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TWDB CONTRACTS

April 30, 2019

National Weather Service Hydrologic Model Calibration

Calibration of Flood Forecasting Models for Sub-basins of the San Jacinto River and Buffalo Bayou in Texas

Prepared for

The Texas Water Development Board
In Cooperation With:
The National Weather Service
West Gulf River Forecast Center

Prepared by

RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

TWDB Contract No. 1800012243

Final Report
1800012243

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March 2019

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The Texas Water Development Board
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Prepared by

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Executive Summary

The Texas Water Development Board (TWDB) is supporting improvements to flood forecasting capacity for the National Weather Service's West Gulf River Forecast Center (WGRFC). Working for the TWDB, RTI International (RTI) calibrated hydrologic models for 28 sub-basins located in southeast Texas in the San Jacinto River and Buffalo Bayou basins. Implementation of these models will enable the WGRFC to improve the forecast accuracy, in terms of timing and magnitude, of large flood events and to expand the number of locations where forecasts are issued. These improvements to flood forecasting capacity will enhance the ability of the WGRFC to protect the public through advance warning of potentially dangerous flood events.

The model calibration activities accomplished by RTI during this study include:

- Pre-Calibration Data Analysis: Prior to beginning the hydrologic model calibration, several datasets were analyzed to provide information to the model calibration team. This information enabled the team to identify any quality issues in the historical time series data, to better understand the impacts of diversions and significant gains/losses within the modeled sub-basins, and to select appropriate model parameter values that are representative of conditions within the modeled areas. The data analysis activities included estimating potential evapotranspiration (PET) demand within the modeled sub-basins and the development of a historical water balance, the results of which are provided in Section 3.5 of this report.

- Unit Hydrograph Model Development: For each modeled sub-basin, RTI developed a 1-hour unit hydrograph (UH) model for use with the calibrated runoff model. For sub-basins with high quality historical observed hourly (or more frequent) streamflow data, manual analysis techniques were utilized. For sub-basins where observed streamflow data were not available or where the data quality were poor, RTI used spatial geo-datasets and Geographic Information Systems (GIS) tools to generate a synthetic UH model. The initially-developed UH models were tested and refined, as needed, during the model calibration analysis. Further information on the UH model development methods is provided in Section 4.3 of this report.

- Streamflow Routing Model Calibration: Of the 28 sub-basins included in the hydrologic model calibration analysis, half are local areas where streamflow from upstream sub-basins must be accounted for when forecasting total flows at the forecast location. In addition, three headwater sub-basins upstream of Addicks Reservoir within the Buffalo Bayou basin receive overflow from Cypress Creek during large flood events. To simulate the movement of these incoming flows through the river network within the sub-basin, routing models were applied and calibrated. These models, which utilize the Lag/K routing method, account for the travel time through the modeled river reach, as well as the attenuation of the flood event peaks which results from channel and overbank storage. Within the 14 modeled local areas, there are a total of 27 upstream river reaches which require Lag/K routing models. More information on the completed streamflow routing model calibration methodology and results is provided in Section 4.1 of this report. Further description of the modeling of the Cypress Creek overflow is provided in Section 4.7.

- Runoff Model Calibration: To model the amount of the event precipitation that yields runoff (both surface and sub-surface) and the corresponding travel time of the runoff to the local stream network, the Sacramento Soil Moisture Accounting (SAC-SMA) model was applied and calibrated for all 28 study sub-basins. The SAC-SMA model provides a conceptual rainfall-runoff model that utilizes various parameters to replicate the physical hydrologic processes. The model calibration analysis involved adjusting the SAC-SMA parameter values until predictions from the model simulation most closely match the historical observed streamflow response. The model calibration team followed the calibration techniques and guidelines published by Anderson (2002). More information on the SAC-SMA model and calibration methods is provided in Section 4.2 of this report.
- Diversion and Gain/Loss Model Development: Within the study region, there are streamflow diversions related to municipal uses, as well as other natural sources of gains/losses that need to be accounted for in the hydrologic modeling. To model these influences, RTI incorporated additional model operations that remove or add flows to the stream channel. The most significant gain/loss in the study area is an overflow of flood runoff that occurs from Cypress Creek into the Addicks Reservoir drainage area. This overflow was modeled using LOOKUP, WEIGH-TS, and LAG/K operations, as described in more detail in Section 4.7.
- Evaluation of Existing Reservoir Modeling: RTI performed an evaluation of the existing WGRFC RES-J models of Addicks and Barker Reservoirs using the collected historical datasets. The evaluation included testing the models in historical simulation mode and identifying where model refinements may be warranted. The results of this evaluation are given in Section 4.8.

Following completion of the model calibration activities, RTI imported the final hydrologic models into the WGRFC's Community Hydrologic Prediction System (CHPS) configuration, tabulated the final hourly simulation statistics using the STAT-Q utility, and assembled the final project report (this document).

The final calibrated hydrologic models will provide the WGRFC with significant improvements to the current flood forecasting skill within the study region. The developed models provide simulation of streamflow at a 1-hour modeling time step, an increase in temporal resolution over the 3-hour time step currently used for forecasts in much of the study region. This improvement is significant, particularly for modeling flood events in the highly developed parts of the west and northwest Houston metropolitan area, where peaks form extremely rapidly.

Within the San Jacinto River basin, the final calibrated models resulted in a correlation (measured as R) between the simulated and observed hourly total streamflow ranging from 0.742 to 0.971 and average discharge ratios (simulated/observed) for the recent major floods of April 2016 (Tax Day Flood), May 2016 (Memorial Day Flood), and August 2017 (Hurricane Harvey) of 1.032, 0.985, and 1.079, respectively. The average annual total streamflow volume bias over the modeled historical calibration period ranged from -12.7% to 12.2%.

Within the Buffalo Bayou basin, the final calibrated models resulted in a correlation (measured as R) between the simulated and observed hourly total streamflow ranging from 0.834 to 0.997 and average discharge ratios (simulated/observed) for the recent major floods of April 2016 (Tax Day Flood) and August 2017 (Hurricane Harvey) of 1.27 and 1.24. The average annual total streamflow volume bias over the modeled historical calibration period ranged from -11.1% to 1.0%.

1. INTRODUCTION

In recent years, several severe flooding events have occurred in southeast Texas, resulting in loss of life and significant property damages. In the San Jacinto River and Buffalo Bayou basins in the Houston metropolitan area, major flooding occurred on April 17-18, 2016, as a result of 12 to 16 inches of rainfall within a 12 hour period. This event, known as the Tax Day Flood, resulted in seven fatalities and flooding of an estimated 9,820 structures. Shortly after this event, additional flooding occurred in north and northwest Harris County on May 26-27, 2016, due to an estimated 8 to 13 inches of rain. This event, known as the Memorial Day Flood, resulted in flooding along Spring, Willow, and Cypress creeks and the San Jacinto River, inundating an estimated 1,300 structures (HCFCD 2018a). In August 2017, Hurricane Harvey resulted in catastrophic flooding over large areas in both the San Jacinto and Buffalo Bayou basins. Rainfall totals from Harvey over a four-day period ranged from 26 to 47 inches within Harris County. These record totals caused an estimated $125 billion in damages and resulted in 36 flood-related deaths (HCFCD 2018b).

In an effort to improve the flood warnings for extreme events such as these, and thereby better protect the public, the Texas Water Development Board (TWDB) is supporting the National Weather Service (NWS) to improve and expand its hydrologic prediction services in southeast Texas. To assist in these efforts, RTI International (RTI) is working with the West Gulf River Forecast Center (WGRFC) to enhance the accuracy of the hydrologic models used for flood forecasting within the San Jacinto River and Buffalo Bayou basins. In completing this task, RTI has performed data quality control and water balance analyses, calibration of the Sacramento Soil Moisture Accounting (SAC-SMA) model for 14 headwater sub-basins and 14 local areas, development of 28 unit hydrograph models (UNIT-HG), and Lag/K routing model calibration for 27 river reaches. In addition, RTI investigated and accounted for streamflow diversions and gains/losses within the modeled areas and evaluated existing modeling of Addicks and Barker Reservoirs to identify potential model (RES-J) improvements.

Figure 1 shows a map of the project region, highlighting the modeled sub-basin areas. Table 1 presents a list of the modeled sub-basin areas along with the NWS identification codes, streamflow station numbers, and sub-basin names.

