Flood Mitigation Type | Cost |
|---|---|---|---|---|
| Flood Warning System | Warn residents downstream of SH 7 of incoming flood wave | Yes | FMS | - |

**Table 1-2 Not Recommended Alternatives Summary**

| Alternative | Description | Recommended for Consideration | Cost | Reason for not Recommending |
|---|---|---|---|---|
| Trinity River Levee | Levee located on the western bank of the Trinity River mainstem | No | \$1,500,000,000 to \$2,500,000,000 | Substantial adverse impacts |
| Spring Creek 2 Levee | Levees located along both banks of Spring Creek 2 | No | \$500,000,000 to \$1,000,000,000 | Substantial adverse impacts |
| Spring Creek 2 Channelization | Widening of the Spring Creek 2 channel | No | \$250,000,000 to \$750,000,000 | Substantial adverse impacts |
| Large-Scale Detention | Inline Dam on the Trinity River mainstem with inline dry retention basin | No | \$15,000,000,000 to \$20,000,000,000 | Substantial adverse impacts |
| Distributed Regional Detention | Dams placed on tributaries along Hurricane Bayou | No | \$100,000,000 to \$400,000,000 | Substantial adverse impacts |

The Region 3 Trinity Regional Flood Planning Group (RFPG) established a deadline of January 27, 2023, for all potentially feasible flood mitigation actions to be submitted for consideration of potential inclusion in the Amended Regional Flood Plan. The alternatives in the Mid-Basin study were being developed at that time. The RFPG deadline did not algin with the Mid-Basin schedule. The flood warning system is recommended to be submitted to the RFPG as a flood mitigation strategy for potential inclusion in the next planning cycle.

# 2 Introduction and background

The Trinity River Mid-Basin Flood Infrastructure Funding Grant Study ("Trinity River Mid-Basin Study") is a comprehensive drainage plan for an approximately 3,200 square mile watershed in Central Texas. The Trinity River Mid-Basin area encompasses all or portions of Anderson, Freestone, Grimes, Houston, Leon, Madison, Polk, San Jacinto, Trinity, and Walker Counties. The Trinity River Authority (Authority) obtained a Texas Water Development Board (TWDB) Flood Infrastructure Funding (FIF) Grant (Project ID 40010) for the development of Phase 2 of the Trinity River Mid-Basin Study. Category 1 studies are focused on determining and describing problems related to flooding, developing solutions to flooding problems, and estimating the benefits and costs of these solutions.

The study leveraged the existing InFRM Trinity River WHA hydrologic model to develop a basin-wide calibrated hydrologic model of the area. Detailed 1D unsteady hydraulic models were prepared for the Trinity River, Gail Creek, Hurricane Bayou, Spring Creek 1, Spring Creek 2, Tantabogue Creek, and White Rock Creek. The Trinity River hydraulic model extends from near the tripoint of Anderson, Houston and Leon Counties downstream to US-190 along the Polk and San Jacinto Counties shared boundary. These models, along with socioeconomic and environmental data, were used to analyze the feasibility of flood reduction alternatives. Flood inundation maps that can be used for development planning and regulation were prepared as part of the study.

See Figure 2-1 for an overview of the study area.

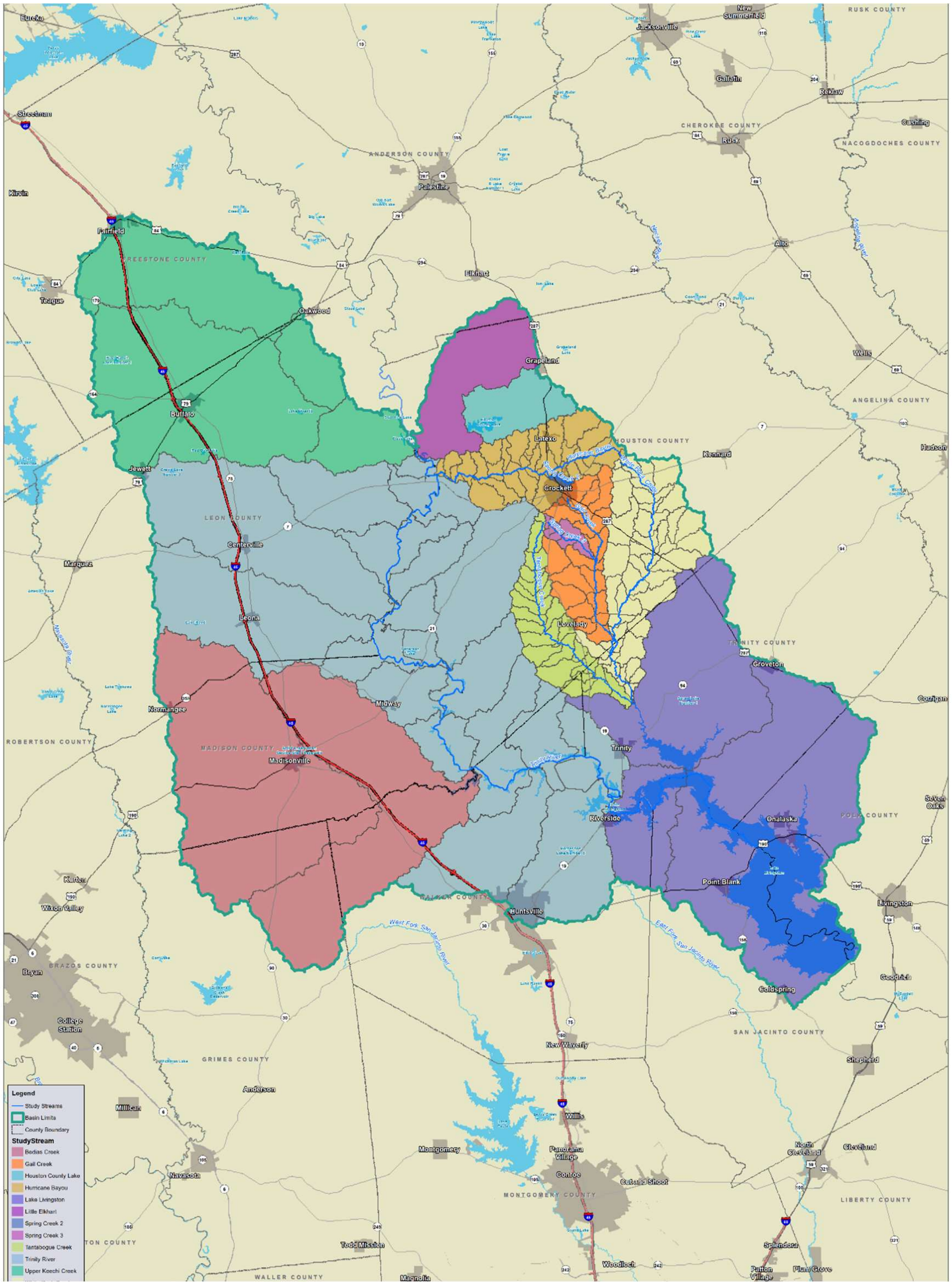


*Figure 2-1 Hydrologic Study Area*

## 2.1 Project need

Communities within the Trinity River Mid-Basin have experienced significant floods over the last 40 years. Eight floods occurred within 13 months, from 2015 to 2016, flooding lowland areas, ranch land, and roadways. In 2019, long-lasting flooding occurred over a duration of two months, causing damage to the agricultural industry within the area. Flooding within the region is complex and there is no recent comprehensive flood study of the area to understand the flood risks and options for flood risk mitigation. The Trinity River Mid-Basin is an integrated system in which the entire basin must be considered, including the interaction of reservoirs, overflows, diversions, bridges, etc., to accurately assess flood impacts and the complex interaction of these elements. A basin-wide floodplain protection planning study was necessary to determine the overall existing flood hazards more accurately and to identify conceptual flood reduction alternatives.

The information from this study can be used to improve the Flood Early Warning System capabilities of the National Weather Service (NWS) and emergency management officials. Emergency management officials can benefit from the updated information to determine the level of service at bridge crossings, as well as provide flood warnings for the surrounding areas.

## 2.2 Project area history

Studies of the Trinity River Mid-Basin have been completed in past years. Documents and modeling were obtained from the Fort Worth District Corps of Engineers (USACE), the Federal Emergency Management Agency (FEMA), the Texas Department of Transportation (TxDOT) and other agencies. These documents and models were reviewed for this study.

### *2.2.1 FEMA base level engineering (2020, 2021)*

FEMA Region VI contracted Compass to complete 1-Dimensional Base Level Engineering (BLE) analyses for the Lower Trinity -Kickapoo (LTK) and Lower Trinity-Tehuacana (LTT) HUC-08 watersheds in Central Texas to support FEMA’s discovery process. LTK and LTT BLEs were completed in 2020 and 2021, respectively. Hydraulic models were developed using automated processes to approximate the 10-, 25-, 50-, 100-, and 500-year annual chance event flowrates and floodplains for all rivers and streams within the watersheds.

### *2.2.2 Interagency Flood Risk Management (InFRM) (2021)*

In 2021, InFRM, a federal partnership comprised of FEMA, USACE, the U.S. Geological Survey (USGS), and the National Weather Service (NWS), which serves under the National Oceanic and Atmospheric Administration (NOAA), performed a Watershed Hydrology Assessment for the Trinity River. InFRM used statistical hydrology, rainfall-runoff modeling, and reservoir period-of-record simulations within the Trinity River Watershed.

### *2.2.3 Current effective FEMA studies*

There are no current effective FEMA studies along the Trinity River or the study streams within the project area. See Section 2.3.1 for the FEMA BLE discussion.

# 3 Data collection

Data collection refers to the process of requesting, organizing, and reviewing information necessary to complete existing flood hazard assessment conditions and develop and prioritize mitigation alternatives. The data collection task includes desktop reviews of flood risk assessments complemented with field reconnaissance efforts. Collected data types include terrain, land use, structures, precipitation, existing models, previous studies, flooding complaints, field reconnaissance, and field survey. All obtained data was compiled and reviewed to extract relevant information for the study. All data collected as part of this study can be found in **Appendix A**.

## 3.1 General data collection

Data collection began at project kickoff and continued throughout the project. Data was collected from multiple sources including: RFPG, USGS, USACE, Trinity River Authority, TWDB, field survey, and local stakeholders.

### *3.1.1 USGS gauges*

To support model calibration, historical rainfall, flow data, and water surface elevation data were obtained from the USGS website (maps.waterdata.usgs.gov). There are six USGS gages located along the studied streams. Of these six gages, only two gages could be used to calibrate the Trinity River mainstem model: USGS Gage 08065350 (Trinity River near Crockett, Texas) and 08066000 (Trinity River at Riverside, Texas). The USGS Gage 08066000 (Trinity River at Riverside, Texas) has no discharge data after 1968, so the hydraulic model was only calibrated to stage data at this gage. All three USGS gages located along the studied tributaries [08065340 (Hurricane Bayou at US-287 near Crockett, Texas), 08066087 (Gail Creek at FM 1280 near Lovelady, Texas), and 08066138 (Tantabogue Creek at FM 230 near Lovelady, Texas)] did not start recording data until August 2021. USGS Gage 08065500 (Trinity River near Midway, Texas), located on the Trinity mainstem, stopped recording data in 1970. The locations of the gages collected for this study are shown in Figure 3-1.


*Figure 3-1 Gage Locations in Study Area*

### *3.1.2 TxDOT and UPRR as-built bridge plans*

TxDOT and Union Pacific Railroad (UPRR) as-built bridge plans were collected for five bridge crossings throughout the Trinity River Mid-Basin. All TxDOT bridges were within the Lufkin District. Exhibit A-2 in Appendix A shows the locations of the TxDOT bridge crossings in the Trinity River Mid-Basin.

Table 3-1 presents the as-built bridge plans collected for the study. The bridge data were used in the development of the hydraulic models for this study.

**Table 3-1 As-Built Bridge Plans.**

| TxDOT District/Railroad | Name | County | River |
|---|---|---|---|
| Lufkin | FM 1280 | Houston | White Rock Creek |
| Lufkin | SH 7 | Houston/Leon | Trinity River |
| Lufkin | SH 19 | Trinity/Walker | Trinity River |
| Lufkin | US 287 | Freestone/Anderson | Trinity River |

### *3.1.3 Flood data*

Flood data was provided by the University of Texas and included georeferenced and time-stamped flood photos. Figure 3-2 shows a satellite photo taken on November 26, 2018. The flood data provided was used to assist in the calibration of the hydraulic models. The flood data used for this study is included in the digital submittal in Appendix G.

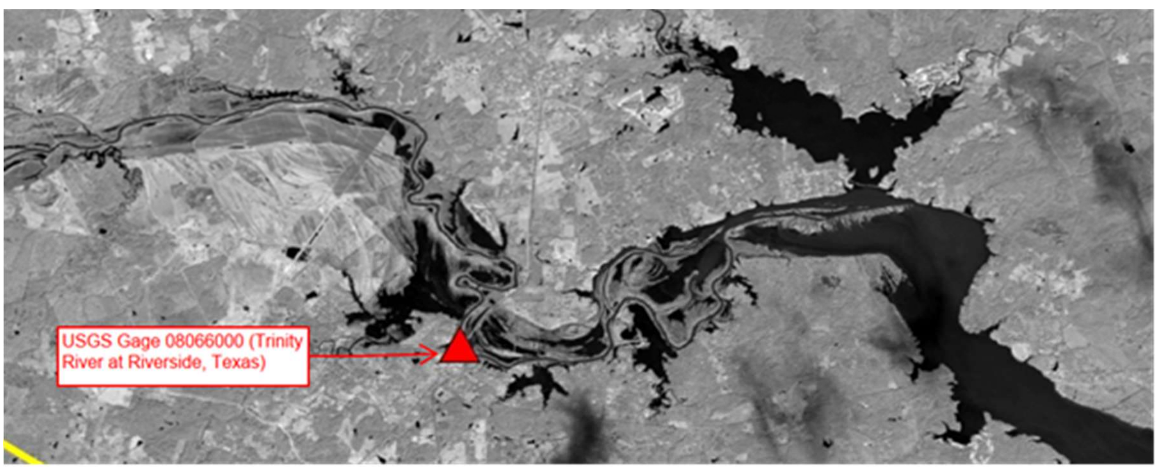


*Figure 3-2 Flooding Photo on the Trinity River on November 26, 2018*

## 3.2 Terrain

Halff acquired lidar data sets for the studied portion of the Trinity River Mid-Basin watershed. Halff also acquired bathymetry for Lake Livingston and the Trinity River from TWDB and The Authority, respectively. The LiDAR data sets and bathymetry were obtained from the following eight data sources:

- 2016 FEMA REGION 6 TX – Neches Basin QL2 LiDAR

- 2017 FEMA Region 6 TX – Red River QL2 LiDAR
- 2017 TNRIS LiDAR - East Texas
- 2018 NRCS Texas – Eastern Texas LiDAR
- 2018 TNRIS LiDAR – Upper Coastal LiDAR
- 2019 TWDB Bathymetry – Lake Livingston
- 2019 TRA Bathymetry – Trinity River

Data sources and their coverage areas are listed in Table 3-2. Figure 3-3 shows the location of the data sources. The lidar data sets and bathymetry were compiled with the field survey data described below in Section 3.3 and developed into a Geographic Information System (GIS) terrain dataset for this study. Appendix B contains additional information on terrain processing and development.