Figure 1. Project Region Showing Final Sub-Basin Delineations

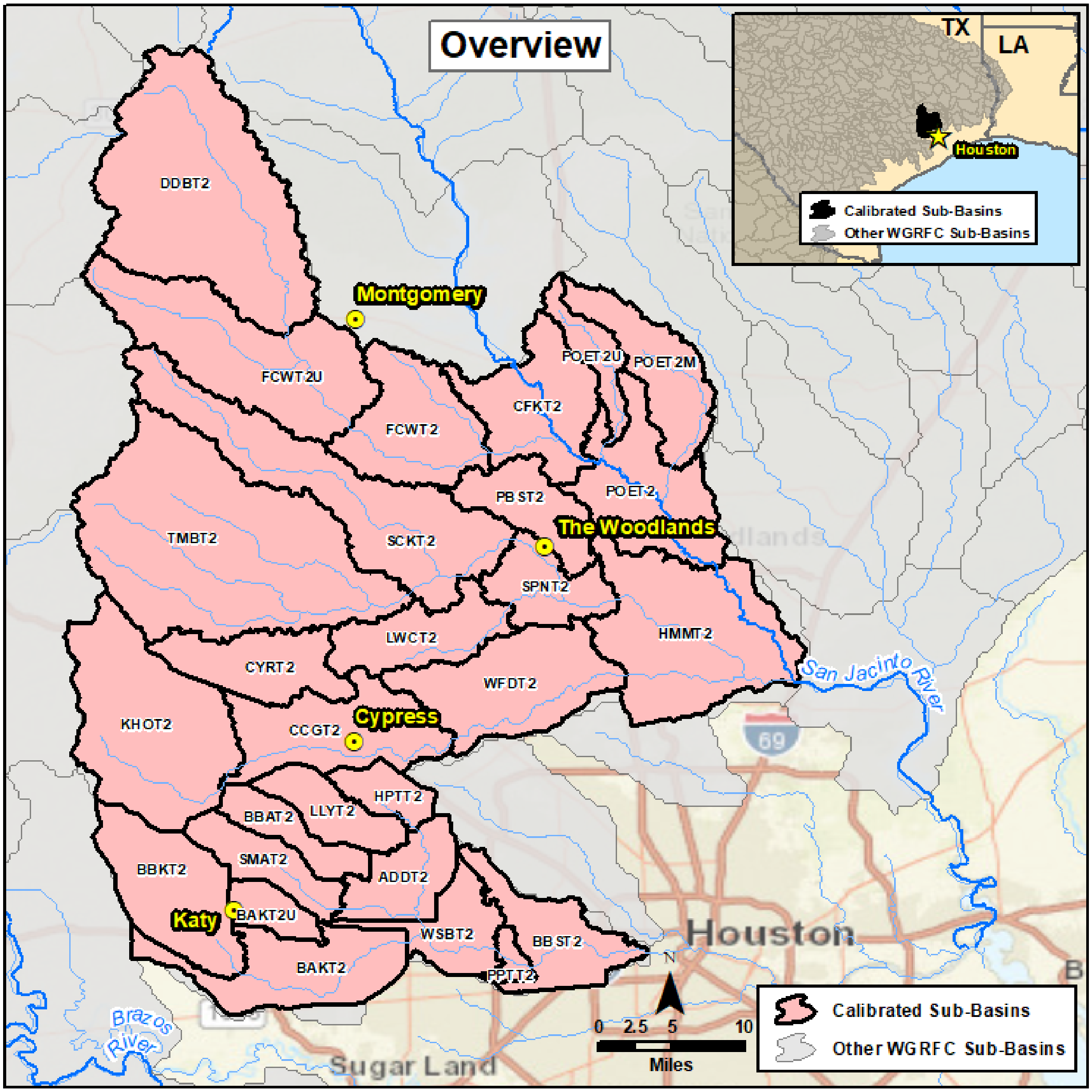


Table 1. List of Modeled Sub-basins

NWS ID	USGS/HCFCD GAGE ID	Sub-basin Name	Sub-basin Type
		San Jacinto River	
DDBT2	08067690	Lake Ck nr Dobbin, TX	Headwater
FCWT2U	08067800	Lake Ck nr Karen, TX	Local Area
FCWT2	08067920	Lake Ck at Sendera Ranch Rd nr Conroe, TX	Local Area
CFKT2	08068000	W Fk San Jacinto Rv nr Conroe, TX	Local Area
POET2U	No Gage	Stewarts Creek at Crighton Rd	Headwater
POET2M	No Gage	Crystal Creek at FM1314	Headwater
POET2	08068090	W Fk San Jacinto Rv Abv Lk Houston nr Porter, TX	Local Area
PBST2	08068450	Panther Br nr Spring, TX	Headwater
TMBT2	08068275/1070	Spring Ck nr Tomball, TX	Headwater
SCKT2	08068310/1060	Spring Ck at Kuykendahl, The Woodlands, TX	Local Area
LWCT2	08068325/1320	Willow Ck nr Tomball, TX	Headwater
SPNT2	08068500/1050	Spring Ck nr Spring, TX	Local Area
CYRT2	08068780/1220	Little Cypress Ck nr Cypress, TX	Headwater
KHOT2	08068720/1180	Cypress Ck at Katy-Hockley Rd nr Hockley, TX	Headwater
CCGT2	08068800/1160	Cypress Ck at Grant Rd nr Cypress, TX	Local Area
WFDT2	08069000/1120	Cypress Ck nr Westfield, TX	Local Area
HMMT2	08069500/760	W Fk San Jacinto Rv nr Humble, TX	Local Area
		Buffalo Bayou	
HPTT2	2130	Horsepen Creek at Trailside Drive	Headwater
LLYT2	08072760/2120	Langham Ck at W Little York Rd nr Addicks, TX	Headwater
BBAT2	08072730/2160	Bear Ck nr Barker, TX	Headwater
SMAT2	08072680	S Mayde Ck at Heathergold Dr nr Addicks, TX	Headwater
ADDT2	08073100/2110	Langham Ck at Addicks Res Outflow nr Addicks, TX	Local Area
BAKT2U	2020	Mason Creek at Prince Cr Dr abv Barker	Headwater
BBKT2	08072300/2030	Buffalo Bayou nr Katy, TX	Headwater
BAKT2	08072600/2010	Buffalo Bayou at State Hwy 6 nr Addicks, TX	Local Area
WSBT2	08073600/2270	Buffalo Bayou at W Belt Dr, Houston, TX	Local Area
PPTT2	08073700	Buffalo Bayou at Piney Point, TX	Local Area
BBST2	08074000/2240	Buffalo Bayou at Houston, TX	Local Area

2. PROJECT DELIVERABLES

As is outlined in the project's scope of work, Exhibit B of the final contract (TWDB Contract No. 1800012243), RTI has delivered the following items to the TWDB and WGRFC upon completion of this study.

- *Final Task Report* - This report provides a summary of the work performed during the study. It serves as a useful reference regarding basin characteristics and hydrologic model performance, particularly for hydrologic forecasters at the WGRFC.
- *CHPS/FEWS Calibration Configurations* – A standalone version of the NWS Community Hydrologic Prediction System (CHPS/FEWS calibration configuration of the study area (San Jacinto River and Buffalo Bayou) was provided by the WGRFC. RTI updated the configuration with final model parameters for the LAG/K, SAC-SMA, and UNIT-HG models and incorporated additional LOOKUP and CHANLOSS operations to model the impacts of the Cypress Creek overflow and municipal diversions downstream of Addicks and Barker Reservoirs. The configuration allowed the WGRFC to review the performance of the calibrations and should ease the transfer of necessary files when updating the operational forecast system.
- *NWSRFS Model Decks and Files* – In addition to the CHPS/FEWS calibration configurations, the legacy NWSRFS decks and files used by RTI for model calibration were provided to the WGRFC as an additional reference. The decks provide a simple guide with respect to the number and sequence of operations defined for a sub-basin in a single file. This can assist in identifying what operations were added and updated in the CHPS/FEWS configurations. Furthermore, the NWSRFS decks and files offer a simple way to compare the performance of the before and after calibration simulations through the use of the Interactive Calibration Program (ICP).
- *Additional Supporting Information* – Throughout the course of the study, RTI provided the WGRFC and TWDB with additional information relevant to the sub-basins and scope of work including spatial data sets, project field photographs, data analysis results, and calibration tools and methodologies.

3. PRE-CALIBRATION DATA ANALYSIS

A thorough analysis of sub-basin characteristics and historical datasets was performed by RTI to provide information to support model calibration. This analysis included an assessment of basin characteristics, soils, and land cover, as described in Section 3.1; an analysis of the historical precipitation time series inputs utilized by the models, described in Section 3.2; development of potential evapotranspiration (PET) estimates, described in Section 3.3; review and quality control of available historical observed streamflow data, described in Section 3.4; and finally, a water balance analysis to identify potential historical data issues or other influences that impact total streamflow volume at observed locations, described in Section 3.5. Conducting these analyses prior to calibration provided the RTI model calibration team with a better understanding of regional basin characteristics, sub-basin hydrologic response, sub-basins that contain potential diversions or other gains/losses, and possible calibration challenges.

3.1 Basin Characteristics

Sub-basin drainage area boundaries were delineated using GIS tools based on forecast point locations provided by the WGRFC and a 30-meter digital elevation model (DEM). These boundaries were used to identify or calculate various basin characteristics including area, elevations, major land resource areas, soil textures, hydrologic soil groups and land cover. This information was beneficial during hydrologic model calibration as an aid to the model calibration team in model parameter selection and for checking the relative consistency of the calibration results between sub-basins. Summaries of the basin characteristics by river basin are provided in Tables 2a and 2b. Descriptions of each characteristic category are also provided in the sub-sections below.

Table 2a. Physical/Hydrologic Characteristics of the Calibrated San Jacinto River Sub-Basins

NWSID	Local/Total Basin Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
DDBT2	155 / 155	475 / 321 / 201	Texas Blackland Prairie, Southern Part; Western Coastal Plain	Clay: 40% Clay Loam: 26% Sand: 21% Minor classes: 13%	A: 0%; B: 27%; C: 21%; D: 52%; W: 0%	Pasture/Hay: 46% Evergreen Forest: 21% Woody Wetlands: 9% Shrub/Scrub: 8% Grassland/Herbaceous: 5% Mixed Forest: 4% Developed, Open Space: 3% Developed, Low Intensity: 2% Other: 2%
FCWT2U	101 / 256	442 / 287 / 166	Texas Blackland Prairie, Southern Part; Western Coastal Plain	Clay: 61% Clay Loam: 15% Sand: 12% Minor classes: 12%	A: 0%; B: 32%; C: 16%; D: 52%; W: 0%	Pasture/Hay: 45% Evergreen Forest: 16% Woody Wetlands: 9% Mixed Forest: 9% Shrub/Scrub: 7% Grassland/Herbaceous: 4% Developed, Open Space: 4% Developed, Low Intensity: 3% Other: 3%
FCWT2	59 / 315	383 / 225 / 127	Texas Blackland Prairie, Southern Part; Western Coastal Plain	Clay Loam: 24% Clay: 22% Sand: 19% Sandy Clay: 18% Minor classes: 17%	A: 0%; B: 49%; C: 18%; D: 33%; W: 0%	Evergreen Forest: 22% Woody Wetlands: 16% Mixed Forest: 14% Grassland/Herbaceous: 13% Pasture/Hay: 10% Developed, Open Space: 8% Shrub/Scrub: 8% Developed, Low Intensity: 6% Other: 3%

(continued)

Table 2a. Physical/Hydrologic Characteristics of the Calibrated San Jacinto River Sub-Basins (continued)

NWSID	Local/Total Basin Drainage Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
CFKT2	57 / 828	380 / 191 / 97	Western Coastal Plain; Western Gulf Coast Flatwoods	Clay: 32% Sandy Clay: 26% Loamy Sand: 13% Sand: 12% Minor classes: 17%	A: 0%; B: 54%; C: 11%; D: 35%; W: 0%	Mixed Forest: 17% Woody Wetlands: 16% Evergreen Forest: 16% Developed, Open Space: 13% Developed, Low Intensity: 12% Shrub/Scrub: 6% Developed, Medium Intensity: 5% Grassland/Herbaceous: 5% Pasture/Hay: 4% Developed, High Intensity: 3% Other: 0%
POET2U	19 / 19	411 / 248 / 118	Western Coastal Plain; Western Gulf Coast Flatwoods	Sandy Clay: 55% Loamy Sand: 27% Sandy Clay Loam: 11% Minor classes: 7%	A: 0%; B: 90%; C: 10%; D: 0%; W: 0%	Developed, Low Intensity: 19% Evergreen Forest: 15% Developed, Open Space: 15% Mixed Forest: 15% Shrub/Scrub: 10% Developed, Medium Intensity: 9% Woody Wetlands: 8% Developed, High Intensity: 4% Grassland/Herbaceous: 3% Other: 2%
POET2M	44 / 44	406 / 225 / 106	Western Coastal Plain; Western Gulf Coast Flatwoods	Sand: 43% Sandy Clay: 26% Sandy Clay Loam: 19% Loamy Sand: 13% Minor classes: -1%	A: 0%; B: 75%; C: 25%; D: 0%; W: 0%	Mixed Forest: 21% Evergreen Forest: 17% Shrub/Scrub: 15% Developed, Open Space: 14% Developed, Low Intensity: 9% Grassland/Herbaceous: 9% Woody Wetlands: 7% Developed, Medium Intensity: 3% Pasture/Hay: 2% Other: 3%

(continued)

Table 2a. Physical/Hydrologic Characteristics of the Calibrated San Jacinto River Sub-Basins (continued)

NWSID	Local/Total Basin Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
POET2	64 / 955	247 / 132 / 59	Western Coastal Plain; Western Gulf Coast Flatwoods	Sand: 34% Silt Loam: 25% Clay: 24% Sandy Clay Loam: 12% Minor classes: 5%	A: 0%; B: 35%; C: 20%; D: 45%; W: 0%	Developed, Open Space: 16% Woody Wetlands: 16% Mixed Forest: 15% Evergreen Forest: 14% Developed, Low Intensity: 13% Developed, Medium Intensity: 6% Grassland/Herbaceous: 5% Shrub/Scrub: 4% Barren Land (Rock/Sand/Clay): 2% Open Water: 2% Developed, High Intensity: 2% Emergent Herbaceous Wetlands: 2% Other: 3%
PBST2	35 / 35	227 / 172 / 105	Western Coastal Plain; Western Gulf Coast Flatwoods	Sandy Clay: 32% Sand: 28% Loamy Sand: 16% Sandy Clay Loam: 14% Silt Loam: 10% Minor classes: 0%	A: 0%; B: 72%; C: 19%; D: 9%; W: 0%	Developed, Low Intensity: 31% Developed, Open Space: 20% Developed, Medium Intensity: 20% Evergreen Forest: 8% Mixed Forest: 6% Woody Wetlands: 5% Shrub/Scrub: 3% Developed, High Intensity: 3% Grassland/Herbaceous: 2% Other: 2%
TMBT2	187 / 187	446 / 263 / 140	Western Coastal Plain; Gulf Coast Prairies	Sand: 29% Sandy Clay Loam: 29% Sandy Clay: 13% Clay Loam: 13% Sandy Loam: 10% Minor classes: 6%	A: 1%; B: 48%; C: 39%; D: 13%; W: 0%	Pasture/Hay: 27% Evergreen Forest: 19% Shrub/Scrub: 12% Developed, Open Space: 11% Mixed Forest: 8% Woody Wetlands: 7% Grassland/Herbaceous: 5% Developed, Low Intensity: 5% Deciduous Forest: 4% Other: 2%

(continued)

Table 2a. **Physical/Hydrologic Characteristics of the Calibrated San Jacinto River Sub-Basins (continued)**

NWSID	Local/Total Basin Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
SCKT2	111 / 299	442 / 239 / 111	Texas Blackland Prairie, Southern Part; Western Coastal Plain; Gulf Coast Prairies	Sandy Clay: 34% Sand: 17% Loamy Sand: 17% Clay Loam: 15% Sandy Clay Loam: 12% Minor classes: 5%	A: 0%; B: 68%; C: 17%; D: 15%; W: 0%	Evergreen Forest: 24% Mixed Forest: 15% Shrub/Scrub: 12% Developed, Open Space: 11% Pasture/Hay: 10% Developed, Low Intensity: 9% Woody Wetlands: 8% Grassland/Herbaceous: 5% Developed, Medium Intensity: 3% Other: 3%
LWCT2	40 / 40	245 / 173 / 117	Western Coastal Plain; Gulf Coast Prairies	Sandy Clay Loam: 60% Sandy Loam: 29% Sand: 11% Minor classes: 0%	A: 2%; B: 13%; C: 71%; D: 14%; W: 0%	Pasture/Hay: 30% Evergreen Forest: 16% Developed, Open Space: 13% Developed, Low Intensity: 12% Developed, Medium Intensity: 6% Grassland/Herbaceous: 5% Deciduous Forest: 4% Shrub/Scrub: 3% Developed, High Intensity: 3% Woody Wetlands: 2% Mixed Forest: 2% Other: 4%
SPNT2	32 / 406	186 / 134 / 78	Western Coastal Plain; Gulf Coast Prairies	Sand: 62% Sandy Clay Loam: 24% Minor classes: 14%	A: 0%; B: 51%; C: 46%; D: 3%; W: 0%	Developed, Low Intensity: 25% Developed, Open Space: 18% Evergreen Forest: 14% Developed, Medium Intensity: 10% Woody Wetlands: 9% Mixed Forest: 8% Pasture/Hay: 7% Shrub/Scrub: 2% Grassland/Herbaceous: 2% Barren Land (Rock/Sand/Clay): 2% Developed, High Intensity: 2%

(continued)

Table 2a. Physical/Hydrologic Characteristics of the Calibrated San Jacinto River Sub-Basins (continued)

NWSID	Local/Total Basin Drainage Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
CYRT2	42 / 42	294 / 216 / 147	Gulf Coast Prairies	Sandy Clay Loam: 62% Sandy Loam: 38% Minor classes: 0%	A: 1%; B: 2%; C: 76%; D: 21%; W: 0%	Pasture/Hay: 49% Cultivated Crops: 16% Developed, Open Space: 7% Woody Wetlands: 5% Developed, Low Intensity: 4% Deciduous Forest: 4% Grassland/Herbaceous: 3% Evergreen Forest: 3% Shrub/Scrub: 2% Developed, Medium Intensity: 2% Other: 5%
KHOT2	104 / 104	315 / 215 / 120	Gulf Coast Prairies	Sandy Clay Loam: 40% Sandy Loam: 34% Clay Loam: 26% Minor classes: 0%	A: 1%; B: 2%; C: 54%; D: 43%; W: 0%	Pasture/Hay: 60% Cultivated Crops: 20% Woody Wetlands: 4% Developed, Open Space: 4% Shrub/Scrub: 3% Emergent Herbaceous Wetlands: 2% Other: 7%
CCGT2	63 / 209	225 / 158 / 101	Gulf Coast Prairies	Sandy Clay Loam: 41% Sandy Loam: 30% Loam: 17% Clay Loam: 12% Minor classes: 0%	A: 0%; B: 1%; C: 57%; D: 42%; W: 0%	Pasture/Hay: 26% Developed, Low Intensity: 14% Developed, Medium Intensity: 14% Developed, Open Space: 13% Cultivated Crops: 10% Woody Wetlands: 7% Evergreen Forest: 3% Developed, High Intensity: 3% Emergent Herbaceous Wetlands: 2% Grassland/Herbaceous: 2% Shrub/Scrub: 2% Other: 4%

(continued)

Table 2a. Physical/Hydrologic Characteristics of the Calibrated San Jacinto River Sub-Basins (continued)

NWSID	Local/Total Basin Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
WFDT2	70 / 280	174 / 132 / 67	Western Coastal Plain; Gulf Coast Prairies	Sandy Clay Loam: 60% Sandy Loam: 39% Minor classes: 1%	A: 0%; B: 1%; C: 75%; D: 24%; W: 0%	Developed, Medium Intensity: 29% Developed, Low Intensity: 26% Developed, Open Space: 20% Developed, High Intensity: 6% Evergreen Forest: 6% Pasture/Hay: 5% Woody Wetlands: 2% Grassland/Herbaceous: 2% Deciduous Forest: 2% Other: 2%
HMMT2	105 / 1746	169 / 96 / 41	Western Coastal Plain; Western Gulf Coast Flatwoods; Gulf Coast Prairies	Sand: 20% Clay: 20% Silt Loam: 18% Sandy Clay Loam: 16% Sandy Loam: 12% Other: 10% Minor classes: 4%	A: 0%; B: 17%; C: 39%; D: 44%; W: 0%	Evergreen Forest: 16% Developed, Medium Intensity: 16% Developed, Low Intensity: 15% Developed, Open Space: 14% Woody Wetlands: 12% Mixed Forest: 10% Developed, High Intensity: 6% Shrub/Scrub: 3% Grassland/Herbaceous: 3% Open Water: 2% Other: 3%