**Table 3-2 Elevation Data Sources.**

| County | Data Source |
|---|---|
| Anderson | 2016 FEMA |
| Freestone | 2017 FEMA and 2018 NRCS |
| Grimes | 2018 NRCS and 2018 TNRIS |
| Houston | 2016 TNRIS, 2018 NRCS, 2018 TNRIS, 2019 TRA Bathymetry and Survey |
| Leon | 2016 FEMA, 2018 NRCS, 2019 TRA Bathymetry, and Survey |
| Madison | 2016 TNRIS, 2018 NRCS, 2018 TNRIS, 2019 TRA Bathymetry and Survey |
| Polk | 2016 FEMA, 2018 NRCS, and 2019 TWDB Bathymetry |
| San Jacinto | 2017 TNRIS, 2018 NRCS, 2018 TNRIS, and 2019 TWDB Bathymetry |
| Trinity | 2016 FEMA, 2018 NRCS, 2018 TNRIS, 2019 TWDB Bathymetry, and Survey |
| Walker | 2017 TNRIS, 2018 NRCS, 2018 TNRIS, 2019 TWDB, 2019 TRA Bathymetry, and Survey |
| Anderson | 2016 FEMA |
| Freestone | 2017 FEMA and 2018 NRCS |
| Grimes | 2018 NRCS and 2018 TNRIS |
| Houston | 2016 TNRIS, 2018 NRCS, 2018 TNRIS, 2019 TRA Bathymetry and Survey |

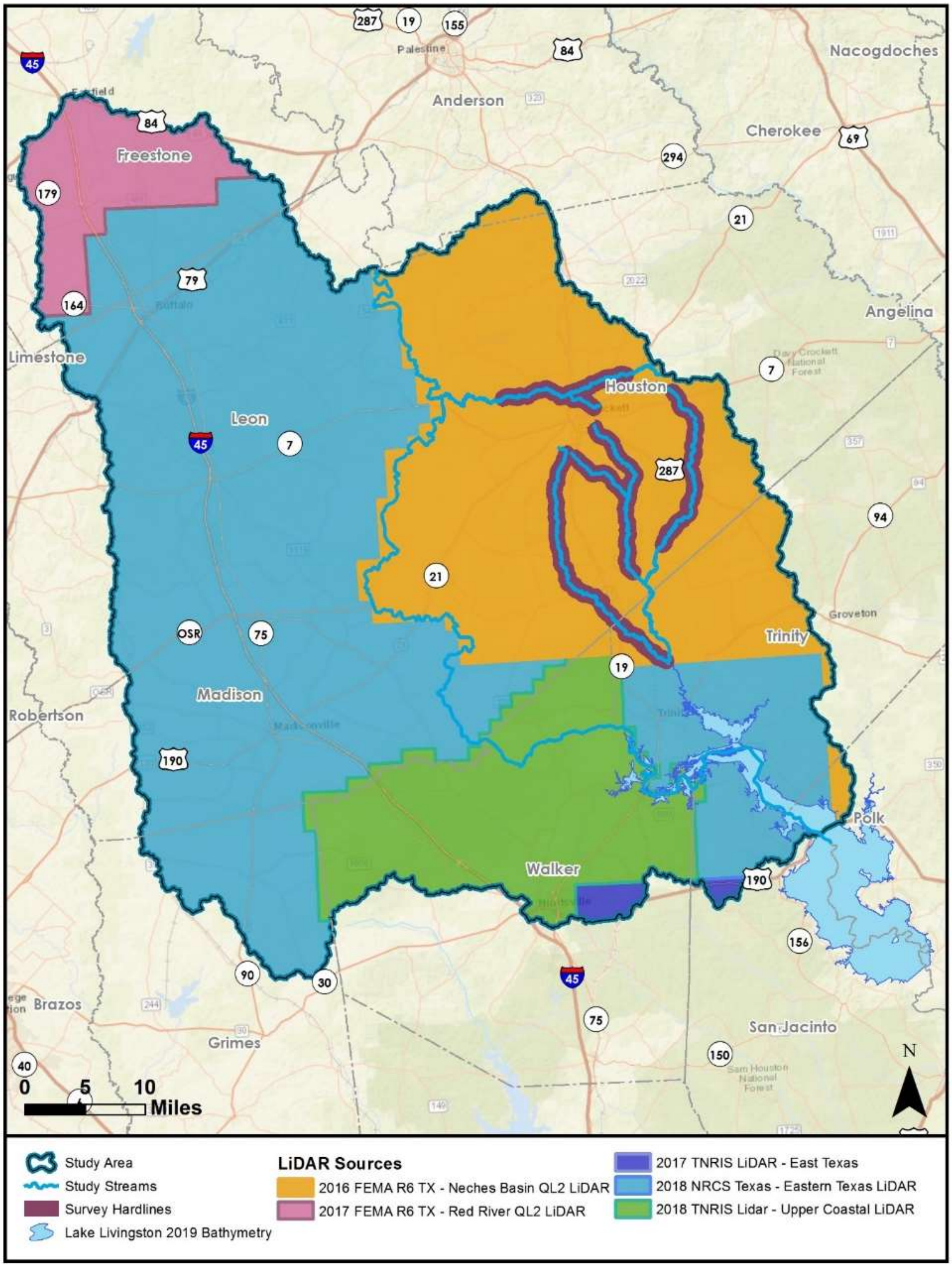


*Figure 3-3 Trinity River Mid-Basin Elevation Data Sources*

## 3.3 Field survey

Field survey data was collected throughout the study area to supplement the LiDAR and bathymetry data. Between March 2022 and August 2022, Halff obtained field survey of bridge/culvert stream crossings and channel geometry along the Trinity River, Gail Creek, Hurricane Bayou, Spring Creek 1, Spring Creek 2, Tantabogue Creek and White Rock Creek, where a high level of accuracy was needed to develop accurate flood models. The project survey initially involved conducting limited field reconnaissance to determine conditions along the studied streams, including:

- types and numbers of hydraulic and/or flood control structures
- apparent maintenance or lack thereof of existing hydraulic structures
- locations of channel cross sections to be surveyed.

Surveyed points for bridges include the deck, low chord, parapet, and channel cross sections at the upstream and downstream faces. For culverts, the deck, culvert invert points, culvert dimensions, and channel cross sections were surveyed at both the upstream and downstream faces. Intermediate channel cross sections were surveyed at accessible locations between structures where a significant change in conveyance occurred between cross sections. Photos and field sketches of crossings and channel cross sections were obtained at each field survey location.

A field visit was also conducted on September 29, 2022, to confirm the survey and measure smaller crossings not previously surveyed along Spring Creek 2 and White Rock Creek.

The survey data used were referenced to the North American Horizontal Datum of 1983 (NAD83) with State Plane Texas South Central Projection (4203). The elevations were referenced to the 1988 North American Vertical Datum (NAVD88). The linear unit used for both horizontal and vertical measurements is U.S. Feet.

The survey data was compiled with the LiDAR and bathymetry data described in Section 3.2 and developed into a GIS terrain dataset for this study. Appendix B contains additional information on terrain processing and development.

A total of thirty (30) bridges, nineteen (19) culverts, and fifty-nine (59) channel cross sections were surveyed. Note that TxDOT as-built bridge plans were used for hydraulic modeling of some structures as described in Appendix A. Appendix C contains additional information on the field survey data collection.

## 3.4 Base map

A base map was created and hosted throughout the life of the project. The base map included information for study stream centerlines, HUC8 and HUC12 basins, USGS Gage locations, city limits, the project study area, FEMA mapping, Texas Department of Transportation roadways, railroads, land use, and soil groups.

## 3.5 Public meetings

Public meetings, stakeholder meetings, and coordination meetings were held throughout the Trinity River Mid-Basin Study. Meetings were held for both government agencies and public stakeholders. Table 3-3 shows the meetings, dates, and locations for the meetings held throughout the project. Sign-in sheets are provided in Appendix A.

**Table 3-3 Progress and Public Meetings Location.**

| | Type | Date | Location |
|---|---|---|---|
| 1 | Government Agency Meeting | May 26, 2022 | Crockett, TX |
| 2 | Public Stakeholder Meeting | June 29, 2022 | Crockett, TX |
| 3 | Coordinate with USACE | July 15, 2022 | Fort Worth, TX |
| 4 | Government Agency Meeting | September 29, 2022 | Crockett, TX |
| 5 | Public Stakeholder Meeting | October 13, 2022 | Crockett, TX |
| 6 | Government Agency Meeting | March 14, 2023 | Crockett, TX |
| 7 | Government Agency and Public Stakeholder Meeting | September 20, 2023 | Crockett, TX |

# 4 Hydrologic analysis

The InFRM Trinity River hydrologic model was used as the basis for the Trinity River Mid-Basin Watershed Study. The InFRM model originates near the Dallas/Fort Worth metroplex and includes the watershed flowing southeast to the Gulf of Mexico. The InFRM hydrologic model encompasses approximately 18,000 square miles. A portion of the InFRM hydrologic model was updated for this study from near the tripoint of Anderson, Houston and Leon Counties downstream to US-190 along the Polk and San Jacinto Counties shared boundary. The study area covers approximately 3,200 square miles. Exhibit D-1 in Appendix D presents the Trinity River Mid-Basin study area. The InFRM subbasins within the study area were divided into additional smaller subbasins. Hydrologic parameters were calculated for the new subbasins. The updated hydrologic model with the additional subbasins was validated with three historical events (June-July 2007, May-June 2015, and October-November 2015) demonstrating the computed flows at USGS Gage 08065350 (Trinity River Near Crockett, Texas) from the updated model and the existing InFRM model are consistent. The frequency storms modeled are the 10%, 4%, 2%, 1%, and 0.2% Annual Chance of Exceedance (ACE) events. The hydrologic model was also validated compared to the existing InFRM frequency storm discharges. The USACE Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HEC-HMS) Version 4.2.1 was utilized for the hydrology modeling for the Trinity River, and HEC-HMS Version 4.3 was utilized for the hydrology modeling for the studied tributaries to be consistent with the versions used for the InFRM models.

## 4.1 Subbasin delineation

The InFRM subbasins within the studied stream watersheds were divided into additional smaller subbasins. These subbasin boundaries were delineated to better represent the studied area. The 10-foot digital elevation model developed for the leveraged Lower Trinity Kickapoo and the Lower Trinity Tehuacana Base Level Engineering (BLE) studies was utilized for the subbasin delineations. Stream centerlines were taken from the National Hydrologic Dataset (NHD) and adjusted based on the BLE terrain. Basin boundaries were adjusted to coincide with major roads and USGS gage locations. Overall, 146 additional subbasins were delineated with areas ranging from 0.6 to 188 square miles with an average size of 55 square miles within the Trinity River mainstem watershed and ranging from 0.062 to 8.4 square miles with an average size of 3.2 square miles within the studied stream watersheds. The new divided subbasin delineations are shown in Exhibit D-2 in Appendix D. The subbasin names are based on the studied stream names. The subbasins are generally numbered in increasing order from upstream to downstream per studied stream watershed. Subbasin "Trinity_River_S140" draining to the Trinity River is at the upstream end of the study area, while subbasin "Trinity_River_S330" is at the downstream end of the study area.

## 4.2 Hydrologic model parameters

The initial and constant loss method and the Snyder unit hydrograph method were used for all subbasins. The selected methods were chosen based on the methodology used by the InFRM hydrologic model. Hydrologic routing along the studied streams was computed with 1D unsteady flow simulations using USACE HEC-River Analysis System (HEC-RAS) Version 6.1. For smaller unstudied streams, Modified Puls storage-outflow relationships were computed with the leveraged BLE hydraulic models using the USACE HEC-River Analysis System (HEC-RAS) Version 4.1.0.

### *4.2.1 Initial and constant loss method*

Initial and constant losses are used to calculate the amount of water infiltrating the soil. The initial loss determines the amount of water the soil can absorb before runoff starts to be produced, and the constant loss accounts for water that continuously infiltrates the soil over the entire storm. Overall, the initial and constant loss determine the ultimate infiltration capacity of the soil. The percent impervious parameter is also utilized in the initial and constant loss method. Weighted percent impervious values were determined by GIS methods for each new subbasin based on USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) maps (Exhibit D-3). See Table D-1 in Appendix D for the weighted percent impervious values per subbasin. Initial and constant (uniform) loss rates were based on the sand and clay composition of each subbasin using the NRCS Soil Survey Geographic (SSURGO) Database hydrologic soil group maps (Exhibit D-4). The Dallas-Fort Worth hydrologic loss rates were used to represent the loss rates of both sand and clay. The range of Dallas-Fort Worth initial and constant loss rates for clay and sand are presented in Table 4-1.

**Table 4-1 Dallas-Fort Worth hydrologic loss rates.**

| Frequency Event | Clay Initial (in) | Clay Constant (in/hr) | Sand Initial (in) | Sand Constant (in/hr) |
|---|---|---|---|---|
| 10-Year | 1.12 | 0.14 | 1.5 | 0.18 |
| 25-Year | 0.95 | 0.12 | 1.3 | 0.15 |
| 50-Year | 0.84 | 0.1 | 1.1 | 0.13 |
| 100-Year | 0.75 | 0.07 | 0.9 | 0.1 |
| 500-Year | 0.5 | 0.05 | 0.6 | 0.08 |

A composite initial and constant loss rate was calculated for each subbasin using a weighted average of the amount of sand and the amount of clay in each basin.

$$\text{Loss} = \frac{\sum(\text{Area of Clay})(\text{Initial or Constant Loss of Clay}) + (\text{Area of Sand})(\text{Initial or Constant Loss of Sand})}{\sum \text{Area}}$$

A summary of the range of calculated initial and constant losses for the new subbasins is shown in Table 4-2 below. The calculated initial and constant losses for each subbasin are presented in Table D-1 in Appendix D.

**Table 4-2 Range of initial and constant losses.**

| Frequency Event | Initial Loss (in) | Constant Loss (in/hr) |
|---|---|---|
| 10% ACE | 1.26 - 1.42 | 0.15 - 0.17 |
| 4% ACE | 1.08 – 1.22 | 0.13 - 0.16 |
| 2% ACE | 0.94 - 1.04 | 0.11 - 0.14 |
| 1% ACE | 0.81 – 0.87 | 0.08 - 0.11 |
| 0.2% ACE | 0.54 - 0.58 | 0.06 - 0.09 |

### *4.2.2 Snyder's unit hydrograph method*

Snyder's unit hydrograph method considers the time distribution of rainfall, the initial rainfall losses to interception and depression storage, and an infiltration rate that decreases during the storm (Source: USACE Engineering Manual (EM 1110-2-1405) Flood-Hydrograph Analysis and Computations). The two parameters associated with Snyder's unit hydrograph method are lag time and Snyder's peaking coefficient.

The Snyder's unit hydrograph utilizes the time to peak of the unit hydrograph in hours. The time to peak represents the lag time from the midpoint of the unit rainfall duration.

Log(tp) = 0.383*log(L*Lca/(Sst0.5))+(Sand*(log(1.81)-log(0.92))+log(0.92))-(BW*Urban/100)

tp = Time to peak of unit hydrograph, hours

L = Length of the longest flow path (miles)

Lca = River mileage from the design point (basin discharge location) to the centroid of gravity of the drainage area. (miles)

Sst = Slope of the longest flow path between 10% and 85% of L (feet/mile)

Sand = Percentage of sand

BW = log(tp) bandwidth between 0% and 100% urbanization = 0.266 (log hours)

Urban = Percentage urbanization factor

The calculated Snyder's lag times for the new subbasins range from 10 minutes to just over 4 hours, with an average lag time of 1.6 hours for the studied tributaries. The calculated lag times for the new subbasins draining to the Trinity River mainstem range from 1.2 to 18 hours, with an average lag time of 6.2 hours. See Table D-2 in Appendix D for the lag time calculations. The InFRM frequency model used a peaking coefficient of 0.6 upstream of USGS Gage 08065350 (Trinity River near Crockett, Texas) and 0.55 downstream of the gage. The same pattern was used for the new subbasins.

## 4.3 Historical storm validation and calibration

The updated hydrologic model with the additional subbasins was executed with historical rainfall from 3 historical events (June-July 2007, May-June 2015, and October-November 2015) to determine if the computed flows at USGS Gage 08065350 (Trinity River Near Crockett, Texas) from the updated model and the existing InFRM model are consistent.

Three historical storm events were analyzed: June-July 2007, May-June 2015, and October-November 2015. Six USGS gages are located within the study area along the study streams. Of these six gages, Halff could only validate the updated hydrologic model with USGS Gage 08065350 (Trinity River near Crockett, Texas). Halff could not validate the hydrologic model to the other five gages since USGS Gage 08065500 (Trinity River near Midway, Texas) stopped recording data in 1970, USGS Gage 08066000 (Trinity River at Riverside, Texas) only records stage data after 1968, and the three gages located along the studied tributaries [USGS Gage 08065340 (Hurricane Bayou at US-287 near Crockett, Texas), 08066087 (Gail Creek at FM 1280 near Lovelady, Texas), and 08066138 (Tantabogue Creek at FM 230 near Lovelady, Texas)] did not start recording data until August 2021.

Historic rainfall data was leveraged from the InFRM WHA model for the three storm events on an approximate 2km x 2km grid in the Hydrologic Rainfall Analysis Project (HRAP) coordinate system and provides the high-quality temporal and spatial distribution of the rainfall. In total, 3,639 HRAP grid cells were utilized to represent the 3,194 square mile Trinity River Mid-Basin Study area.

The InFRM model was previously calibrated to these same three storm events. The InFRM calibrated initial and uniform loss parameters were input into the hydrology model to validate the updated model with additional subbasins. Table 4-3 summarizes the calibrated parameters utilized from the InFRM calibration models. The InFRM calibrated peaking coefficient of 0.4 for all three events was also utilized. The percent imperious values and lag times calculated for this study were used.

**Table 4-3 Calibrated hydrologic parameter summary.**

| **June–July 2007** | **June–July 2007** | **May–June 2015** | **May–June 2015** | **October–November 2015** | **October–November 2015** |
|---|---|---|---|---|---|
| **Initial Loss (in)** | **Constant Loss (in/hr)** | **Initial Loss (in)** | **Constant Loss (in/hr)** | **Initial Loss (in)** | **Constant Loss (in/hr)** |
| 2 | 0.32 | 0.6 | 0.2 | 0.5 | 0.1 |

### *4.3.1 June – July 2007 validation and calibration*

The June–July 2007 storm event was a long high-flow event that occurred along the Trinity River. The storm's time frame extends from July 5, 2007, to July 31, 2007, and consists of one peak. Per the InFRM statistical analysis of the USGS Gage 80065350 (Trinity River near Crockett, Texas), this storm was between a 20% and 10% ACE event. Figure 4-1 shows a comparison of the computed flows to the original InFRM calibrated flows and the observed flows.

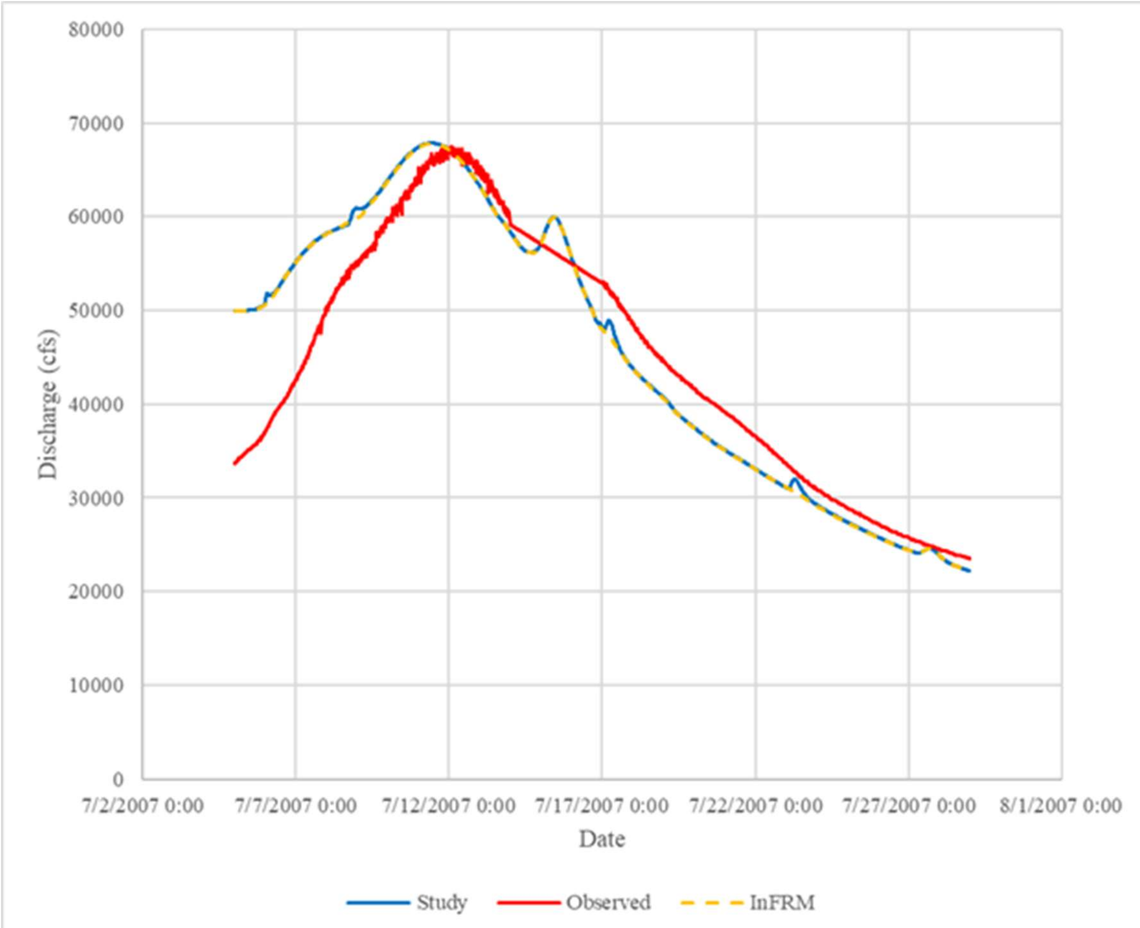


*Figure 4-1 USGS Gage 08065350 (Trinity River near Crockett, Texas) June – July 2007 Calibration Results*

Table 4-4 below shows that the updated model results in a similar computed peak flow and volume as the InFRM calibrated model. As shown in Figure 4-1 and **Error! Reference source not found.**, the updated model is calibrated to the June - July 2007 event at USGS Gage 08065350 (Trinity River near Crockett, Texas).

**Table 4-4 Crockett Gauge June-July 2007 Validation and Calibration Results (USGS ID 08065350).**

| Date | Recorded Peak Flow (cfs) | InFRM HEC-HMS Historical Storm Analysis | Current Study HEC-HMS Historical Storm Analysis |
|---|---|---|---|
| Peak Flow (cfs) | 67,500 | 67,800 | 67,800 |
| Volume (acre-feet) | 8,900,000 | 9,010,000 | 9,030,000 |

### *4.3.2 May-June 2015 validation and calibration*

The May–June 2015 storm event was a long high-flow event along the Trinity River. The event was modeled from May 24, 2015 to June 25, 2015, and consisted of one peak. Per the InFRM statistical analysis of the USGS Gage 80065350 (Trinity River near Crockett, Texas), this storm was approximately a 10% ACE event. Figure 4-2 shows a comparison of the computed flows to the original InFRM calibrated flows and the observed flows.

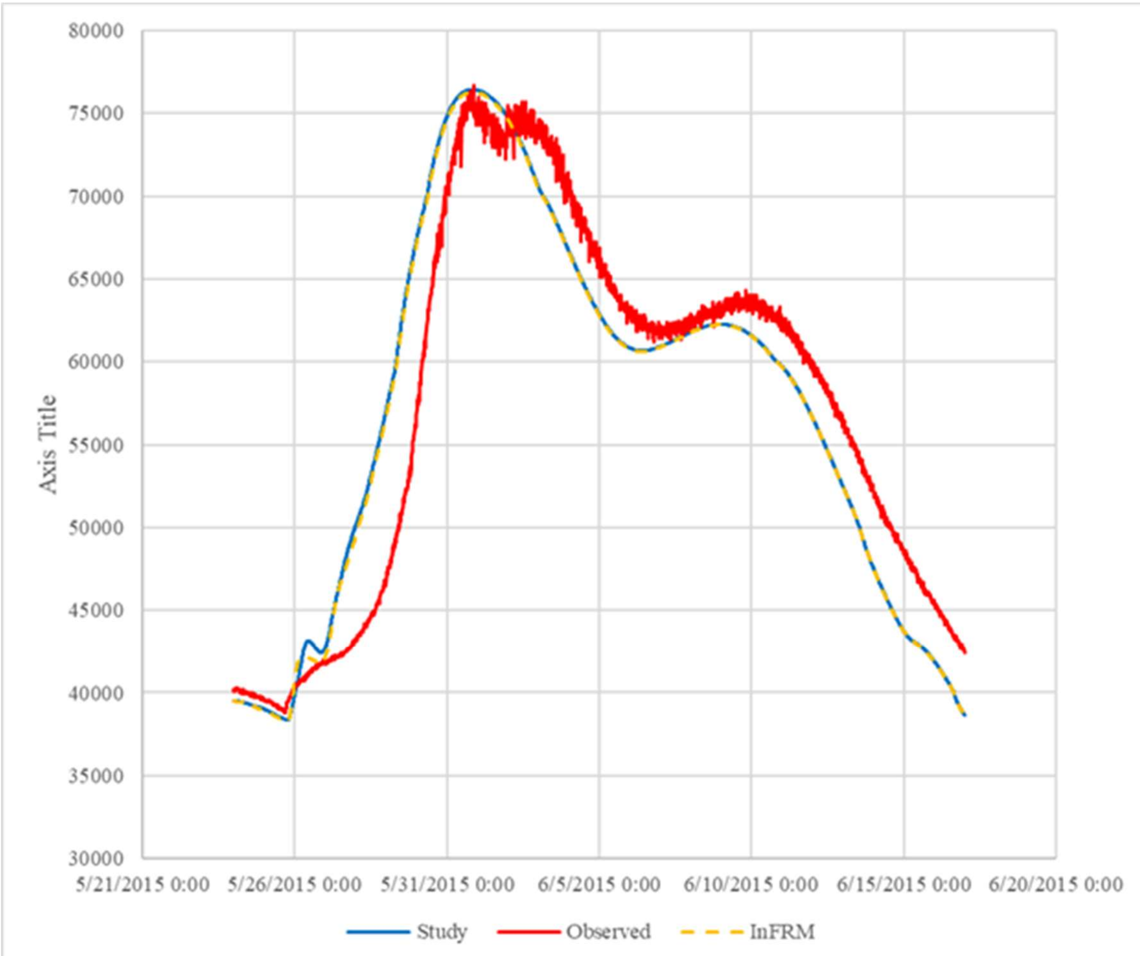


*Figure 4-2 USGS Gage 08065350 (Trinity River near Crockett, Texas) May–June 2015 Calibration Results*

Table 4-6 below shows that the updated model results in similar computed peak flow and volume as the InFRM calibrated model. As shown in Figure 4-2 and Table 4-6, the updated model is calibrated to the May-June 2015 event at USGS Gage 08065350 (Trinity River near Crockett, Texas).

**Table 4-5 Crockett Gauge May–June 2015 Validation and Calibration Results (USGS ID 08065350).**

| Date | Recorded Peak Flow (cfs) | InFRM HEC-HMS Historical Storm Analysis | Current Study HEC-HMS Historical Storm Analysis |
|---|---|---|---|
| Peak Flow (cfs) | 76,700 | 76,300 | 76,300 |
| Volume (acre-feet) | 13,100,000 | 12,900,000 | 12,900,000 |

### *4.3.3 October – November 2015 validation and calibration*

The October–November 2015 storm event was a long high-flow event that occurred along the Trinity River. This event was modeled from October 24, 2015 to November 10, 2015 and consists of a single peak. Per the InFRM statistical analysis of the USGS Gage 80065350 (Trinity River near Crockett, Texas), this storm was between a 10% and 4% ACE event. Figure 4-3 shows a comparison of the computed flows to the original InFRM calibrated flows and the observed flows.

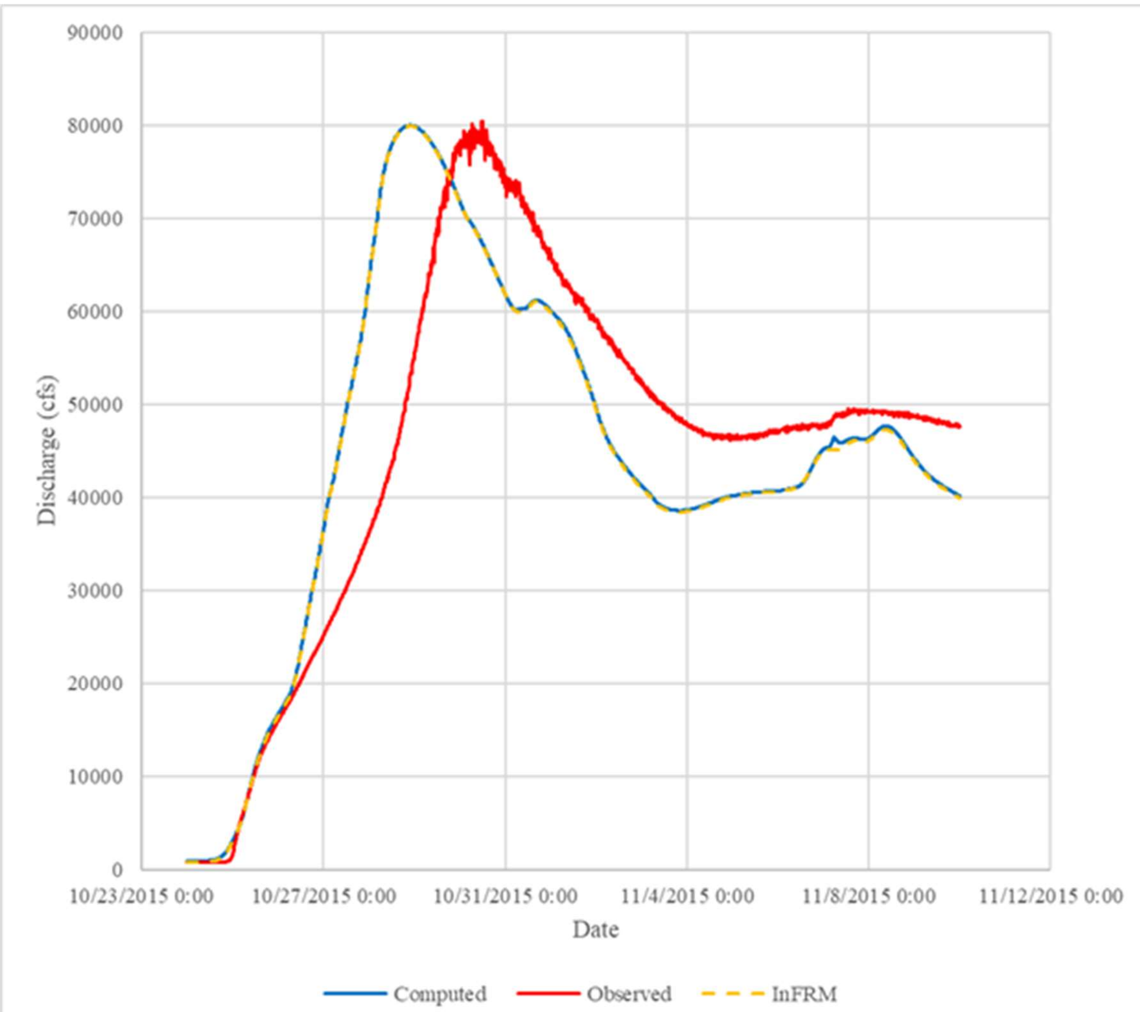


*Figure 4-3 USGS Gage 08065350 (Trinity River near Crockett, Texas) October-November 2015 Calibration Results*

Table 4-6 below shows that the updated model results in similar computed peak flow and volume as the InFRM calibrated model. As shown in Figure 4-3 and Table 4-6, the updated model is calibrated to the October - November 2015 event at USGS Gage 08065350 (Trinity River near Crockett, Texas).

**Table 4-6 Crockett Gauge October-November 2015 Validation and Calibration Results (USGS ID 08065350).**

| Date | Recorded Peak Flow (cfs) | InFRM HEC-HMS Historical Storm Analysis | Current Study HEC-HMS Historical Storm Analysis |
|---|---|---|---|
| Peak Flow (cfs) | 80,400 | 79,900 | 79,900 |
| Volume (acre-feet) | 6,160,000 | 6,020,000 | 6,030,000 |

### *4.3.4 Validation and calibration results*

Results from the updated hydrologic model show very little change in peak flow compared to the calibrated InFRM model. The results validate the updated model with additional subbasins compared to the InFRM model. As shown by the tables and graphs above, the updated and InFRM models compute similar calibration results to the peak flow at USGS Gage 08065350 (Trinity River near Crockett, Texas). Hurricane Bayou and Spring Creek 2 have very little effect on the peak flow at USGS Gage 08065350 (Trinity River near Crockett, Texas) and peak much sooner than the hydrograph along the Trinity River mainstem.

## 4.4 Frequency storm hydrologic models

The updated hydrologic model was also executed with the 10%, 4%, 2%, 1%, and 0.2% ACE frequency events. The updated model uses the frequency storm rainfall data from the InFRM model. This study utilizes the two approaches from the InFRM model. First, the tributaries were modeled using the uniform rainfall and the standard aerial-reduction curves outlined in TP-40. Second, since the drainage area for the Trinity mainstem exceeds the 400 square miles threshold for aerial reduction outlined in TP-40, an elliptical design storm method was utilized for the mainstem. The initial and constant loss, percent impervious values, and lag times calculated for this study were input for the new subbasins. See Tables D-1 and D-2 in Appendix D for the parameter calculations. The peaking coefficients from the InFRM frequency model were also input for the new subbasins.

The frequency rainfall hyetographs were input into the HEC-HMS model to generate runoff hydrographs for the various frequency events. The HEC-HMS frequency simulations produced peak flows at the Trinity River near Crockett gage that are very similar to the peak frequency flows computed by the InFRM hydrologic model. Table 4-7 shows the computed peak frequency flows along with the InFRM computed peak frequency flows. The table also presents a comparison to the statistical gage analysis flows at the Crockett gage prepared in the InFRM study. Similar comparisons are shown in Table 4-8 for the USGS Gage 08066000 (Trinity River at Riverside, Texas). Table 4-9 shows the computed 1% peak frequency flows for the studied streams.

**Table 4-7 HEC-HMS Peak Frequency Flows at the Trinity River near Crockett Gage.**

| Frequency | Computed Peak Flow (cfs)<br><br>InFRM HEC-HMS Frequency Storm Analysis | Computed Peak Flow (cfs)<br><br>Current Study HEC-HMS Frequency Storm Analysis | Computed Peak Flow (cfs)<br><br>InFRM Statistical Analysis of USGS Gage 08065350 (1964-2016) | Percent Difference Current Study to InFRM |
|---|---|---|---|---|
| 10% ACE | 71,500 | 71,800 | 71,800 | 0.3% |
| 4% ACE | 98,700 | 99,000 | 89,800 | 0.4% |
| 2% ACE | 122,000 | 122,000 | 103,000 | 0.1% |
| 1% ACE | 140,000 | 138,000 | 115,000 | 1.4% |
| 0.2% ACE | 235,000 | 236,000 | 141,000 | 0.5% |

**Table 4-8 HEC-HMS Peak Frequency Flows at the Trinity River near Riverside Gage.**

| Return Period | Computed Peak Flow (cfs)<br><br>InFRM HEC-HMS Frequency Storm Analysis | Computed Peak Flow (cfs)<br><br>Current Study HEC-HMS Frequency Storm Analysis | Computed Peak Flow (cfs)<br><br>InFRM Statistical Analysis of USGS Gage 08066000 (1903-1968) | Percent Difference Current Study to InFRM |
|---|---|---|---|---|
| 10% ACE | 71,800 | 113,000 | 60,600 | 77,400 |
| 4% ACE | 109,000 | 162,000 | 80,400 | 100,700 |
| 2% ACE | 134,000 | 205,000 | 102,000 | 119,000 |
| 1% ACE | 159,000 | 260,000 | 121,000 | 137,000 |
| 0.2% ACE | 249,000 | 397,000 | 188,000 | 180,000 |

**Table 4-9 Current Study HEC-HMS 1% Peak Frequency Flows for Studied Streams.**

| Location | Contributing Drainage Area (square miles) | Computed Peak Flow (cfs) |
|---|---|---|
| Confluence of Gail Creek with White Rock Creek | 80 | 45,600 |
| Confluence of Hurricane Bayou with Trinity River | 99 | 46,200 |
| Confluence of Spring Creek 1 with Hurricane Bayou | 2.2 | 54,000 |
| Confluence of Spring Creek 2 with Gail Creek | 7.9 | 13,100 |
| Confluence of Tantabouge Creek with White Rock Creek | 76 | 40,000 |
| Confluence of White Rock Creek with Tantabouge Creek | 226 | 67,000 |
| Trinity River at Lake Livingston | 15,600 | 260,000 |
| Trinity River at SH-21 | 14,400 | 125,000 |
| Confluence of Trinity River and Bedias Creek | 15,200 | 125,000 |
| Confluence of Gail Creek with White Rock Creek | 80 | 45,600 |

## 4.5 Hydrologic analysis conclusions

The goal of the hydrologic analysis was to generate synthetic frequency flow hydrographs to be used for unsteady HEC-RAS hydraulic analyses. A comparison between the updated HEC-HMS model and the existing InFRM hydrologic model results confirmed the historical and frequency peak flows computed by the updated model are consistent with the InFRM peak flows. The updated hydrologic model generated peak flows that were consistent with the peak flows established by the InFRM hydrologic model at USGS Gage 08065350 (Trinity River near Crockett, Texas) and USGS Gage 08066000 (Trinity River at Riverside, Texas). The hydrologic analysis was successful in generating frequency flow hydrographs for use with the other modeling tools associated with the Trinity River Mid-Basin Flood Infrastructure Funding Study.