Table 2b. Physical/Hydrologic Characteristics of the Calibrated Buffalo Bayou Sub-Basins

NWSID	Local/Total Basin Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
HPTT2	13 / 13	169 / 136 / 100	Gulf Coast Prairies	Clay Loam: 48% Sandy Loam: 30% Sandy Clay Loam: 14% Minor classes: 8%	A: 0%; B: 0%; C: 27%; D: 73%; W: 0%	Developed, Medium Intensity: 36% Developed, Low Intensity: 21% Developed, Open Space: 17% Developed, High Intensity: 8% Grassland/Herbaceous: 3% Woody Wetlands: 3% Evergreen Forest: 2% Cultivated Crops: 2% Open Water: 2% Other: 6%
LLYT2	26 / 26	164 / 142 / 82	Gulf Coast Prairies	Clay Loam: 48% Sandy Loam: 28% Loam: 13% Sandy Clay Loam: 11% Minor classes: 0%	A: 0%; B: 0%; C: 23%; D: 77%; W: 0%	Pasture/Hay: 31% Developed, Medium Intensity: 21% Cultivated Crops: 16% Developed, Low Intensity: 12% Developed, Open Space: 8% Developed, High Intensity: 3% Grassland/Herbaceous: 2% Shrub/Scrub: 2% Other: 5%
BBAT2	23 / 23	177 / 147 / 100	Gulf Coast Prairies	Clay Loam: 70% Sandy Loam: 30% Minor classes: 0%	A: 0%; B: 0%; C: 7%; D: 93%; W: 0%	Pasture/Hay: 41% Cultivated Crops: 20% Developed, Medium Intensity: 9% Developed, Low Intensity: 7% Developed, Open Space: 7% Shrub/Scrub: 5% Woody Wetlands: 3% Evergreen Forest: 2% Grassland/Herbaceous: 2% Developed, High Intensity: 2% Other: 2%

(continued)

Table 2b. Physical/Hydrologic Characteristics of the Calibrated Buffalo Bayou Sub-Basins (continued)

NWSID	Local/Total Basin Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
SMAT2	28 / 28	177 / 147 / 103	Gulf Coast Prairies	Clay Loam: 70% Sandy Loam: 30% Minor classes: 0%	A: 0%; B: 0%; C: 7%; D: 93%; W: 0%	Pasture/Hay: 41% Cultivated Crops: 23% Developed, Medium Intensity: 11% Developed, Low Intensity: 7% Developed, Open Space: 7% Shrub/Scrub: 3% Grassland/Herbaceous: 2% Developed, High Intensity: 2% Other: 4%
ADDT2	34 / 125	145 / 107 / 50	Gulf Coast Prairies	Clay Loam: 62% Sandy Loam: 26% Loam: 12% Minor classes: 0%	A: 0%; B: 0%; C: 7%; D: 93%; W: 0%	Developed, Medium Intensity: 27% Woody Wetlands: 18% Developed, Open Space: 14% Developed, Low Intensity: 13% Evergreen Forest: 7% Developed, High Intensity: 7% Shrub/Scrub: 3% Deciduous Forest: 3% Grassland/Herbaceous: 3% Mixed Forest: 3% Other: 2%
BAKT2U	15 / 15	184 / 137 / 95	Gulf Coast Prairies	Clay Loam: 70% Sandy Loam: 30% Minor classes: 0%	A: 0%; B: 0%; C: 7%; D: 93%; W: 0%	Developed, Medium Intensity: 26% Developed, Low Intensity: 16% Pasture/Hay: 15% Developed, Open Space: 11% Cultivated Crops: 11% Developed, High Intensity: 8% Grassland/Herbaceous: 4% Barren Land (Rock/Sand/Clay): 4% Shrub/Scrub: 2% Other: 3%

(continued)

Table 2b. Physical/Hydrologic Characteristics of the Calibrated Buffalo Bayou Sub-Basins (continued)

NWSID	Local/Total Basin Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
BBKT2	61 / 61	204 / 161 / 99	Gulf Coast Prairies	Clay Loam: 67% Sandy Loam: 29% Minor classes: 4%	A: 0%; B: 0%; C: 7%; D: 93%; W: 0%	Pasture/Hay: 43% Cultivated Crops: 30% Developed, Open Space: 8% Developed, Low Intensity: 5% Developed, Medium Intensity: 4% Shrub/Scrub: 2% Woody Wetlands: 2% Grassland/Herbaceous: 2%
BAKT2	58 / 134	171 / 111 / 80	Gulf Coast Prairies	Clay Loam: 63% Sandy Loam: 27% Minor classes: 10%	A: 0%; B: 0%; C: 8%; D: 91%; W: 0%	Developed, Medium Intensity: 25% Woody Wetlands: 16% Developed, Low Intensity: 13% Developed, Open Space: 10% Shrub/Scrub: 7% Pasture/Hay: 7% Cultivated Crops: 7% Developed, High Intensity: 5% Grassland/Herbaceous: 3% Emergent Herbaceous Wetlands: 3% Barren Land (Rock/Sand/Clay): 2% Deciduous Forest: 2%
WSBT2	31 / 290	139 / 86 / 45	Gulf Coast Prairies	Loam: 43% Clay Loam: 22% Sandy Loam: 15% Clay: 14% Minor classes: 6%	A: 0%; B: 1%; C: 16%; D: 83%; W: 0%	Developed, Medium Intensity: 29% Developed, Low Intensity: 17% Developed, High Intensity: 17% Woody Wetlands: 14% Developed, Open Space: 13% Evergreen Forest: 5% Shrub/Scrub: 2% Other: 3%

(continued)

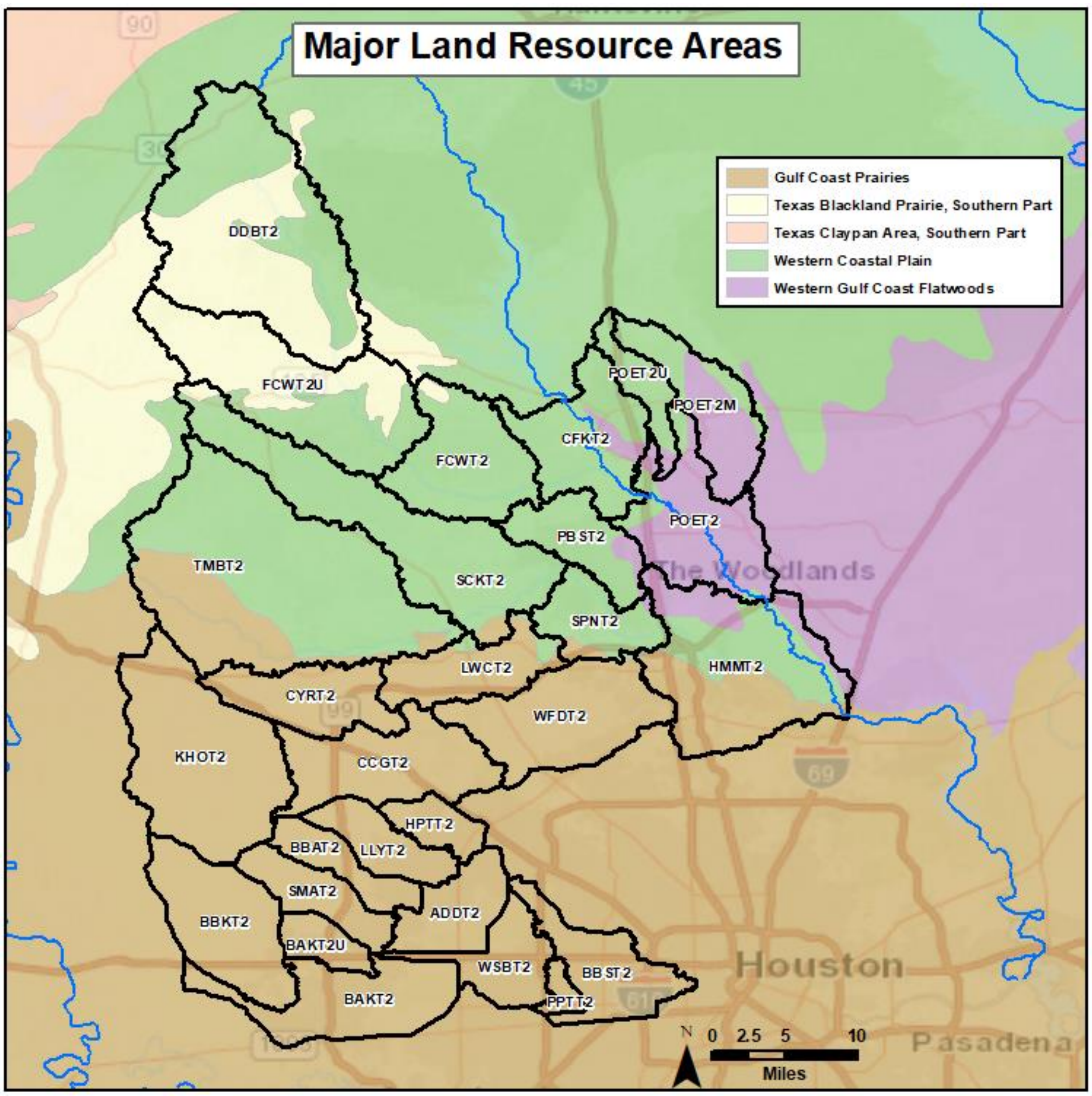
Table 2b. Physical/Hydrologic Characteristics of the Calibrated Buffalo Bayou Sub-Basins (continued)