# 5 Hydraulic analysis

Halff modeled the studied streams using the Hydrologic Engineering Center River Analysis System (HEC-RAS), version 6.1, 1D unsteady analysis to produce water surface elevations with the flows from the hydrologic analysis. The studied streams include the Trinity River, Gail Creek, Hurricane Bayou, Spring Creek 1, Spring Creek 2, Tantabogue Creek, and White Rock Creek. The Trinity River hydraulic model extends from near the tripoint of Anderson, Houston, and Leon Counties downstream to US-190 along the Polk and San Jacinto Counties shared boundary. The calibration storms consisted of the May–June 2015 and October - November 2015 events and were validated using the June - July 2007 event. The modeled frequency storms were the 10%, 4%, 2%, 1%, and 0.2% ACE events. All water surface elevations shown in this report are referenced to the NAVD 88 vertical datum. The hydraulic modeling was used to establish floodplain extents and identify areas that could benefit from flood mitigation.

## 5.1 Geometric data

Geometric data within the model is a representation of the topography being utilized for hydraulic modeling and mapping of the floodplains. Topography sources are discussed in detail within Section 3 of this report.

### *5.1.1 Cross section geometry*

Cross section data were developed using ArcGIS software, specifically the HEC-GeoRAS toolbar in ArcMap, to create cross section profiles. The Lower Trinity Kickapoo and the Lower Trinity Tehuacana Base Level Engineering (BLE) cross section layouts were leveraged for the study. The cross section layout was adjusted, and cross sections were added as necessary. Ground elevation data was extracted from the terrain described in Section 3.2 and Appendix B. Since the hydraulic modeling consisted of a 1D unsteady analysis, Hydraulic Table (HTab) parameters were established to determine the stage and hydraulic parameter relationships for each cross section.

### *5.1.2 Trinity River*

The Trinity River was modeled from near the tripoint of Anderson, Houston and Leon Counties downstream to US-190 along the Polk and San Jacinto Counties shared boundary. The cross section alignment generally followed the BLE cross section alignment with some adjustments to confirm perpendicularity to the stream channel and floodplain. Cross sections were spaced at an average interval of 0.5 miles with minimum and maximum spacing of 0.1 miles and approximately 2 miles, respectively. Ineffective areas were added at structures and in overbank areas where no conveyance was assumed based on the terrain data and mapping. Storage areas were added at major tributaries to store backwater and account for attenuation in the floodwave. The storage curves were obtained using the existing terrain. The geometric layout for the Trinity River is shown in Exhibit E-1 in Appendix E.

### *5.1.3 Gail Creek*

Gail Creek was modeled from approximately 1,500 feet north of E Loop 304 to its confluence with White Rock Creek. Cross section alignment generally followed the BLE cross section alignment with some adjustments to confirm perpendicularity to the stream channel and floodplain. Cross sections were spaced at an average interval of 500 feet with minimum and maximum spacing of 100 feet and approximately 1,000 feet, respectively. Ineffective areas were added at structures and in overbank areas where no conveyance was assumed based on the terrain data and mapping. The geometric layout for Gail Creek is shown in Exhibit E-1 in Appendix E.

### *5.1.4 Hurricane Bayou*

Hurricane Bayou was modeled from approximately 1,000 feet upstream of FM 3187 to its confluence with the Trinity River. Cross section alignment generally followed the BLE cross section alignment with some adjustments to confirm perpendicularity to the stream channel and floodplain. Cross sections were spaced at an average interval of 500 feet with minimum and maximum spacing of 75 feet and approximately 700 feet, respectively. Ineffective areas were added at structures and in overbank areas where no conveyance was assumed based on the terrain data and mapping. At the State Highway 21 crossing, the 0.2% ACE floodplain overtops the road and spills into the adjacent ditch on the northern side of the floodplain. The overflow area is outside the limits of this study. The cross sections were not extended beyond the high point and stop at the crest of the roadway. The geometric layout for Hurricane Bayou is shown in Exhibit E-1 in Appendix E.

### *5.1.5 Spring Creek 1*

Spring Creek 1 is modeled from approximately 1,000 feet upstream of E Loop 304 to its confluence with Hurricane Bayou. Cross section alignment generally followed the BLE cross section alignment with some adjustments to confirm perpendicularity to the stream channel and floodplain. Cross sections were spaced at an average interval of 300 feet, with a minimum and maximum spacing of 20 feet and approximately 700 feet, respectively. Ineffective areas were added at structures and in overbank areas where no conveyance was assumed based on the terrain data and mapping. At the first Loop 304 crossing (cross section 23222), the flow in Spring Creek 1 splits; some flow continues southwest while some flow goes northwest. The split flow is modeled with a lateral structure. Some cross sections along Loop 304 in the split flow reach and at SH-7 along the mainstem are overtopped by the floodplain. Water overtops the cross sections in several locations and spills over adjacent roadways. These areas where the water spills into are outside the limits of this study. The geometric layout for Spring Creek 1 and the split flow tributary are shown in Exhibit E-1 in Appendix E.

### *5.1.6 Spring Creek 2*

Spring Creek 2 is modeled from approximately 2,000 feet upstream of SH 19 to its confluence with Gail Creek. Cross section alignment generally followed the BLE cross section alignment with some adjustments to confirm perpendicularity to the stream channel and floodplain. Cross sections were spaced at an average interval of 400 feet with minimum and maximum spacing of 50 feet and approximately 700 feet, respectively. Ineffective areas were added at structures and in overbank areas where no conveyance was assumed based on the terrain data and mapping. The geometric layout for Spring Creek 2 is shown in Exhibit E-1 in Appendix E.

### *5.1.7 Tantabogue Creek*

Tantabogue Creek is modeled from approximately 3,500 feet upstream of FM 2110 to its confluence with White Rock Creek. Cross section alignment generally followed the BLE cross section alignment with some adjustments to confirm perpendicularity to the stream channel and floodplain. Cross sections were spaced at an average interval of 500 feet with a minimum and maximum spacing of 50 feet and approximately 3,000 feet, respectively. Ineffective areas were added at structures and in overbank areas where no conveyance was assumed based on the terrain data and mapping. The geometric layout for Tantabogue Creek is shown in Exhibit E-1 in Appendix E.

### *5.1.8 White Rock Creek*

White Rock Creek is modeled from approximately 3 miles upstream of SH 7 to its confluence with Tantabogue Creek. Cross section alignment generally followed the BLE cross section alignment with some adjustments to confirm perpendicularity to the stream channel and floodplain. Cross sections were spaced at an average interval of 1,000 feet with minimum and maximum spacing of 50 feet and approximately 5,000 feet, respectively. Ineffective areas were added at structures and in overbank areas where no conveyance was assumed based on the terrain data and mapping. The geometric layout for White Rock Creek is shown in Exhibit E-1 in Appendix E.

### *5.1.9 Manning's "n" values*

Manning's "n" roughness values for each cross section were assigned manually using aerial imagery provided by Esri, Maxar, Earthstar Geographies, IGN, and the GIS Community. Manning's "n" values ranged from 0.015 for asphalt to 0.1 for heavily forested areas in the overbanks and 0.05 for unforested to 0.055 for forested channels. See Table 5-1 for Manning's "n" values for each studied stream.

**Table 5-1 Manning's "n" Values.**

| Stream | *Manning's "n" Values Channel* | *Manning's "n" Values* **Overbank** |
|---|---|---|
| Trinity River | 0.05 | 0.023 – 0.1 |
| Gail Creek | 0.05 – 0.055 | 0.05 - 0.1 |
| Hurricane Bayou | 0.05 – 0.055 | 0.015 – 0.1 |
| Spring Creek 1 | 0.05 – 0.055 | 0.015 – 0.1 |
| Spring Creek 2 | 0.055 | 0.05 – 0.1 |
| Tantabogue Creek | 0.05 – 0.055 | 0.015 – 0.1 |
| White Rock Creek | 0.05 - 0.055 | 0.05 – 0.1 |

### *5.1.10 Bridges*

A total of 53 bridges were modeled in the Trinity River and studied stream models. Bridge data was either surveyed by Halff, determined from as-built plan sets provided by TxDOT and Union Pacific Railroad, or inferred based on aerial imagery. Since a 1D unsteady analysis was conducted, HTab parameters were established for each bridge to determine the stage and hydraulic parameter relationships.

#### *5.1.11 Lateral structures*

Lateral structures were used to model inflow into the Spring Creek 1 split flow and to model water overtopping the road within the split flow and reentering the Spring Creek 2 mainstem. The geometry for the later weirs was extracted from the terrain described in Section 3.2 above and imported into the hydraulic model. Weir coefficients were assigned to the lateral structures with a value between 1 and 1.5 based on guidance in the HEC-RAS manual for lateral structures that are roads less than three feet above the ground. Weir coefficients were adjusted as needed to ensure a level water surface elevation between connected areas.

## 5.2 Unsteady flow data

The hydraulic models were executed with historical and frequency flows computed in the hydrologic analysis. The hydraulic model was calibrated with the May – June 2015 and the October - November 2015 computed flows and validated with the June - July 2007 computed flows. The modeled frequency flows include the 10%, 4%, 2%, 1%, and 0.2% ACE events. Data entered into the unsteady flow editor was added as boundary conditions under three different categories: upstream, internal and downstream boundaries. These categories are discussed below in detail, and a table of the locations of the boundary conditions is shown in Table E-3 in Appendix E.

### *5.2.1 Upstream boundary conditions*

The upstream boundary condition of each model consists of a flow hydrograph from the hydrologic model. For the Trinity River, the upstream boundary flow hydrograph is applied at the tripoint of Anderson, Houston and Leon Counties and includes the contributing Trinity River basins north of the study area. Approximately 13,100 square miles of drainage area contribute to the upstream cross section. For the modeled tributaries, the models extend upstream into their respective headwater basins. To account for this, the headwater basins were ratioed to the contributing drainage area upstream of the upstream most cross section. The remaining headwater basin flow is applied as an internal boundary condition, as discussed in Section 5.3.2. All upstream boundary conditions include a minimum flow for model stability. The RAS technical manual recommends that the minimum flow is less than 10% of the maximum flow from the headwater basin. However, Spring Creek 2's minimum flow is set to 17% of its maximum inflow to stabilize the model due to the steepness of the creek.

### *5.2.2 Internal boundary conditions*

Internal boundary conditions consisted of lateral inflow hydrographs and uniform lateral inflow hydrographs. These internal boundary conditions modeled drainage basins and incoming tributaries. Lateral hydrographs are flow boundaries set at a specified cross section within a river reach and are typically used to model inflow from incoming river systems. The hydrograph is applied at a single location downstream of the specified cross section in the flow data. Uniform lateral inflow hydrographs are applied to a range of cross sections within a river reach and usually model an internal drainage area. The inflow is distributed uniformly across the range of cross sections specified.

### *5.2.3 Downstream boundary conditions*

The downstream boundary condition for the Trinity River hydraulic model is a stage hydrograph for Lake Livingston. The stage hydrograph was created by the hydrologic model discussed in section 4 for each frequency event. The peak elevations from the hydrologic model are shown in Table 5-2. The downstream boundary condition for the other studied streams is the normal depth method. The normal depth boundary condition uses Manning's equation to estimate a stage for each computed flow. This method requires a friction slope (slope of the energy grade line) for the reach. The friction slope was estimated by measuring the bed slope of the channel.

**Table 5-2 Lake Livingston Stillwater Elevations.**

| Frequency Event | Lake Livingston Peak Elevation (feet) |
|---|---|
| 10% ACE | 133.69 |
| 4% ACE | 134.79 |
| 2% ACE | 135.55 |
| 1% ACE | 136.42 |
| 0.2% ACE | 136.42 |

## 5.3 Trinity River model calibration and validation

To improve the accuracy and precision of the Trinity River hydraulic model, the computed historical flows from the hydrologic analysis were simulated in the hydraulic model and certain parameters were adjusted to calibrate the hydraulic model. Two historical storm events were used to calibrate the model, the May–June 2015 and the October - November 2015 events. A third historical storm event, the June-July 2007 event, was used to validate the model. The calibration process utilized the flow roughness factors option in the unsteady flow analysis to adjust the hydraulic model computed water surface elevations until they were similar to the observed data at the USGS gages. The flow roughness factors option allows the modeler to apply a factor to Manning's "n" values of a specified range of cross sections based on changes in flow. Roughness factors can be raised or lowered until the computed water surface elevations adequately reflect the observed data.

There are six USGS gages located along the studied streams. Of these six gages, only two gages could be used to calibrate the Trinity River mainstem hydraulic model: USGS Gage 08065350 (Trinity River near Crockett, Texas) and 08066000 (Trinity River at Riverside, Texas). The USGS Gage 08066000 (Trinity River at Riverside, Texas) has no discharge data after 1968, so the hydraulic model was only calibrated to stage data at this gage. All three USGS gages located along the studied tributaries [08065340 (Hurricane Bayou at US-287 near Crockett, Texas), 08066087 (Gail Creek at FM 1280 near Lovelady, Texas), and 08066138 (Tantabogue Creek at FM 230 near Lovelady, Texas)] did not start recording data until August 2021. USGS Gage 08065500 (Trinity River near Midway, Texas), located on the Trinity mainstem, stopped recording data in 1970.

To calibrate to the observed data, the roughness factors were adjusted along the Trinity River to produce a hydrograph similar to the observed hydrograph recorded by the USGS gage. This process was completed for both USGS gages along the Trinity River, starting from upstream to downstream.

### *5.3.1 May – June 2015 calibration*

The May – June 2015 storm event was a long high-flow event along the Trinity River. The event was modeled from May 24, 2015 to June 25, 2015 and consisted of one peak at Crockett and multiple peaks at Riverside. The hydraulic model was calibrated to both USGS gages for this event.

*5.3.1.1 USGS Gage 08065350 Trinity River Near Crockett, Texas*
Several iterations were simulated, varying the roughness factors to determine the best fit to the observed data. A graph of comparisons between the observed and modeled data is shown below in Figure 5-1.

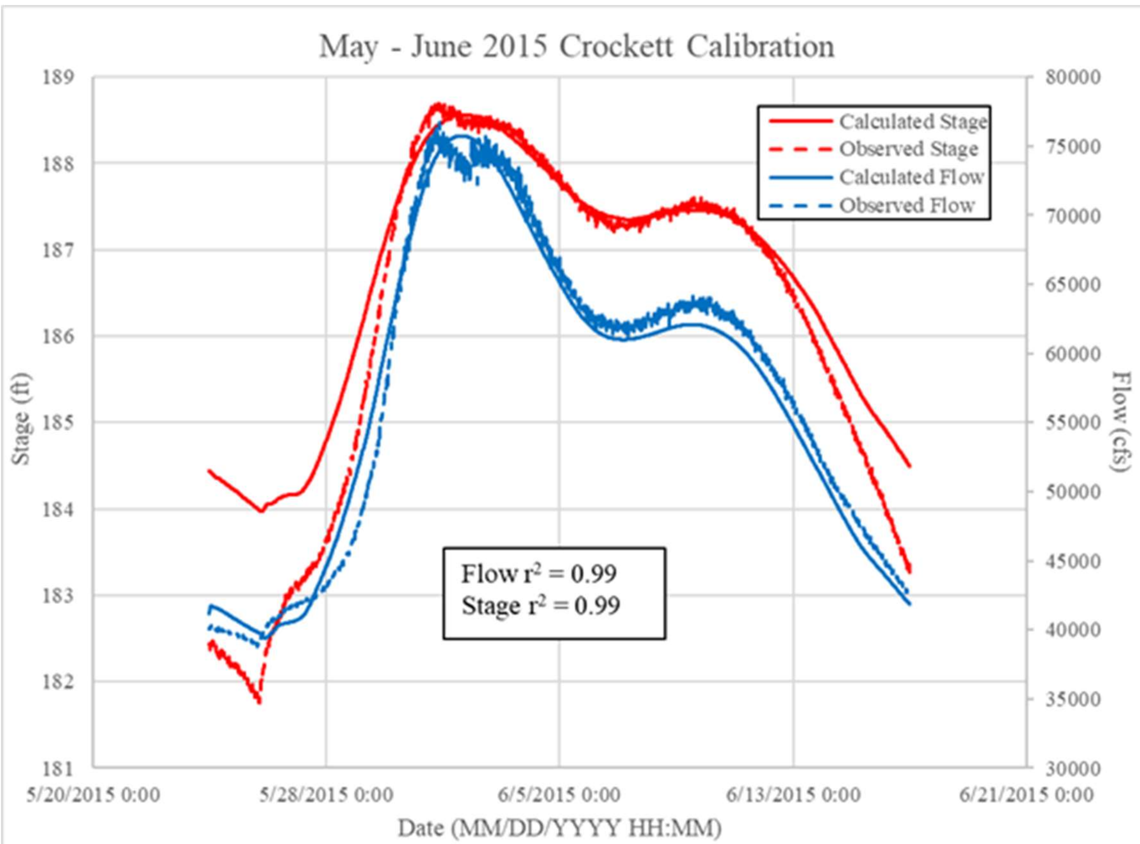


*Figure 5-1 May – June 2015 Crockett Stage and Discharge Calibration*

The results showed that the calculated stage hydrograph matched the observed data throughout the high flows of the storm event but eventually diverged on the tail end of the hydrograph. The calculated discharge hydrograph matched the observed peak discharge. Both the calculated stage and discharge hydrographs started higher than the observed data but did not affect the overall calibration of the storm event. The calculated peak stage during this event was 188.56 feet and occurred approximately 15 hours after the peak observed stage of 188.73 feet. The calculated peak discharge during this event was 75,700 cfs and occurred approximately 19 hours after the observed peak discharge of 76,300 cfs.

*5.3.1.2 USGS Gage 08066000 Trinity River at Riverside, Texas*
No flow data exists for this gage, so only stage data was used for calibration. A graph of comparisons between the observed and modeled data is shown below in Figure 5-2.

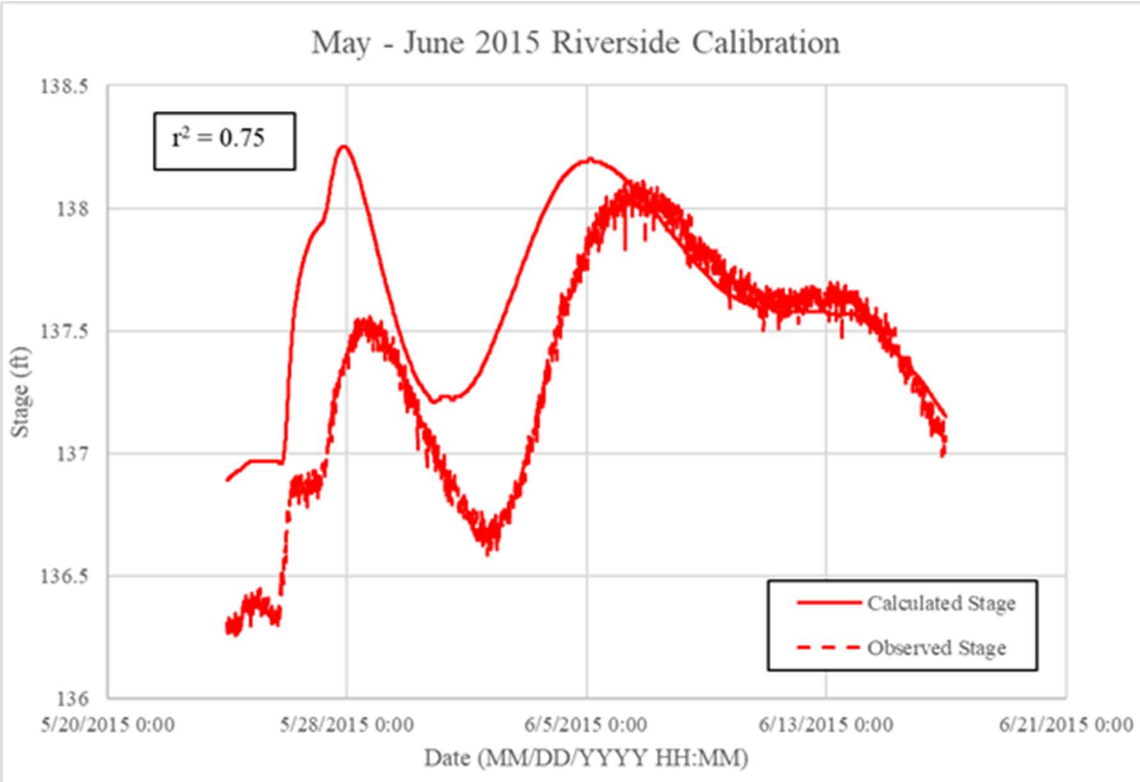


*Figure 5-2 May – June 2015 Riverside Stage Calibration*

The results showed that the calculated stage hydrograph is roughly half a foot higher than the observed data but follows the trend of the data. The calculated peak stage during this event was 138.31 feet and occurred several days after the observed peak stage of 138.12 feet during the third peak.

### *5.3.2 October – November 2015 calibration*

The October-November 2015 storm event was a long high-flow event that occurred along the Trinity River. This event was modeled from October 24, 2015 to November 10, 2015 and consists of a single peak.

*5.3.2.1 USGS Gage 08065350 Trinity River near Crockett, Texas*
Several iterations were simulated, varying the roughness factors to determine the best fit to the observed data. A graph of comparisons between the observed and modeled data is shown below in Figure 5-3.

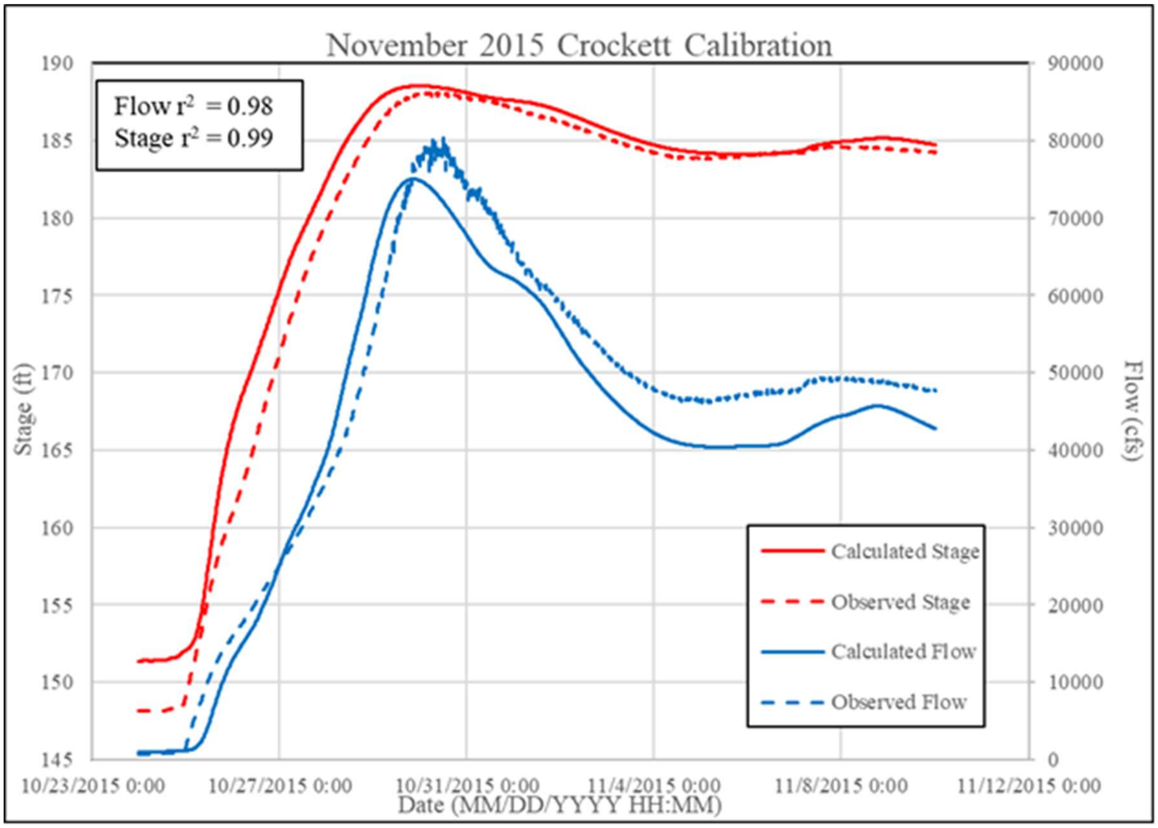


*Figure 5-3 October – November 2015 Crockett Stage and Discharge Calibration*

The results showed that the calculated stage hydrograph matched the relative trend of the observed stage hydrograph. The calculated discharge hydrograph follows the relative trend of the observed data but peaks much earlier and has lower flows through the run when compared to the observed data. The calculated peak stage during this event was 188.53 feet and occurred approximately 11 hours before the peak observed stage of 188.14 feet. The calculated peak discharge during this event was 75,000 cfs and occurred 23 hours before the peak observed discharge of 80,400 cfs.

*5.3.2.2 USGS Gage 08066000 Trinity River at Riverside, Texas*

No flow data exists for this gage, so only stage data was used for calibration. A graph of comparisons between the observed and modeled data is shown below in Figure 5-4.

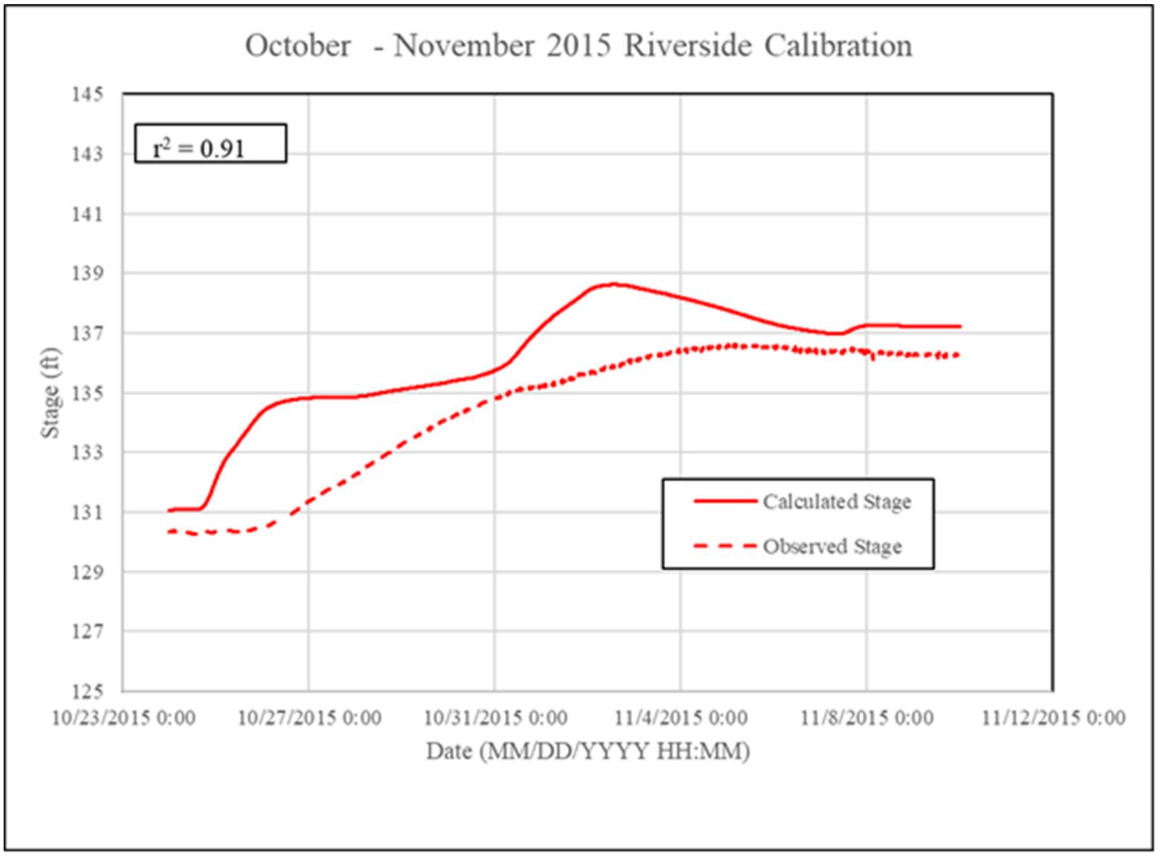


*Figure 5-4 October–November 2015 Riverside Stage Calibration*

The results showed that the calculated stage hydrograph was a few feet higher than the observed data and peaked several days earlier. The calculated peak stage during this event was 137.68 feet and occurred approximately three days before the peak observed stage of 136.64 feet.

### *5.3.3 June – July 2007 validation*

The June-July 2007 storm event was a long high-flow event that occurred along the Trinity River. The event was modeled from July 5, 2007, to July 31, 2007 and consisted of one peak. This historical storm confirmed that the selected roughness factors along the Trinity River accurately portray the hydraulic conditions. The 2007 event has no stage data recorded at the USGS gages, so only the flow hydrograph data was used for this storm event.

#### *5.3.3.1 USGS Gage 08065350 Trinity River near Crockett, Texas*

The May - June 2015 and October - November 2015 calibrated roughness factors were checked at the Crockett USGS gage. The results showed that the calculated discharge hydrograph follows the relative trend of the observed data. The peak calculated discharge is 67,000 cfs and the timing occurred 1 hour and 15 minutes after the observed peak flow of 67,500. A comparison graph between the observed and modeled data is shown below in Figure 5-5.

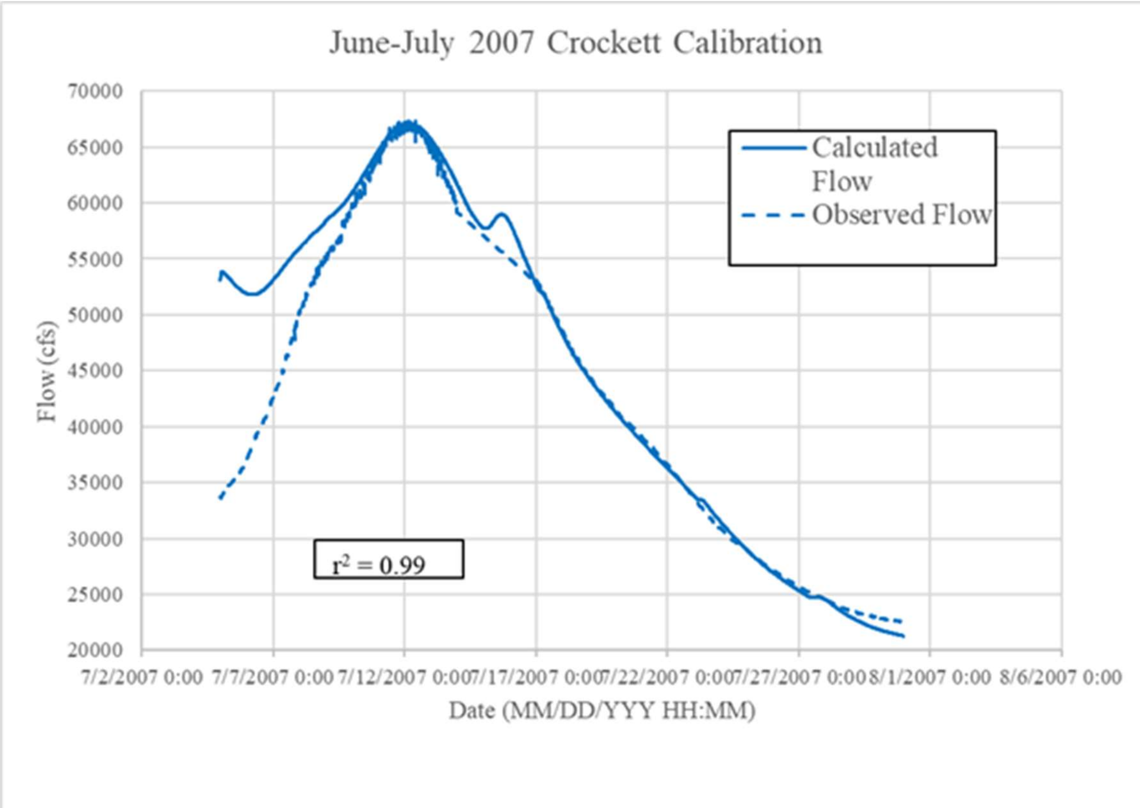


*Figure 5-5 2007 Crockett Discharge Validation*

### *5.3.4 Calibration and validation summary*

The model calibration aimed to validate the Trinity River mainstem hydraulic model and provide more accurate model geometry. The same calibrated roughness factors were used for the final calibration of the May – June 2015 and October – November 2015 events, as well as the June - July 2007 validation event. The final calibrated roughness factors are shown below in Table 5-3. The calibrated roughness factors tended to be less than or equal to one for the lower flows. For higher flows, the calibrated roughness factors tended to be greater than one to simulate observed stage and hydrograph data at the Crockett gage and less than one to simulate observed stage data at the Riverside gage. Since vegetative conditions, scour and soil depositions change the hydraulic nature of the Trinity River over time, roughness factors calculated for each historical event were determined to be the best method to calibrate the model.

**Table 5-3 Final Calibrated Roughness Factors.**

| *Discharge (cfs)* | **Roughness Factors per River Reach Cross Sections 638233 to 306766** | **Roughness Factors per River Reach Cross Sections 303011 to 1335** |
|---|---|---|
| 10,000 | 0.8 | 1 |
| 20,000 | 0.9 | 0.75 |
| 30,000 | 0.9 | 0.65 |
| 40,000 | 1.1 | 0.65 |
| 50,000 | 1.1 | 0.65 |
| 60,000 | 1.2 | 0.65 |
| 70,000 | 1.2 | 0.65 |
| 80,000 | 1.3 | 0.65 |
| 90,000 | 1.3 | 0.65 |
| 100,000 | 1.2 | 0.65 |

## 5.4 Frequency storm hydraulic models

The hydraulic models for the Trinity River and studied tributaries were executed with the frequency flows computed in the hydrologic analysis. The calibrated roughness factors were only applied to the Trinity River hydraulic model since it was the only hydraulic model calibrated to USGS gages. Peak water surface elevations were computed for the 10%, 4%, 2%, 1%, and 0.2% ACE flood frequency events. Each of these frequency events was mapped using the RAS Mapper tool.

Discharge and stage comparisons were made at the USGS Gage 08065350 (Trinity River near Crockett, Texas), as shown below in Table 5-4. The table compares the peak flows from the InFRM model, the peak flows computed in the calibrated hydrology model, and the peak flows computed in the unsteady HEC-RAS model. The table also presents a comparison to the statistical gage analysis flows at the Crockett gage prepared in the InFRM study. A comparison of the computed peak water surface elevations to the rating curve gage analysis peak elevations is also shown. Similar comparisons are shown in Table 5-5 for the USGS Gage 08066000 (Trinity River at Riverside, Texas).