NWSID	Local/Total Basin Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Hydrologic Soil Groups	Predominant Land Cover (NLCD 2011)
PPTT2	6 / 297	106 / 72 / 37	Gulf Coast Prairies	Loam: 43% Clay: 34% Clay Loam: 13% Sandy Loam: 10%	A: 0%; B: 0%; C: 12%; D: 88%; W: 0%	Developed, Low Intensity: 34% Developed, Medium Intensity: 30% Developed, High Intensity: 21% Developed, Open Space: 13%
BBST2	41 / 338	118 / 70 / 3	Gulf Coast Prairies	Loam: 46% Clay: 38% Minor classes: 16%	A: 0%; B: 0%; C: 11%; D: 89%; W: 0%	Developed, Low Intensity: 30% Developed, Medium Intensity: 29% Developed, High Intensity: 24% Developed, Open Space: 13% Evergreen Forest: 4%

3.1.1 Major Land Resource Areas

Major land resource areas (MLRAs) are part of the US Natural Resources Conservation Service (NRCS) land classification system, in which geographically similar regions are defined and described by similar soils, land use, climate, and hydrologic characteristics. The MLRA classifications are helpful for hydrologic model calibration by providing general information on properties which have a known influence on model parameters values. There are five MLRAs within the study area. Figure 2 shows a map of the MLRAs and sub-basin delineation. Descriptions of each MLRA are available in the United States Department of Agriculture Handbook 296. The MLRA data were obtained from 2006 MLRA Geographic Database, version 4.2 (USDA-NRCS 2006).

Figure 2. Major Land Resource Areas in the Study Area



3.1.2 Soils Data

Analysis of soil properties helps the model calibration team assess values for the model parameters that primarily control the simulation of percolation and baseflow. Guidelines for these parameters (ZPERC, REXP, and PBASE [calculated as LZFPM*LZPK+LSFSM*LZSK]) are shown in Table 3 (Anderson 2002 Table 7-5-2). By understanding the physical properties of the soil column, one can assess whether these align with the conceptual parameters of the model.

Table 3. SAC-SMA Parameter Ranges for Various Soil Types (Anderson 2002 Table 7-5-2)

General soil type	Hydrograph characteristics	Initial ZPERC and REXP
Clay	Frequent surface runoff, Little baseflow (max of 1 mm/day), PBASE: 2 - 4 mm/day	ZPERC: 150 - 300 REXP: 2.5 - 3.5
Silt	Some surface runoff - especially during larger storms, Moderate amount of baseflow (max of around 2 mm/day), PBASE: 4 - 8 mm/day	ZPERC: 40 - 150 REXP: 1.8 - 2.5
Sandy	No surface runoff or only during the very largest storm events, Considerable baseflow (max greater than 2.5 mm/day), PBASE: greater than 8 mm/day	ZPERC: 20 - 40 REXP: 1.4 - 1.8

Gridded soil texture and hydrologic soil groups datasets were obtained from Pennsylvania State University's Center for Environmental Informatics (CEI) Soil Information for Environmental Modeling and Ecosystem Management (Pennsylvania State University 2006). The CEI developed soil characteristics data sets based on the State Soil Geographic Database (STATSGO) available from the NRCS.

The soil texture data includes 1-km grids of the dominant soil texture for 11 different depths below the surface as defined in Figure 3. Soil-DOM, a GIS tool developed by RTI was used to calculate the percentages of each soil texture within each sub-basin boundary. Texture classes covering less than 10% of the sub-basin area were grouped as minor classes.

Figure 3. Soil Texture Classifications (Pennsylvania State University 1999)

Standard Layer	Thickness (cm)	Depth to Top of Layer (cm)	Depth to Bottom of Layer (cm)
1	5	0	5
2	5	5	10
3	10	10	20
4	10	20	30
5	10	30	40
6	20	40	60
7	20	60	80
8	20	80	100
9	50	100	150
10	50	150	200
11	50	200	250

Soil Depth

Class No.	Soil Texture Class	Class Abbreviation
1	Sand	S
2	Loamy Sand	LS
3	Sandy Loam	SL
4	Silt Loam	SiL
5	Silt	Si
6	Loam	L
7	Sandy Clay Loam	SCL
8	Silty Clay Loam	SiCL
9	Clay Loam	CL
10	Sandy Clay	SC
11	Silty Clay	SiC
12	Clay	C
13	Organic Materials	OM
14	Water	W
15	Bedrock	BR
16	Other	O

Soil Texture Class

The hydrologic soils groups (HSGs) were established by the NRCS to determine a soil's associated runoff curve number, which is used to estimate direct runoff from rainfall in the TR-55 method (USDA-NRCS 2007). A summary of the HSG classifications (A,B,C, D, and W) follows (Purdue University 2017).

HSG Class A*. This class includes sands, loamy sands, or sandy loams that have low runoff potential and high infiltration rates, even when thoroughly wetted. Soil layers are primarily deep, well-drained to excessively drained, and have a high rate of water transmission.*

HSG Class B*. This class includes silt loams and loams that have a moderate infiltration rate when thoroughly wetted. Soil layers are primarily moderately deep to deep, moderately well-drained to well-drained, and have a moderate rate of water transmission.*

HSG Class C*. This class includes sandy clay loams that have low infiltration rates when thoroughly wetted. Soil layers often include features that impede downward movement of water and have a slow rate of water transmission.*

HSG Class D*. This class includes clay loams, silty clay loams, sandy clays, silty clays, and clays. This HSG has the highest runoff potential, with soil layers that have very low infiltration rates when thoroughly wetted. Soils in this class are often characterized by high swelling potentials, permanent high water tables, claypan or clay layers at or near the surface, and shallow depths over nearly impervious material. These soils have a very slow rate of water transmission.*

HSG Class W*. This class includes all permanent water features*.

The HSG gridded dataset is a 1-km resolution grid, which shows the percentages of the HSG classes contained within each cell. In conjunction with this dataset, Soil-HSG, a GIS tool developed by RTI, was used to calculate the total HSG percentages within each sub-basin boundary.

3.1.3 Land Cover

Similar to soils data, land cover and land use (LCLU) summaries can help inform and provide the model calibration team with a physical basis for specifying model parameter values. Spatial data (at a resolution of 30 meters) on land cover/land use were obtained from the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Database (NLCD) (NLCD 2011). The total area of each LCLU classification was computed for each modeled sub-basin using GIS tools and then converted to a percentage. LCLU classes consisting of less than 1% of the sub-basin area were grouped as "other".

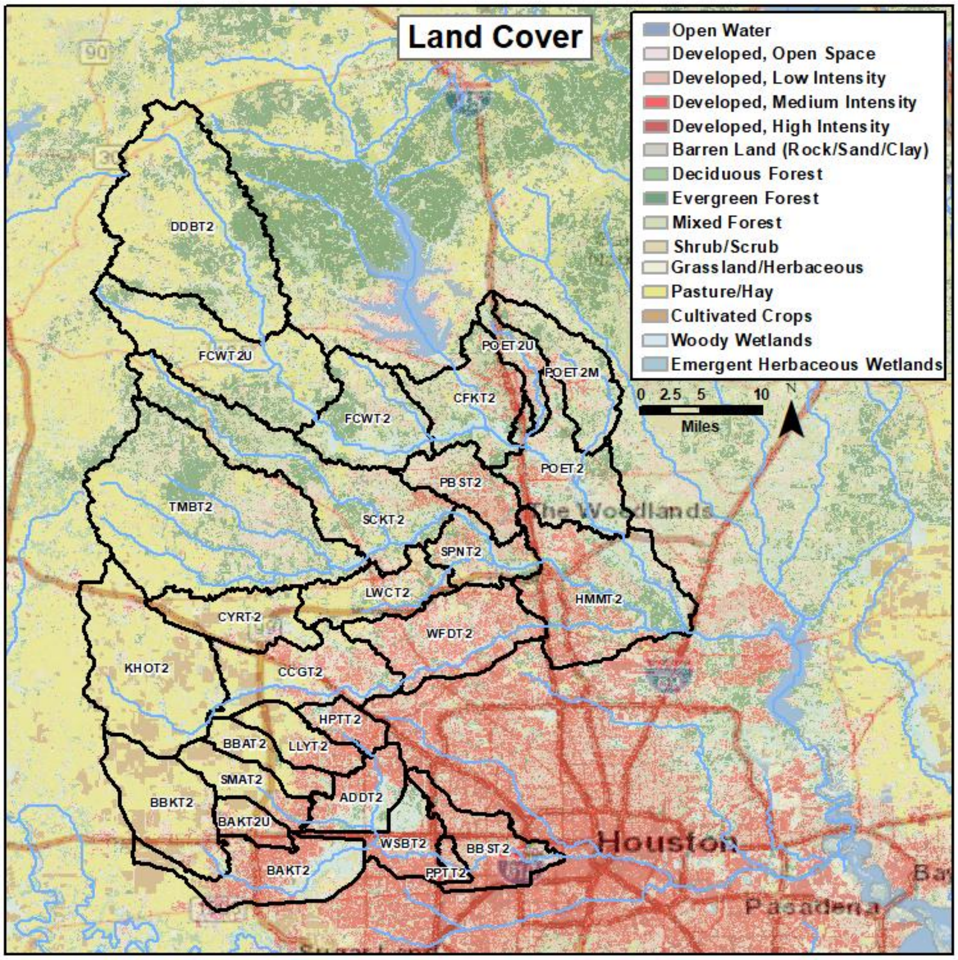
Figure 4 shows a map of the modeled sub-basins with the associated 15 LCLU classes in the region. Descriptions (from NLCD 2011 metadata information) of these classes are provided below:

1. *Open Water- areas of open water, generally with less than 25% cover of vegetation or soil.*
2. *Developed, Open Space- areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.*
3. *Developed, Low Intensity- areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.*
4. *Developed, Medium Intensity -areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.*
5. *Developed High Intensity-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.*
6. *Barren Land (Rock/Sand/Clay) - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.*
7. *Deciduous Forest- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.*
8. *Evergreen Forest- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.*

9. *Mixed Forest- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.*
10. *Shrub/Scrub- areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.*
11. *Grassland/Herbaceous- areas dominated by graminoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.*
12. *Pasture/Hay-areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.*
13. *Cultivated Crops -areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.*
14. *Woody Wetlands- areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.*
15. *Emergent Herbaceous Wetlands- Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.*

Of note are the highly urbanized, or “developed” areas within the Houston metropolitan area, which are visible in red in Figure 4. These areas result in a high degree of quickly-developing direct runoff, which can result in flash floods.