**Table 5-4 Crockett Discharge and Elevation Comparisons.**

| Return Period | Computed Peak Discharge (cfs) InFRM HEC-HMS Frequency Storm Analysis | Computed Peak Discharge (cfs) Current Study HEC-HMS Frequency Storm Analysis | Computed Peak Discharge (cfs) Current Study HEC-RAS Frequency Storm Analysis | Computed Peak Discharge (cfs) InFRM Statistical Analysis of USGS Gage 08066000 (1903-1968) | Water Surface Elevation (feet NAVD 88) Current Study HEC-RAS Frequency Storm Analysis | Water Surface Elevation (feet NAVD 88) USGS Gage Analysis* |
|---|---|---|---|---|---|---|
| 10% ACE | 71,500 | 71,800 | 67,000 | 71,800 | 187.67 | 187.93 |
| 4% ACE | 98,700 | 99,000 | 104,000 | 89,800 | 189.04 | 189.62 |
| 2% ACE | 122,000 | 122,000 | 120,000 | 103,000 | 189.78 | 190.06 |
| 1% ACE | 140,000 | 138,000 | 136,000 | 115,000 | 190.46 | 190.12 |
| 0.2% ACE | 235,000 | 236,000 | 224,000 | 141,000 | 192.86 | -** |

*Water surface elevations are derived from the Crockett USGS Rating Curve (Version 15) using the Current Study HEC-RAS Frequency Analysis discharges

**Frequency Storm Discharge not found within the USGS rating curve

**Table 5-5 Riverside Discharge and Elevation Comparisons.**

| Return Period | Computed Peak Discharge (cfs) InFRM HEC-HMS Frequency Storm Analysis | Computed Peak Discharge (cfs) Current Study HEC-HMS Frequency Storm Analysis | Computed Peak Discharge (cfs) Current Study HEC-RAS Frequency Storm Analysis | Computed Peak Discharge (cfs) InFRM Statistical Analysis of USGS Gage 08066000 (1903-1968) | Water Surface Elevation (feet NAVD 88) Current Study HEC-RAS Frequency Storm Analysis | Water Surface Elevation (feet NAVD 88) USGS Gage Analysis* |
|---|---|---|---|---|---|---|
| 10% ACE | 71,800 | 113,000 | 67,000 | 77,400 | 187.67 | 187.93 |
| 4% ACE | 109,000 | 162,000 | 104,000 | 100,700 | 189.04 | 189.62 |
| 2% ACE | 134.000 | 205,000 | 120,000 | 119,000 | 189.78 | 190.06 |
| 1% ACE | 159,000 | 260,000 | 136,000 | 137,000 | 190.46 | 190.12 |
| 0.2% ACE | 249,000 | 397,000 | 224,000 | 180,000 | 192.86 | -** |

*Water surface elevations are derived from the Crockett USGS Rating Curve (Version 15) using the Current Study HEC-RAS Frequency Analysis discharges

**Frequency Storm Discharge not found within the USGS rating curve

The results show the peak discharges from the hydrologic analysis closely align with those of the unsteady hydraulic analysis. The HEC-HMS results are within the 95% confidence limits of the statistical gage analysis. The computed water surface elevations are slightly lower than the water surface elevations from the USGS Crockett gage rating curve gage analysis for all storm events except the 1% ACE, which is slightly higher.

Table 5-6 below compares the computed peak flows computed in the hydrology model and the unsteady HEC-RAS models at the confluences of the studied streams, the Trinity River at Lake Livingston, and the Trinity River at key locations.

**Table 5-6 1% Peak Frequency Flow Comparison for Studied Streams.**

| Location | Computed Peak Flow (cfs) Current Study HEC-HMS Frequency Analysis | Computed Peak Flow (cfs) Current Study HEC-RAS Frequency Storm Analysis |
|---|---|---|
| Confluence of Gail Creek with White Rock Creek | 65,200 | 45,600 |
| Confluence of Hurricane Bayou with Trinity River | 87,500 | 46,200 |
| Confluence of Spring Creek 1 with Hurricane Bayou | 6,700 | 5,400 |
| Confluence of Spring Creek 2 with Gail Creek | 12,400 | 12,100 |
| Confluence of Tantabouge Creek with White Rock Creek | 73,300 | 40,000 |
| Confluence of White Rock Creek with Tantabouge Creek | 142,000 | 67,000 |
| Trinity River at Lake Livingston | 260,000 | 121,000 |
| Trinity River at SH-21 | 125,000 | 130,000 |
| Confluence of Trinity River and Bedias Creek | 125,000 | 125,000 |
| Confluence of Gail Creek with White Rock Creek | 65,200 | 45,600 |

The frequency storm peak water surface elevation tables for all studied streams are located in Appendix E. The inundation mapping for the 1% and 00.2% ACE events are shown in Exhibits E-1 and E-2, respectively, in Appendix E. The inundation mapping for both the 1% ACE and 0.2 % ACE is shown in Exhibit E-3 in Appendix E. The 1% ACE velocity mapping is shown in Exhibit E-4 in Appendix E.

## 5.5 Trinity River boundary condition sensitivity analysis

The downstream boundary condition for the Trinity River hydraulic model was changed from the normal pool elevation of Lake Livingston to a normal depth boundary condition to determine any impacts of tailwater on the modeling results. The revised normal depth boundary condition resulted in a maximum decrease in water surface elevation of 8 feet at cross section 1335 upstream of the lake. The decrease in water surface elevation extends to just downstream of FM-3478 at cross section 213714. The floodplain reduction due to the change in boundary conditions is approximately 5,200 acres, a reduction of approximately 4% of the impacted area.  Seven structures are removed from the 1% ACE event due to the change in downstream boundary conditions. Figure 5-6 compares the 1% ACE inundation mapping with the normal pool boundary condition and the normal depth boundary condition.

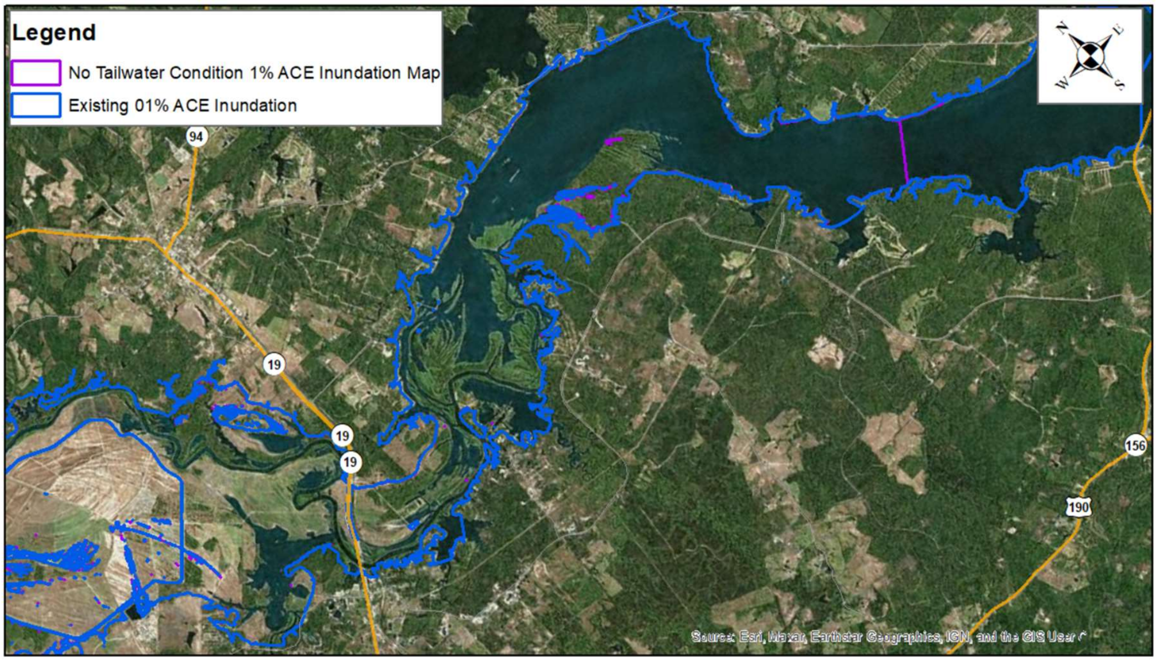


*Figure 5-6 Normal Pool vs. Normal Depth Boundary Condition 1% ACE Inundation Mapping*

## 5.6 Hydraulic analysis conclusions

1D unsteady HEC-RAS models were developed for the Trinity River, Gail Creek, Hurricane Bayou, Spring Creek 1, Spring Creek 2, Tantabogue Creek, and White Rock Creek using flows from the hydrology analysis. The Trinity River hydraulic model was calibrated to two historical events (May-June 2015 and October-November 2015) and validated to one historical event (June-July 2007). Flow roughness factors were used to calibrate the Trinity River mainstem hydraulic model. Factors such as vegetative cover, changing banks, and flowline elevations directly impact a river system's response to varying flows. Since these factors change over time in the Trinity River, the calibration may need to be updated over time and when more historical data is available. Peak water surface elevations were computed for the 10%, 4%, 2%, 1%, and 0.2% ACE flood frequency events for all studied streams. The results show that the peak discharges from the hydrologic analysis are closely aligned with those of the unsteady hydraulic analysis. Inundation mapping for each studied stream was created for the studied streams based on hydraulic modeling results. See Appendix E for an overview of the inundation mapping.

# 6 Environmental review

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

Through this GIS-based evaluation process, a geographic dataset was compiled for the entire study area representing environmental features with the potential to present regulatory constraints (i.e., potential permitting and/or mitigation constraints), including stream impoundments, wetlands, soil types, impaired water surfaces, groundwater resources, water management entities, groundwater wells, endangered species, critical habitat, cultural resources, oil and gas, prime farmland and USACE nationwide permit regional conditions. The purpose of this dataset was to provide the Authority and stakeholders with a planning and scoping tool for prospective flood mitigation projects within the Trinity River Mid-Basin. Additional information about the GIS-based environmental analysis is included in Appendix F.

# 7 Flood mitigation alternatives

A broad range of conceptual flood mitigation alternatives was evaluated to potentially mitigate flooding along the studied streams. The flood mitigation alternatives consisted of levees, dams for distributed regional detention, channelization, and large-scale detention. A flood warning system was also analyzed within the project area. Flood mitigation alternatives were generally evaluated based on the following criteria:

- ability to provide benefits to as many impacted structures as possible
- avoid measurable increases in the extent and magnitude of flooding in another area
- avoid negative impacts to buildings and roadways
- benefit to cost ratio (BCR) equal to one or greater where the total average annual benefits should equal or exceed total average annual costs

Existing structures at risk of flooding were generally dispersed throughout the study area, making identifying specific locations and benefits of flood mitigation alternatives difficult. Also, public participation and stakeholder input helped identify general flooding concerns but not specific locations or preferences for alternatives.

Any negative impacts associated with these alternatives will need to be further evaluated and mitigated per local criteria. Each flood mitigation alternative discussed in this section was independently evaluated utilizing the updated modeling performed as part of this study. Preliminary cost estimates have been developed when appropriate. The preliminary costs are intended for conceptual planning purposes only and are not intended for grant application, bidding, or construction. If pursued, the next step would be to perform detailed studies for these conceptual alternatives before design.

The conceptual flood mitigation alternatives in this report are presented as projects that local sponsors may further consider and evaluate to reduce flood risk. As such, the conceptual flood mitigation alternatives presented do not reflect the position of the Trinity River Authority or study partners as to whether these alternatives should be implemented or how they should be prioritized.

## 7.1 Levees

A broad range of conceptual flood mitigation alternatives were evaluated to mitigate flooding to structures located along the Trinity River, including levees to protect areas prone to flooding from the 1% ACE storm event. A conceptual analysis was prepared with a cursory look at the following:

- hydraulic impacts
- environmental permitting impacts
- project costs
- potential benefits

Levees prevent flood waters from reaching flood-prone areas, reducing the damage to structures and flooding of roadways. FEMA criteria require levees to have a minimum freeboard (height above the 1% ACE water level) of at least three feet for the entire length of the levee and 4 feet of freeboard at the upstream and downstream tie-in locations.

Figure 7-1 shows a typical levee cross section utilized for this analysis. The proposed levees would include a 15-foot-wide crest with an all-weather access/maintenance road on top. The height of the levee was assumed to be four feet above the 1% ACE water level to ensure that FEMA freeboard requirements were met. The proposed levee template was assumed to have 4:1 side slopes with right-of-way to be acquired at a distance of 20 feet beyond each toe. The levee template includes an inspection trench of one-half of the levee height. This conceptual analysis assumes that embankment material suitable for levee construction is located within borrow areas for interior sump drainage.

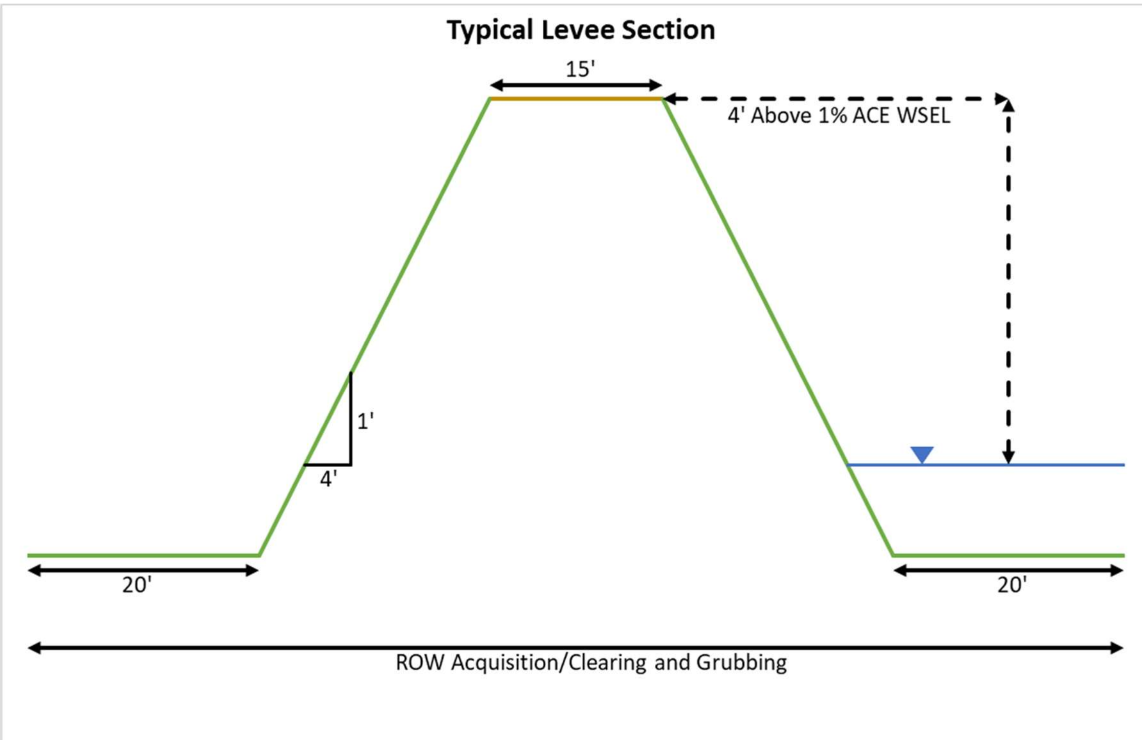


*Figure 7-1 Typical Levee Section*

Several high-level assumptions were made in preparing the cost estimate for new levees, including:

- Start-up/Mobilization: 5% of construction total
- Utility relocation: 3% of construction total
- Levee embankment: 30% compaction factor
- Unit cost of levee embankment: $25 per cubic yard given no geotechnical information (note that levee may have to be zoned, stabilized, and/or suitable fill material hauled in for construction to meet geotechnical requirements)
- Pump station costs: $40 per gallon per minute (pumping capacity assumed equal to one cfs per acre of internal drainage area)

- Sump volume: 0.4 acre-feet per acre of internal drainage area
- Roadway replacement: 6-inch flex base plus 6-inch Hot Mix Asphalt Concrete (HMAC)
- Right-of-way acquisition: $2 per square foot of land
- Construction contingency: 30% due to high-level assumptions
- Operation and maintenance costs not included
- Environmental costs not included

Levees typically require substantial amounts of additional conveyance along the stream corridor because of the reduction in conveyance of the natural valley floodplain. Any negative impacts to flood elevations and severity caused by the reduction in conveyance may require mitigation and a more detailed analysis, which is beyond the scope of this study. Levees also require internal drainage systems to accommodate localized rainfall and associated stormwater runoff from within the levees. Levee interior drainage systems typically include a storm drainage network (ditches and conduit), storage areas (sumps) and an outlet that could include gravity outlets and/or pumping stations. The interior drainage systems were not evaluated for this high-level conceptual analysis.

### *7.1.1 Trinity River levee*

A levee around portions of Trinity River could protect residential structures from the 1% ACE flood. The estimated average height of the levee would be roughly 25 feet tall and have a length of 68,200 feet (13 miles). Interior drainage systems would be required to store and convey runoff from approximately 25,000 acres. The high-level conceptual cost estimate was determined by approximate sizing for pump stations and a sump. The proposed levee could eliminate structural flooding for approximately 11 homes and 27 industrial buildings from the 1% ACE. The proposed alignment can be seen in Exhibit G-2.

**Cost Estimation**

- The estimated project cost for the proposed Trinity River Levee is **between $1,500,000,000 and $2,500,000,000.**

**Environmental Impacts**

- **Land Use** - The levee appears to be located on maintained grassland throughout most of the alignment.
- **Potential Impacts** - The proposed levee would not impact any known cultural or historical sites, oil and gas facilities, park systems, or areas where threatened or endangered species have been observed to occur.
- **Wetlands** - The U.S. Fish and Wildlife Service (USFWS) National Wetland Inventory (NWI) maps indicate several wetlands along the western extent of the levee. A wetland ranking map created by Halff (see Appendix F) suggests several areas of medium wetland potential present along the southeastern and southwestern limits of the proposed levee.

- **Waters of the United States** - A National Hydrography Data (NHD) flowline is seen crossing the southwestern portion of the levee. If it is determined any construction activity would place fill within any water of the United States, coordination with the United States Army Corps of Engineers (USACE) Galveston District will be required.

**Land & Easement Acquisition Required**

- The right-of-way required for the proposed Trinity River Levee is approximately **49 acres**. This includes an estimate for the interior drainage facility, including an area for the sump, pump station, and 20 feet beyond the toe of the levee embankment.

**Benefits**

- **Moderate timeline for implementation** – The estimated timeline for implementation (not including time to obtain funding) is 7-10 years due to the required property and easement acquisition and estimated timeline to construct the levee.
- **Remove property from the 1% ACE floodplain** – This flood mitigation alternative could be utilized to eliminate structural flooding for all 11 at-risk homes from the 1% ACE in the Trinity River floodplain.

**Constraints**

- **Levee compliance and permitting** – The levee must be designed and constructed following FEMA's levee criteria to remove the 1% ACE floodplain from the FEMA Flood Insurance Rate Maps (FIRM). The regulations governing levees and related flood risk management are primarily found in Title 44 of the Code of Federal Regulations (44 CFR). Specifically, 44 CFR Part 65 contains the National Flood Insurance Program (NFIP) regulations related to floodplain management and levee certification. These regulations outline the requirements for levee certification, maintenance, and flood risk management within the context of the NFIP. Compliance with these regulations is necessary for communities to participate in the NFIP and for property owners to be eligible for federal flood insurance. Once a levee is constructed, the owner would be responsible for the significant effort required to maintain FEMA compliance, including**:**
    - Inspections: Frequent inspections by qualified personnel to identify and address any issues, such as erosion or damage, promptly
    - Vegetation Management: Proper maintenance of vegetation on levees to prevent root penetration that could compromise structural integrity
    - Monitoring and Surveillance: Ongoing monitoring of conditions, including instrumentation to detect seepage or breaches
    - Operation and Maintenance Manual: Development and adherence to a comprehensive manual outlining regular maintenance tasks and procedures
    - Emergency Action Plan: Preparation of an emergency response plan to address potential breaches or failures

  - Record Keeping: Accurate records of maintenance activities, inspections, and certifications
  - Community Education: Public education and awareness programs to inform local communities about levee risks, maintenance, and emergency response
- **Environmental impacts** – Construction could potentially impact water quality, wildlife, and trees.
- **Internal drainage challenges** –Internal drainage for the local rainfall that falls behind the levee must be considered to avoid increasing localized flooding inside the proposed levee. An internal drainage system would be required to drain approximately 25,000 acres of drainage area located inside the levee.

##### *7.1.1.1 Trinity River levee results*

The levee was added to the unsteady HEC-RAS model along the Trinity River to analyze the hydrologic and hydraulic impacts due to the levee. A summary of the results is provided below.

- The local flow being held by the levee peaks much earlier than the flood wave caused by the headwaters, resulting in no reduction to the peak flow and an increase in water surface elevations upstream (maximum of 2.75 ft).
- This change in water surface elevation increases the flood severity on several existing structures, and resultant increases in the flood inundation impact additional structures previously not inundated.
- The levee also causes a longer period of inundation downstream due to the reduction in conveyance through the levee.
- The peak flow decreases downstream of the levee. However, this decrease is insignificant (less than 1% difference) and results in longer periods of inundation both upstream and downstream of the levee.

### *7.1.2 Spring Creek 2 levees*

A levee was placed on each bank of Spring Creek 2 from SH 19 to just upstream of its confluence with Gail Creek to analyze the potential hydraulic impacts a levee could have along a tributary. Each levee is approximately 20 feet tall and 6 miles long. The approximate internal drainage area of both levees combined is 5,400 acres. The two levees protect seven houses from the 1% ACE flood event. The alignment of the levees is shown in Figure 7-4.

**Cost Estimation**

- The estimated project cost for the proposed Spring Creek 2 Levees is **between $500,000,000 and $1,000,000,000**.

**Environmental Impacts**

- **Land Use** - The levee appears to be located on maintained grassland throughout most of the alignment.

- **Potential Impacts** - The proposed levee would not impact any known cultural or historical sites, oil and gas facilities, park systems, or areas where threatened or endangered species have been observed to occur.
- **Wetlands** - The U.S. Fish and Wildlife Service (USFWS) National Wetland Inventory (NWI) maps indicate several wetlands along the western extent of the levee. A wetland ranking map created by Halff (see Appendix F) suggests several areas of medium wetland potential present along the southeastern and southwestern limits of the proposed levee.
- **Waters of the United States** - A National Hydrography Data (NHD) flowline is seen crossing the southwestern portion of the levee. If it is determined any construction activity would place fill within any water of the United States, coordination with the United States Army Corps of Engineers (USACE) Galveston District will be required.

**Land & Easement Acquisition Required**

- The right-of-way required for the proposed Spring Creek 2 Levees is approximately 95 acres. This includes an estimate for the interior drainage facility, including an area for the sump, pump station, and 20 feet beyond the toe of the levee embankment.

**Benefits**

- **Moderate timeline for implementation** – The estimated timeline for implementation (not including time to obtain funding) is 7-10 years due to the required property and easement acquisition and estimated timeline to construct the levee.
- **Remove property from the 1% ACE floodplain** – This flood mitigation alternative could be utilized to eliminate structural flooding for all seven at-risk homes from the 1% ACE in the Trinity River floodplain.

**Constraints**

- **Levee compliance and permitting** – The levees must be designed and constructed following FEMA's levee criteria to remove the 1% ACE floodplain from the FEMA Flood Insurance Rate Maps (FIRM). The regulations governing levees and related flood risk management are primarily found in Title 44 of the Code of Federal Regulations (44 CFR). Specifically, 44 CFR Part 65 contains the National Flood Insurance Program (NFIP) regulations related to floodplain management and levee certification. These regulations outline the requirements for levee certification, maintenance, and flood risk management within the context of the NFIP. Compliance with these regulations is necessary for communities to participate in the NFIP and for property owners to be eligible for federal flood insurance. Once a levee is constructed, the owner is responsible for the significant effort required to maintain FEMA levee compliance, including**:**
  - Inspections: Frequent inspections by qualified personnel to identify and address any issues, such as erosion or damage, promptly

- Vegetation Management: Proper maintenance of vegetation on levees to prevent root penetration that could compromise structural integrity
- Monitoring and Surveillance: Ongoing monitoring of conditions, including instrumentation to detect seepage or breaches
- Operation and Maintenance Manual: Development and adherence to a comprehensive manual outlining regular maintenance tasks and procedures
- Emergency Action Plan: Preparation of an emergency response plan to address potential breaches or failures
- Record Keeping: Accurate records of maintenance activities, inspections, and certifications
- Community Education: Public education and awareness programs to inform local communities about levee risks, maintenance, and emergency response

- **Environmental impacts** – Construction could potentially impact water quality, wildlife, and trees.
- **Internal drainage challenges** –Internal drainage for the local rainfall that falls behind the levees must be considered to avoid increasing localized flooding inside the proposed levee. An internal drainage system would be required to drain approximately 5,400 acres of drainage area located inside the levees.

##### *7.1.2.1 Spring Creek 2 levee results*

The levees were added to the unsteady HEC-RAS model along Spring Creek 2 to analyze the hydrologic and hydraulic impacts due to the levee. A summary of the results is provided below.

- The local flow being held by the levee peaks much earlier than the flood wave caused by the headwaters, resulting in no reduction to the peak flow and an increase in water surface elevations upstream (maximum of 3.73 ft).
- This change in water surface elevation increases the flood severity to SH19, just upstream.
- The peak flow decreases downstream of the levee. However, this decrease is insignificant (less than 1% difference) and results in longer periods of inundation both upstream and downstream of the levee.
- Impacts to flow rates due to the levees were calculated along Gail Creek downstream, causing increases in water surface elevations.

## 7.2 Spring Creek 2 channelization

Channelization along the downstream end of Spring Creek 2 from approximately 8000 ft downstream oc CR 4020 to its confluence with Gail Creek was considered as well. The channel geometry consisted of a trapezoidal section with a bottom width of 500 feet and 4:1 (horizontal: vertical) side slopes. The bed slope is set at a 0.3% slope to ensure that water will still drain after the channelization. Figure 7-2 shows a typical channel section for the proposed channelization.

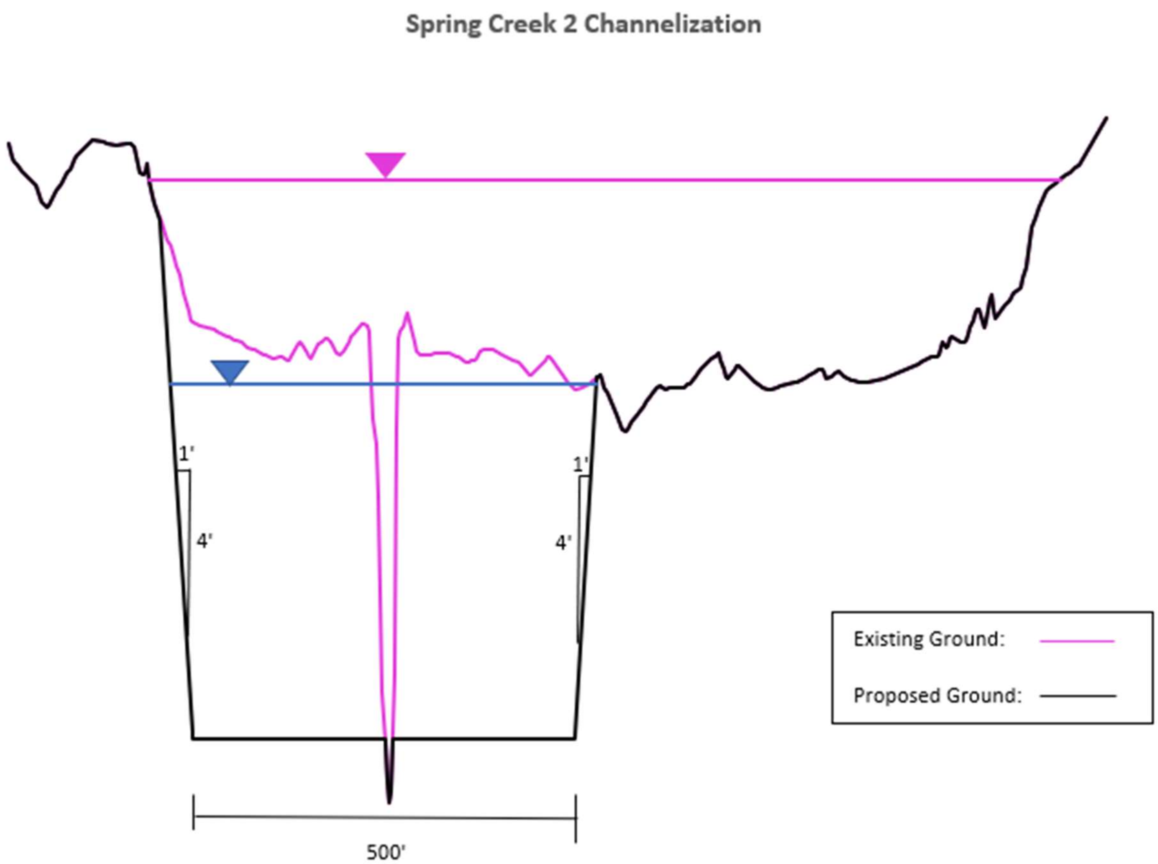


*Figure 7-2 Typical Channelization Cross Section*

**Cost Estimation**

- The estimated project cost for the proposed Spring Creek 2 Channelization is **between $250,000,000 to $750,000,000**.

**Benefits**

- **Lower Water Surface Elevations** – The channelization results in lower water surface elevations (up to **3.5 feet** along Spring Creek 2 and up to **0.05 feet** along Gail Creek).

**Constraints**

- **Excavation** – Approximately **1.8 million cubic yards** of excavation is needed.
- **Permitting –** The excavation analyzed is below the ordinary high-water mark, which requires special permitting.
- **Reduction of Overall Inundation** – The total reduction in inundated area is approximately 100 acres (2%).

#### *7.2.1.1 Spring Creek 2 channelization results*

The levees were added to the unsteady HEC-RAS model along Spring Creek 2 to analyze the hydrologic and hydraulic impacts due to the levee. A summary of the results is provided below.

- The local flow being held by the levee peaks much earlier than the flood wave caused by the headwaters, resulting in no reduction to the peak flow and an increase in water surface elevations upstream (maximum of 3.73 ft).
- This change in water surface elevation increases the flood severity to SH19, just upstream.
- There is a decrease in the peak flow downstream of the levee. However, this decrease is insignificant (less than 1% difference) and again results in larger periods of inundation both upstream and downstream of the levee.
- Impacts to flowrates due to the levees were calculated along Gail Creek downstream, causing increases in water surface elevations.

## 7.3 Large-Scale detention

A large-scale detention alternative was evaluated to determine the scale of mitigation required to measurably reduce discharges downstream. Detention was evaluated at the upstream end of the study area along the main stem of the Trinity River to mitigate flooding in repetitive loss areas. A conceptual inline dam was modeled at the Anderson County line with an inline dry detention basin. The potential storage volume created by the impoundment is modeled as filling a stage-storage curve, calculated based on the topography above the conceptual inline dam. This conceptual analysis only reviewed the hydrologic parameters of this alternative, investigating the volume requirements for a discharge reduction of 50% for the 1% ACE. Future conceptual analysis of this alternative should include considerations for the hydraulic design of the detention area, inline structure, and outlet.

**Cost Estimation**

- The estimated conceptual project cost for the large-scale detention is approximately **$15 – $20 billion**.

**Benefits**

- **Lower water surface elevations in the Trinity River** – Water surface elevations would be lowered in the Trinity River from the Anderson County line to the headwaters of Lake Livingston, ranging from **0.01 feet to 5.5 feet**.
- **Mitigates repetitive loss areas** – Reduction of repetitive loss areas during the 1% ACE.

**Constraints**

- **Land acquisition** – Requires approximately 80,000 acres of land.
- **Required Volume** - Requires approximately **1.5 million-acre–feet** of detention to reduce water surface elevations in the Trinity River.
- **Non-Uniform Mitigation Impacts** – Mitigation impacts along the Trinity River are not uniform. For some areas, the flood mitigation is excessive, while flooding in other areas requires additional flood mitigation beyond the regional detention.
- **Environmental Impacts** – The proposed regional detention area could potentially impact water quality, wildlife, and trees.

The large-scale detention has an approximate volume of 1,500,000 acre-feet and covers 77,400 acres (121 square miles). The peak elevation calculated within the detention area was mapped. Figure 7-3 shows the location of the potential regional detention to demonstrate the size of this alternative.

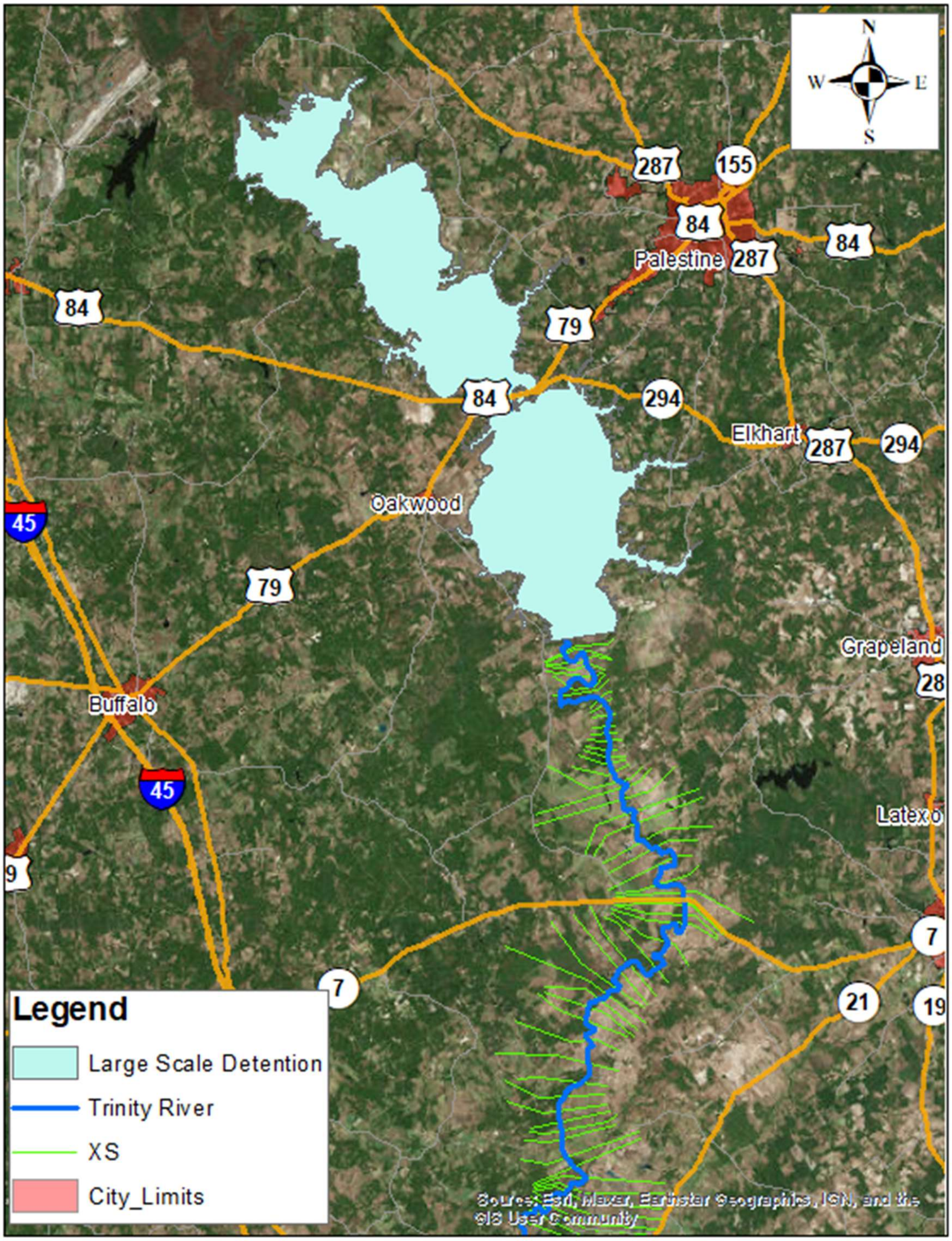


*Figure 7-3 Potential Large-Scale Regional Detention Location*

## 7.4 Distributed regional detention

National Resource Conservation Service (NRCS) dams are placed on tributaries along streams to help reduce peak inflow by slowing the release of water into the stream during storm events. Because these dams are placed along the stream, the floodplain is reduced along the whole stream instead of one or two localized areas. NRCS dams were analyzed along Hurricane Bayou, with a total of three dams being modeled.