Figure 4. Land Cover/Land Use Characteristics in the Study Area



3.2 Mean Areal Precipitation

Mean areal precipitation (MAP) time series are necessary inputs for modeling the hydrologic response. They can be derived through spatial averaging techniques of observed precipitation station data or from gridded sources such as weather radar-derived products. Within the study area, the WGRFC utilizes radar-based MAP time series, also called MAPX, as the forcings to drive the hydrologic models used for flood forecasts. To be consistent with how the WGRFC runs the hydrologic models operationally, it was important for the calibration analysis to utilize these precipitation datasets. However, radar-based MAPX data can have significant biases when compared with historical ground-based station observations, as noted in past project experiences in nearby areas such as the Sabine, Neches, Brazos, and Colorado river basins (Riverside 2005-2017), and in discussions with WGRFC staff (Lander 2017). For this reason, a quality control check of the MAPX time series was conducted before beginning the calibration analysis to identify any periods of significant bias.

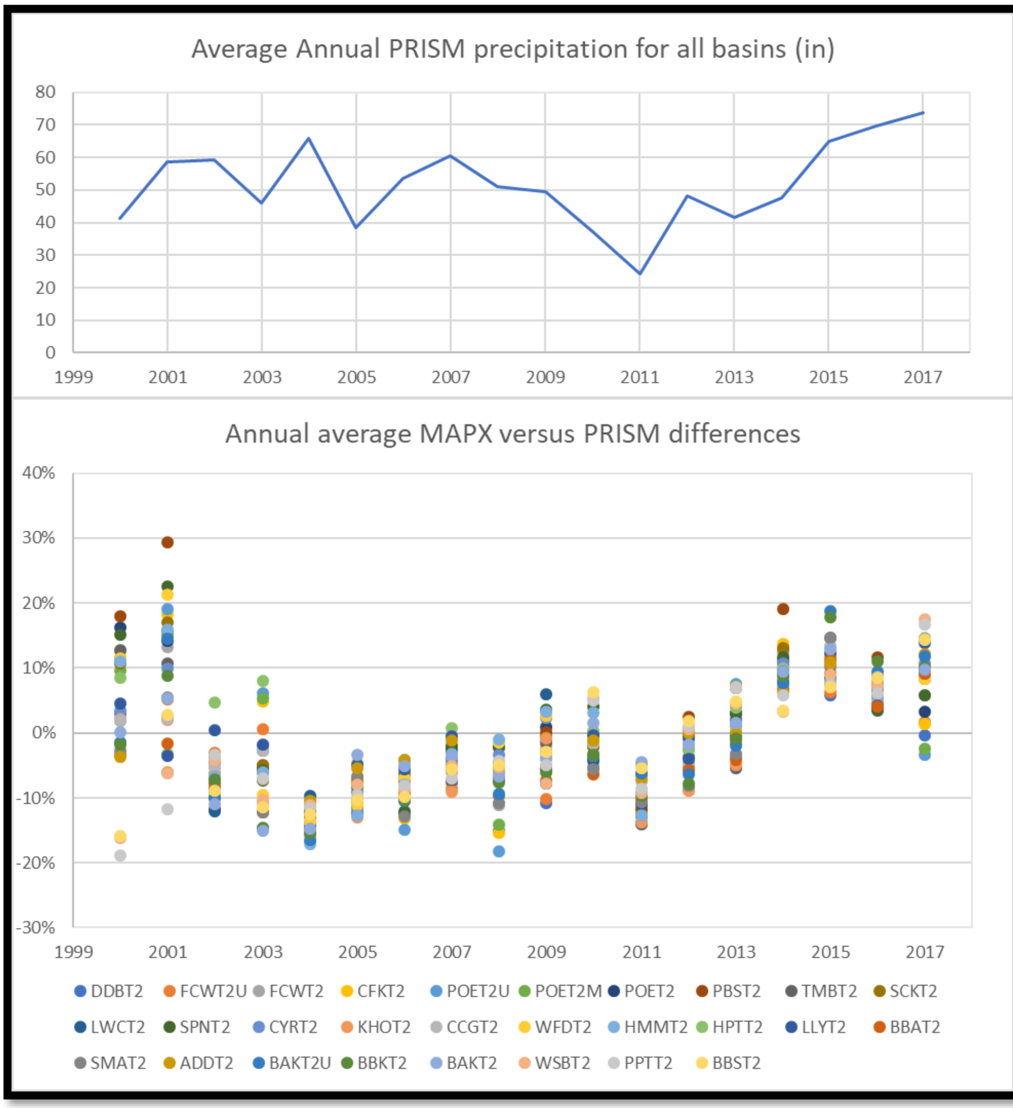
Radar-based MAPX time series were provided by WGRFC for each sub-basin. The MAPX time series were compared with the Oregon State Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Data set (PRISM 2017) for the 18-year period 2000-2017 where the datasets overlap. Table 4 shows the percent difference between the annual average MAPX precipitation and the PRISM precipitation dataset over this period.

Table 4. Comparison of MAPX with PRISM 2000–2017

Sub-basin	MAPX (in)	PRISM (in)	% Diff
San Jacinto River			
DDBT2	47.5	49.3	-3.5%
FCWT2U	48.8	50.0	-2.4%
FCWT2	50.2	50.7	-1.1%
CFKT2	50.0	50.4	-0.9%
POET2U	49.4	50.2	-1.7%
POET2M	50.0	50.5	-1.0%
POET2	51.3	51.6	-0.5%
PBST2	52.3	51.0	2.5%
TMBT2	50.3	50.7	-0.9%
SCKT2	51.4	51.2	0.4%
LWCT2	52.6	52.4	0.4%
SPNT2	53.3	52.9	0.7%
CYRT2	50.7	50.4	0.6%
KHOT2	46.8	48.0	-2.5%
CCGT2	51.7	51.6	0.1%
WFDT2	53.7	53.3	0.8%
HMMT2	55.2	55.1	0.1%
Buffalo Bayou			
HPTT2	53.6	52.5	2.1%
LLYT2	51.9	51.7	0.5%
BBAT2	49.2	50.9	-3.2%
SMAT2	49.2	50.5	-2.5%
ADDT2	52.8	53.0	-0.4%
BAKT2U	50.7	51.3	-1.2%
BBKT2	49.1	49.7	-1.2%
BAKT2	51.7	52.0	-0.6%
WSBT2	53.9	54.8	-1.5%
PPTT2	55.1	56.1	-1.9%
BBST2	56.5	57.4	-1.5%

In this table, no absolute differences greater than 5% are observed, indicating good long-term agreement of calibration inputs compared to PRISM. To investigate if there are temporal trends or if any particular year or period compared poorly, an analysis was done to compare the annual average difference for each year within the 2000-2017 period. A detailed table of these differences is provided in Appendix A, and a summary is given in Figure 5. The bottom plot of this figure shows the annual average MAPX versus PRISM differences for each sub-basin, while the top plot shows the PRISM precipitation accumulated annually across all sub-basins. The top plot allows for an assessment of whether the amount of rainfall had an impact on the percent differences observed between the MAPX and PRISM datasets.

Figure 5. Average PRISM Precipitation and Percent Difference, MAPX vs. PRISM (2000-2017)



From Figure 5, it is clear that the range of percent differences between MAPX and PRISM narrows significantly following 2001. The standard deviation of differences across all sub-basins improved from 9.5% and 9.9% in 2000 and 2001 respectively to ranges of 2.1 to 6.2% from 2002 to 2017. However, it is also clear from both Table 4 and Figure 5 that the radar-based MAPX data tends to slightly under-estimate the accumulated rainfall when compared with station-based PRISM data, particularly from 2003 to 2012. This aligns with similar observations from RTI's previous model calibration work for the WGRFC (Riverside 2005-2017).

The analysis also revealed that there may be a correlation with the magnitude of rainfall and the annual differences with PRISM. This is evident in 2001 and 2014-2017, which are the five wettest years in the analyzed period and which also have the largest five positive percent differences. Meanwhile the relatively drier years of 2003 to 2012 all have negative percent differences. However, there does not appear to be a discernable correlation between the annual standard deviations and rainfall amounts. Excluding 2000 and 2001, the highest standard deviations of differences (for all sub-basins for each analyzed year) are 6.2% (2003, a dry year of 43 inches) and 5.4% (2017, the wettest year of the period at 80 inches). The remaining years rarely exceed 4% regardless of total rainfall.

Considering the basin-by-basin comparison of the entire period of record in Table 4 along with the small standard deviations over time in Figure 5, the precipitation inputs over the calibration period considered (2000-2018) were deemed appropriate for use in the calibration analysis. In several cases, calibration periods for the individual sub-basins were limited by the historical streamflow data (both in terms of availability and quality). While 2018 PRISM data were not available at the time of the precipitation data analysis, we suspect that the results would be similar to prior years, and that the 2018 precipitation data are appropriate for use in model calibration.

3.3 Potential Evapotranspiration

The SAC-SMA model requires daily time series or average monthly estimates of PET as input into the model. For the modeled sub-basin calibrations, the PET curves were derived by RTI from available data using a simplified FAO Penman-Montieth method. Details of this method are described below. Initial values from this method assume a grass reference vegetative surface. Within a specific sub-basin, however, both the magnitude and the temporal distribution of the individual PET curves are influenced by the actual vegetative cover (see Jensen et al. 1990, for further discussion); therefore, adjustments to these curves were made during calibration in response to the simulated monthly volume bias values as described in Section 3.3.2.

3.3.1 FAO Penman-Montieth Method

Description of the employed PET estimation method is given in the FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998). Further guidance on application of this method was acquired from Jensen et al. (1990).

For implementation of this method under simplifying assumptions, the following data were required:

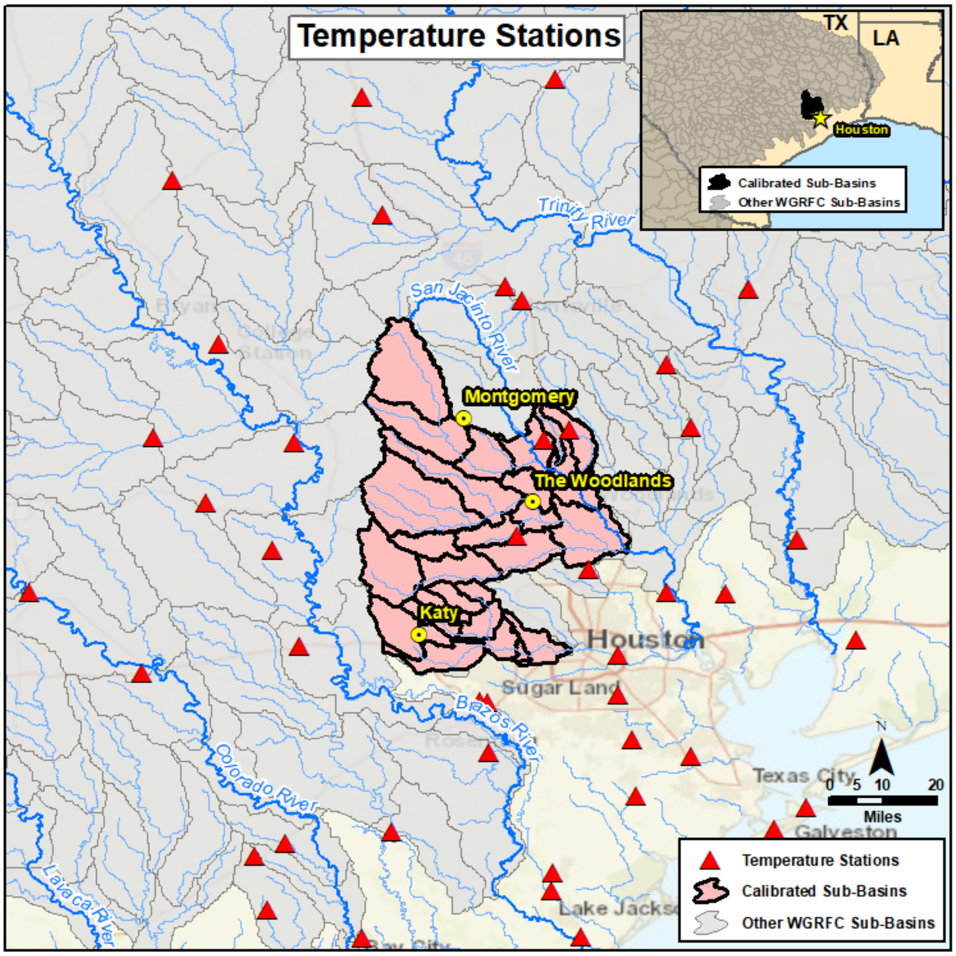
- Average wind speed in the region
- Monthly Average Maximum Daily Temperature at each weather station to be included in the analysis (12 values per station)
- Monthly Average Minimum Daily Temperature at each weather station to be included in the analysis (12 values per station)
- Temperature Station Latitude
- Temperature Station Longitude
- Temperature Station Elevation
- Sub-basin Centroid Latitude
- Sub-basin Centroid Longitude

An average wind speed of 7.4 miles per hour (3.3 m/s) was calculated from the average monthly reported measurements of an airport station in the Houston metropolitan region (Houston - ID 12960) based on data obtained from the NOAA National Centers for Environmental Information (NCEI) (NCDC-NCEI 2018a).

Additional simplifying assumptions required for implementation of the FAO Penman-Montieth method include approximating values for solar radiation and relative humidity. Reasonable assumptions for these types of values on a monthly scale can be made based on the geographic location of the areas of interest. Another important assumption made in calculating PET is that a reference surface of short grass is adequate to describe basin-wide conditions. This has proven to be a reasonable first approximation based on RTI's experience in this region of Texas.

Required temperature data were obtained from 44 stations in the study region as shown in Figure 6. These monthly maximum and minimum temperature normals were obtained from NOAA NCEI (NCDC-NCEI 2018b) based on data from the period 1981-2010. Once PET estimates were generated for the 44 temperature station locations, mean values for the modeled sub-basins were derived using inverse distance weighting techniques with the sub-basin centroids.

Figure 6. Temperature Stations used to Derive Potential Evapotranspiration Estimates



3.3.2 PET Adjustments

The initial PET curves described previously in Section 3.3.1 were refined during model calibration. These refinements account for a variety of factors, including climatological and physiographic effects not captured in the simplified methodology, adjustments due to vegetative cover impacts, and other land-use impacts. The PET adjustment analysis included the following steps:

- Sub-basins were grouped based on MLRA as shown in Table 5. These groupings represent sub-basins with generally similar land cover/soils characteristics, geographically oriented roughly along the same line of latitude.
- Simulated monthly volume bias values from the initial calibration model runs were reviewed to determine if any tendencies were evident within the group. Sub-basins where observed data were noisy or where the calibration period was short (and therefore the monthly volume bias values were large) were omitted from the analysis.

- Adjustments to the initial PET monthly values were specified based on the average simulated monthly volume bias calculated for the group. For months with an average negative volume bias, the PET values were reduced. For months with an average positive volume bias, the PET values were increased. For months where the average monthly volume bias was near zero, no adjustment was applied.
- Models for each sub-basin in the group were run iteratively to refine the adjustments until the average monthly volume bias values were reduced to near zero (or as much as possible with reasonable adjustments).
- Final PET curves were compared across groups to verify regionally consistency and ensure that adjustments are physically realistic.
- Available historical daily potential evaporation (PE) grids (used by the WGRFC operationally) were analyzed over the calibration period to derive monthly adjustment factors for each sub-basin. These factors represent the ratio of the final PET divided by the PE. The final adjustment factors for each sub-basin (given in Table 6) are specified in the SAC-SMA operation to convert the incoming PE datasets into values that emulate the calibrated PET curves.

Table 5. Grouping of Sub-basins by MLRA for PET Curve Adjustments

	MLRA Name			
	TX Blackland Prairie/W Coastal Plain (Group 1)	***W Coastal Plain/W Gulf Coast Fltwds (Group 2)***	***Gulf Coast Prairies, North (Group 3)***	***Gulf Coast Prairies, South (Group 4)***
Sub-basins	DDBT2	SCKT2	CYRT2	BBKT2
	FCWT2U	TMBT2	LWCT2	SMAT2
	FCWT2	PBST2	KHOT2	BBAT2
	CFKT2	SPNT2	CCGT2	LLYT2
	POET2U	POET2	WFDT2	HPTT2
	POET2M	HMMT2		ADDT2
				BAKT2U
				BAKT2
				WSBT2
				PPTT2
				BBST2

Table 6. Monthly PE Adjustment Factors by Sub-basin for Use in the SAC-SMA Operation