Three tributaries to Hurricane Bayou were identified that had high peak flows with noticeable impacts on the Hurricane Bayou floodplain. The three tributaries identified were Flat Branch (confluence at cross section 150206), Hammond Creek (confluence at cross section 136106), and Spring Creek (confluence at cross section 119677). Adding the NRCS Dams to each tributary decreased the water surface elevations, ranging from 0.01 to 2.5 feet and a reduction in flow ranging from 6,000 to 17,000 cfs beginning at cross section 150829.

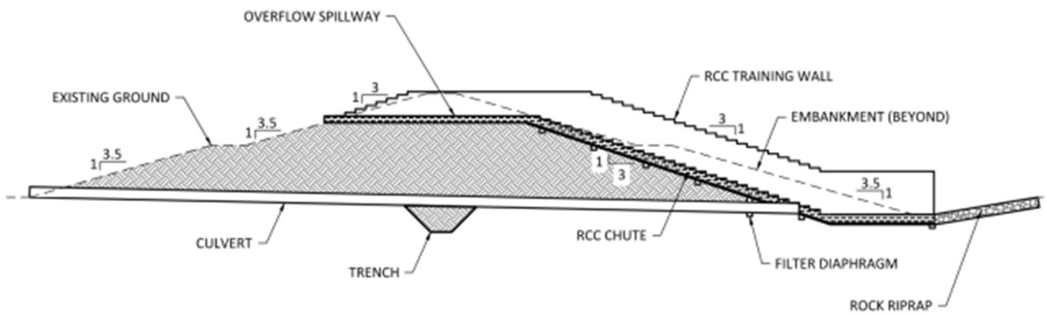


*Figure 7-4 Typical NRCS Dam Cross section*

**Cost Estimation**

- The estimated conceptual project cost for all three NRCS dams is **$121,356,000**.

**Benefits**

- **Lower 1% ACE water surface elevations** – Water surface elevations are lowered in Hurricane Bayou, ranging from **0.01 feet to 2.5 feet**.
- **Mitigates impacts** – Reduced flooding along Hurricane Bayou results in a smaller 1% ACE flood inundation area.

**Constraints**

- **Excavation** - Approximately 2 million cubic yards of fill is needed to construct the embankment.
- **Environmental impacts** - The proposed NRCS dams could potentially impact water quality, wildlife, and trees.

## 7.5 Flood warning analysis

A flood warning analysis was performed for the USGS gage near Crockett, Texas. The purpose of developing a flood warning system is to warn people about an approaching flood with adequate time to evacuate and provide information about nearby roads and properties that could become inundated. To analyze a potential flood warning system, a multitude of flows applied in the Trinity River model starting at the USGS Gage near Crockett, Texas. At each bridge downstream of SH 7, Halff determined the amount of flow that the USGS gage would detect that would cause the roadway to become inundated as well as the time until the roadway would become inundated. Table 7-1 shows the minimum flows for inundation for each road crossing downstream of SH 7 along the Trinity River, as well as the amount of time it would take for the flood wave to inundate the road. Figure 7-5 shows an example of the inundation mapping for the 100,000 cfs flow at SH 19 and Union Pacific Railroad. Figure 7-6 shows the SH 19 cross section maximum inundation result from the model.

**Table 7-1 Bridge Flood Warning System at USGS Gage near Crockett.**

| Road | Minimum Flow for Inundation (cfs) | Approximate Time Until Inundation | Road | Minimum Flow for Inundation (cfs) |
|---|---|---|---|---|
| SH 21 | 100,000 | 16 hours | SH 21 | 100,000 |
| FM 3478 | 75,000 | 54 hours | FM 3478 | 75,000 |
| SH 19 | 100,000 | 64 Hours | SH 19 | 100,000 |
| Union Pacific Railroad | 150,000 | 64 Hours | Union Pacific Railroad | 150,000 |

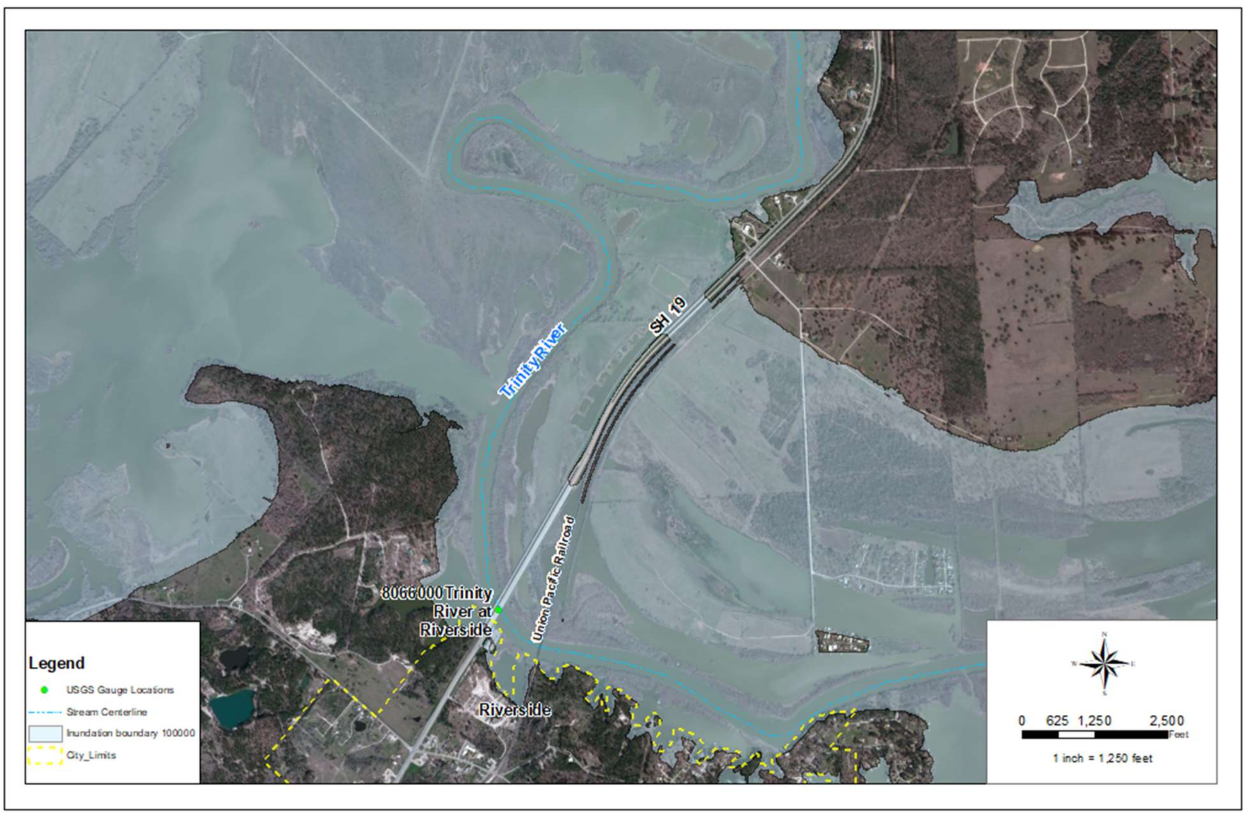


*Figure 7-5 Flood Warning Mapping*

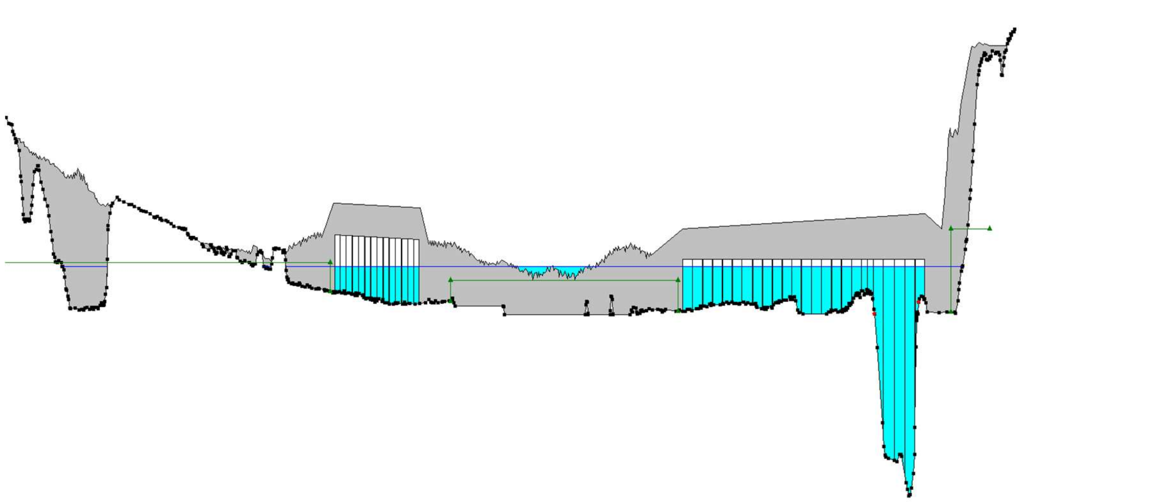

*Figure 7-6 SH 19 100,000 CFS Maximum Inundation*

**Benefits**

- **Relatively low cost** – potential grants for new gages
- **More data** – Additional gages provide a better understanding of the study area from a hydrologic and hydraulic perspective and more accurate models in the future. More data could also lead to better emergency response decisions.

**Constraints**

- **Maintenance** – Gages are typically maintained by USGS, involving a partnership and maintenance costs.
- **Environmental impacts** - The proposed NRCS Dams could potentially impact water quality, wildlife, and trees.

### *7.5.1 Future Flood Warning Analysis on Tributaries*

Due to a lack of gages and data along the tributaries, no flood warning analysis could be performed during this study. USGS Gages were put in place and began recording data in 2021 on Gail Creek, Hurricane Bayou, and Tantabogue Creek (USGS Gage08066087 Gail Ck at FM 1280 Near Lovelady, Texas, USGS Gage 08065340 Hurricane Bayou at US-287 Near Crockett, Texas, and USGS Gage Tantabogue Creek at FM 230 Near Lovelady, Texas respectively). These gages currently only record stage data and do not have existing rating curves. In the future, flood warning systems could be analyzed for these streams as more data becomes available.

## 7.6 Potential alternative environmental impacts

Levee height improvements may entail lateral expansion of the levee footprint, introducing potential impacts to waters of the United States regulated under Section 404 of the Clean Water Act (Section 404). USACE utilizes nationwide permits for categories of activities that cause only minimal individual and cumulative negative impacts. Nationwide Permit 3 – *Maintenance* (NWP 3) is often used to authorize levee rehabilitation, replacement, or improvement projects where the proposed action involves fill in waters of the United States. In determining the applicability of nationwide permits, the project must also assess the project's effects on threatened and endangered species and cultural resources, each of which can often be mitigated if present. According to the nationwide permit regional conditions for the USACE Galveston District, the District will not issue a nationwide permit authorization for activities in the Columbia Bottomland land cover type. NWP 3 is an exception to this condition; however, the applicant must notify the USACE before commencing the project.

In contrast, the scope of large-scale detention would require large land acquisition in the Mid Trinity River 0.1% ACE inundation areas in Anderson and Freestone counties. Either of these alternatives would impact the United States' waters, the scale of which would likely exceed those allowed under a nationwide or standard individual permit. All regulatory actions under Section 404 must comply with the National Environmental Policy Act (NEPA). NEPA requires an environmental impact statement (EIS) when a project is federally controlled (or federally permitted), and the project is likely to significantly impact the quality of the human environment, even after mitigation factors are considered. Although requirements differ among scenarios, an EIS must address the total impact on the environment and consider numerous factors, including but not limited to:

- the environmental impact of the proposed action (e.g., waters of the United States, threatened and endangered species, downstream flows, cultural resources, land use/communities)
- any negative environmental effects which cannot be avoided should the proposal be implemented
- alternatives to the proposed action
- mitigation actions

The completion of an EIS is the responsibility of the federal agency controlling the project (USACE), which is also responsible for any legal consequences of the EIS. The USACE may prepare its own EIS or may require the permit applicant to hire a contractor to work with the USACE to prepare an EIS as part of the permit decision process. If the document is prepared under a contract, the USACE must participate in the preparation and will independently evaluate the statement before its approval. The EIS is used as a comprehensive document when deciding to approve or deny the proposed Section 404 action.

## 7.7 Economic analysis

An economic analysis was developed to identify and quantify the extent of flood problems and, on a comparable basis, evaluate solutions to reduce flood losses. The FEMA Benefit-Cost Analysis (FEMA BCA, Version 6.0) software was utilized to develop the economic analysis of the flood reduction alternatives. For each alternative, a base flood damage assessment was developed to represent the expected (average) annual damages if no alternatives were implemented based on the water surface elevations computed with the hydraulic model developed for this study (see Appendix E). A “with the project” flood damage assessment was developed to represent the expected annual damages if the alternative was selected and implemented.

Parcel data was collected for Houston, Leon, Madison, Polk, San Jacinto, Trinity, and Walker County appraisal districts and compiled into a single shapefile. The estimated finished floor elevation was developed by intersecting the parcel layer with the study terrain data. Survey elevations of structures were not obtained for this high-level feasibility economic analysis. The parcel data included the building use which consisted of commercial, single-family houses, or mobile homes. Structure value and land value were included for each parcel.

Damage curves were assigned to each building type based on the occupancy type. The damage curves define the relations of damage to a structure for each foot of flood height in the building. The damage is determined as a percentage of the total structure value. Damage curves were also used to determine the amount of damage to the contents of each building in relation to the flood depths.

Water surface profile elevations for flood events based on the Trinity River Mid-Basin Watershed Study results were used for the base flood damage assessment, and additional hydraulic models were developed for each local alternative to determine the reduction in the water surface elevations. Estimated reduction in damages for each alternative are included in Appendix G.

## 7.8 Benefit cost analysis

A Benefit-Cost Analysis (BCA) was performed for the flood mitigation alternatives. The BCA was established as the standard to provide technical and financial assistance for implementing flood or hazard mitigation undertakings. The BCA compares the future flood risk reduction benefits of a proposed project to the cost of implementing the project, which results in a benefit-cost ratio (BCR). The minimum criteria for state and federal funding is a BCR of 1.0 or greater, meaning that the benefit(s) of the proposed project would equal or exceed the cost of the project. Benefit increases if flooding occurs at structures during more frequent storm events. Halff calculated BCRs for five alternatives, as shown in Figure 7-2. High-level cost estimates for each project are included in Appendix G.

**Table 7-2 Cost benefit ratios.**

| Alternative | Estimated Total Project Cost | Damages Prevented or Avoided | BCR |
|---|---|---|---|
| Trinity River Levee | $1,500,000,000 to $2,500,000,000 | $12,000,000 | 0.01 |
| Spring Creek 2 Levee | $500,000,000 to $1,000,000,000 | $400,000 | 0.01 |
| Spring Creek 2 Channelization | $250,000,000 to $750,000,000 | $320,000 | 0.01 |
| Large Scale Detention | $15,000,000,000 to $20,000,000,000 | $50,000,000 | 0.01 |
| Distributed Regional Detention | $100,000,000 to $400,000,000 | $330,000 | 0.01 |

*Notes: Discount Rate assumed to be 7%, analysis period is 50 years, and monetary values reflect 2023 dollars and cost estimates*

## 7.9 Conclusion and recommendations

The Trinity River Mid-Basin Watershed Study evaluated several high-level feasibility alternatives to reduce flood risk along the Trinity River and several of its tributaries. The flood mitigation objectives were to minimize flooding risk to structures within the 1% ACE floodplain and to focus on areas with large numbers of FEMA flood insurance claims and repetitive losses.

Local levee alternatives were analyzed along Trinity River and Spring Creek 2. The revised modeling shows significant hydrologic and hydraulic impacts created by constructing these potential levees. These local alternatives have a high project cost, lengthy development period, complex permitting, and potentially significant environmental impacts.

Distributed Regional Detention could be implemented along Hurricane Bayou to offer flood protection for crops and pasture lands.

Large-scale alternatives were found to provide flood protection to some areas and little to no protection to other areas. The large alternatives have an extremely high cost, lengthy development period, complex permitting, challenging property acquisition, and significant environmental impacts.

The flood mitigation alternatives developed for the Trinity River Mid-Basin Watershed Study are high-level feasibility studies. The alternatives, damages, and costs were analyzed at a preliminary level. Any results from this study, including post-project flood risk and estimated project costs, must be refined if selected for further evaluation. A no negative impact analysis will be required in order to meet criteria to classify the alternative as a flood mitigation project.

Based on local feedback, the losses due to flooding are primarily crops and cattle. Landowners could benefit greatly through the implementation of a flood warning system. The flood warning system could alert landowners before flooding, allowing them to move cattle, harvest crops, or implement emergency flood protection measures before flood waters inundate their land. The modeling provided with this study provides timing, severity of inundation, and length of inundation for multiple events and can be used as a basis for designing a flood warning system. Additional streamflow gages along the major tributaries, Upper and Lower Keechi, Boggy Creek, and Bedias Creek, would help strengthen the flood warning system and future modeling within the area. A flood warning system would need to be analyzed further to be implemented. However, no structural flood mitigation alternative is recommended based on the findings of this study.

A BCA was performed for the flood mitigation alternatives. The minimum criteria for state and federal funding is a BCR of 1.0 or greater, meaning that the benefit(s) of the proposed project would equal or exceed the cost of the project.  The calculated BCR for each flood mitigation alternative is approximately 0.01.

The Region 3 Trinity Regional Flood Planning Group (RFPG) established a deadline of January 27, 2023, for all potentially feasible flood mitigation actions to be submitted for consideration of potential inclusion in the Amended Regional Flood Plan. The alternatives in the Mid-Basin study were being developed at that time. The RFPG deadline did not algin with the Mid-Basin schedule. The flood warning system is recommended to be submitted to the RFPG as a flood mitigation strategy for potential inclusion in the next planning cycle.

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