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
DDBT2	1.12	1.20	1.09	1.10	1.18	1.18	1.22	1.35	1.55	1.43	1.55	1.54
FCWT2U	1.22	1.30	1.19	1.19	1.27	1.26	1.31	1.45	1.68	1.54	1.69	1.68
FCWT2	1.25	1.31	1.18	1.16	1.25	1.24	1.29	1.43	1.67	1.54	1.72	1.73
CFKT2	1.23	1.29	1.17	1.12	1.21	1.22	1.27	1.39	1.61	1.49	1.71	1.70
POET2U	1.13	1.19	1.09	1.05	1.13	1.14	1.20	1.31	1.51	1.38	1.58	1.55
POET2M	1.16	1.22	1.12	1.08	1.15	1.16	1.20	1.33	1.56	1.43	1.62	1.59
POET2	1.12	1.18	1.07	1.03	1.09	1.10	1.15	1.26	1.47	1.37	1.57	1.57
PBST2	1.06	1.11	1.01	0.98	1.04	1.05	1.10	1.21	1.41	1.32	1.48	1.49
TMBT2	1.25	1.33	1.20	1.21	1.27	1.27	1.33	1.48	1.72	1.58	1.72	1.71
SCKT2	1.12	1.19	1.09	1.07	1.14	1.14	1.19	1.32	1.53	1.42	1.56	1.56
LWCT2	1.25	1.30	1.18	1.18	1.25	1.17	1.27	1.44	1.66	1.52	1.65	1.80
SPNT2	0.97	1.03	0.96	0.93	0.97	0.97	1.04	1.13	1.31	1.25	1.39	1.42
CYRT2	1.14	1.19	1.05	1.07	1.13	1.06	1.11	1.29	1.50	1.32	1.44	1.55
KHOT2	1.01	1.05	0.93	0.94	1.00	0.94	0.98	1.14	1.32	1.15	1.25	1.34
CCGT2	1.04	1.08	0.97	0.97	1.03	0.97	1.02	1.17	1.35	1.20	1.31	1.43
WFDT2	1.03	1.09	1.00	0.98	1.03	0.97	1.06	1.19	1.37	1.26	1.38	1.51
HMMT2	1.08	1.14	1.05	1.03	1.07	1.08	1.13	1.24	1.43	1.33	1.51	1.51
HPTT2	1.00	1.04	1.01	0.81	0.98	0.86	0.90	1.07	1.20	1.11	1.18	1.37
LLYT2	1.01	1.04	1.01	0.81	0.99	0.86	0.90	1.08	1.21	1.11	1.17	1.36
BBAT2	1.14	1.17	1.14	0.92	1.12	0.97	1.02	1.22	1.37	1.26	1.32	1.52
SMAT2	1.15	1.17	1.15	0.93	1.13	0.98	1.03	1.23	1.38	1.26	1.32	1.52
ADDT2	1.12	1.15	1.13	0.91	1.10	0.95	1.00	1.19	1.33	1.22	1.30	1.51
BAKT2U	1.15	1.17	1.15	0.93	1.12	0.98	1.02	1.22	1.36	1.25	1.32	1.52
BBKT2	1.17	1.20	1.16	0.94	1.14	1.00	1.04	1.25	1.40	1.28	1.34	1.54
BAKT2	1.14	1.16	1.13	0.93	1.12	0.98	1.02	1.22	1.35	1.23	1.31	1.51
WSBT2	1.11	1.15	1.11	0.90	1.09	0.95	1.00	1.19	1.32	1.20	1.29	1.50
PPTT2	1.10	1.14	1.10	0.88	1.08	0.95	0.99	1.18	1.30	1.19	1.27	1.48
BBST2	1.10	1.14	1.11	0.89	1.09	0.95	0.99	1.18	1.30	1.19	1.28	1.48

For Group 1, the PET adjustment analysis was not performed due to a lack of available observed streamflow data from which to calculate monthly volume biases. Therefore, for this group we applied the adjustment factors derived for Group 2. The final PET curves for all calibrated sub-basins are provided in Table 7. In addition, plots of the final PET curves, organized by river basin, are provided in Figures 7 and 8. A comparison plot of the average PET curve by river basin is given in Figure 9. As indicated in this comparison plot, the average PET is slightly lower for the Buffalo Bayou sub-basins than for the sub-basins in the San Jacinto. This is likely due to the land cover characteristics, where there is generally a higher level of urban/suburban development, and therefore less vegetative PET demand, in the Buffalo Bayou basin.

Table 7. Final Monthly PET Daily Rates (mm/day) by Sub-basin

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
DDBT2	1.78	2.27	3.19	4.32	5.70	6.87	6.90	7.28	6.22	4.03	2.94	2.16
FCWT2U	1.89	2.40	3.37	4.55	6.00	7.21	7.26	7.63	6.53	4.26	3.12	2.30
FCWT2	1.87	2.37	3.34	4.44	5.85	7.01	7.03	7.34	6.33	4.17	3.10	2.28
CFKT2	1.84	2.32	3.31	4.31	5.73	6.88	6.87	7.10	6.11	4.02	3.05	2.23
POET2U	1.67	2.11	3.02	3.99	5.29	6.35	6.35	6.60	5.67	3.69	2.76	2.01
POET2M	1.70	2.15	3.04	4.06	5.33	6.33	6.28	6.61	5.81	3.76	2.79	2.03
POET2	1.68	2.11	2.96	3.89	5.09	6.08	6.05	6.29	5.51	3.68	2.77	2.06
PBST2	1.58	2.01	2.83	3.73	4.90	5.85	5.88	6.11	5.31	3.55	2.64	1.97
TMBT2	1.90	2.41	3.38	4.56	6.00	7.20	7.27	7.62	6.55	4.31	3.15	2.34
SCKT2	1.69	2.15	3.03	4.05	5.33	6.38	6.44	6.72	5.79	3.83	2.81	2.09
LWCT2	1.95	2.45	3.42	4.56	5.96	6.65	6.89	7.44	6.40	4.24	3.09	2.49
SPNT2	1.48	1.90	2.68	3.51	4.60	5.47	5.58	5.76	5.02	3.44	2.53	1.92
CYRT2	1.79	2.21	3.05	4.13	5.41	6.08	6.17	6.76	5.78	3.73	2.75	2.18
KHOT2	1.60	1.96	2.70	3.67	4.79	5.40	5.46	6.00	5.14	3.30	2.44	1.93
CCGT2	1.68	2.07	2.86	3.84	5.00	5.61	5.69	6.20	5.35	3.49	2.59	2.07
WFDT2	1.65	2.08	2.89	3.83	5.00	5.57	5.78	6.22	5.38	3.61	2.63	2.14
HMMT2	1.69	2.13	2.96	3.91	5.09	6.07	6.03	6.28	5.50	3.71	2.78	2.08
HPTT2	1.66	2.02	3.01	3.22	4.85	5.01	5.04	5.77	4.86	3.33	2.39	2.04
LLYT2	1.67	2.02	3.01	3.23	4.86	5.02	5.05	5.79	4.87	3.33	2.39	2.04
BBAT2	1.88	2.28	3.39	3.64	5.48	5.67	5.68	6.53	5.49	3.74	2.69	2.29
SMAT2	1.89	2.28	3.39	3.65	5.48	5.67	5.69	6.54	5.50	3.74	2.70	2.30
ADDT2	1.88	2.26	3.36	3.59	5.39	5.57	5.56	6.37	5.39	3.69	2.68	2.29
BAKT2U	1.90	2.28	3.39	3.65	5.48	5.67	5.67	6.52	5.49	3.74	2.71	2.30
BBKT2	1.90	2.29	3.39	3.66	5.50	5.71	5.74	6.60	5.55	3.76	2.70	2.29
BAKT2	1.91	2.28	3.39	3.64	5.46	5.64	5.61	6.45	5.44	3.72	2.72	2.32
WSBT2	1.89	2.26	3.35	3.58	5.36	5.53	5.49	6.30	5.34	3.67	2.68	2.30
PPTT2	1.88	2.25	3.33	3.56	5.32	5.49	5.44	6.23	5.30	3.64	2.67	2.29
BBST2	1.86	2.24	3.31	3.53	5.29	5.46	5.41	6.19	5.27	3.62	2.65	2.27

Figure 7. Final PET Curves for the San Jacinto River Basin

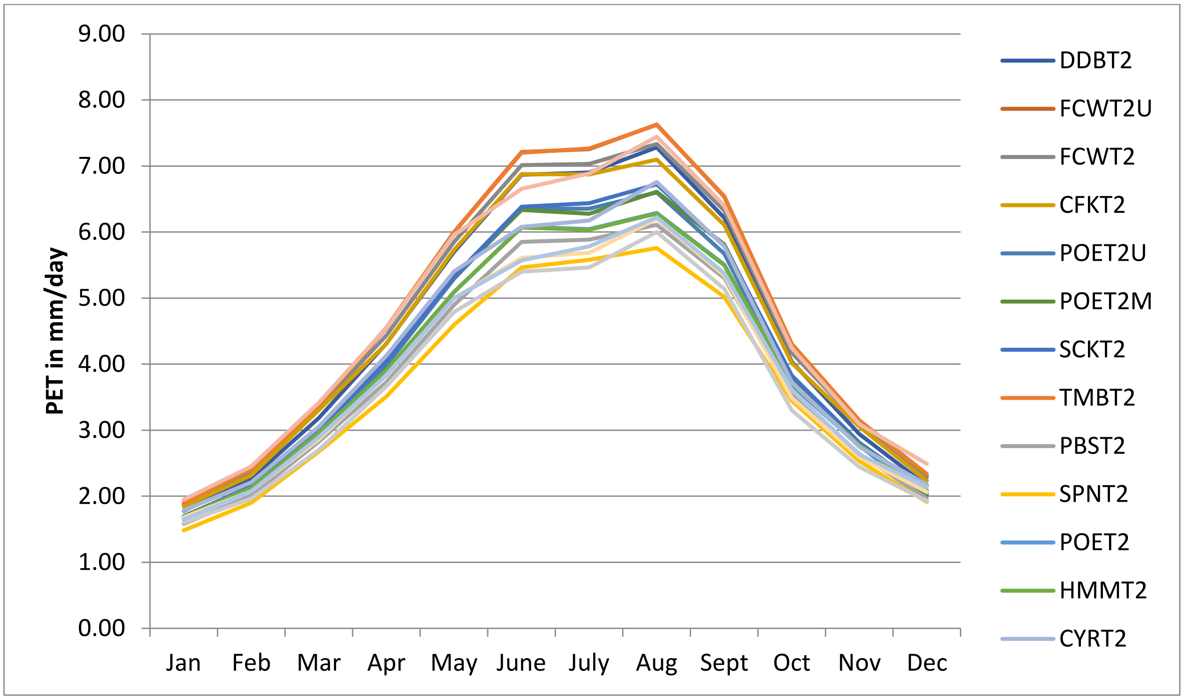


Figure 8. Final PET Curves for the Buffalo Bayou Basin

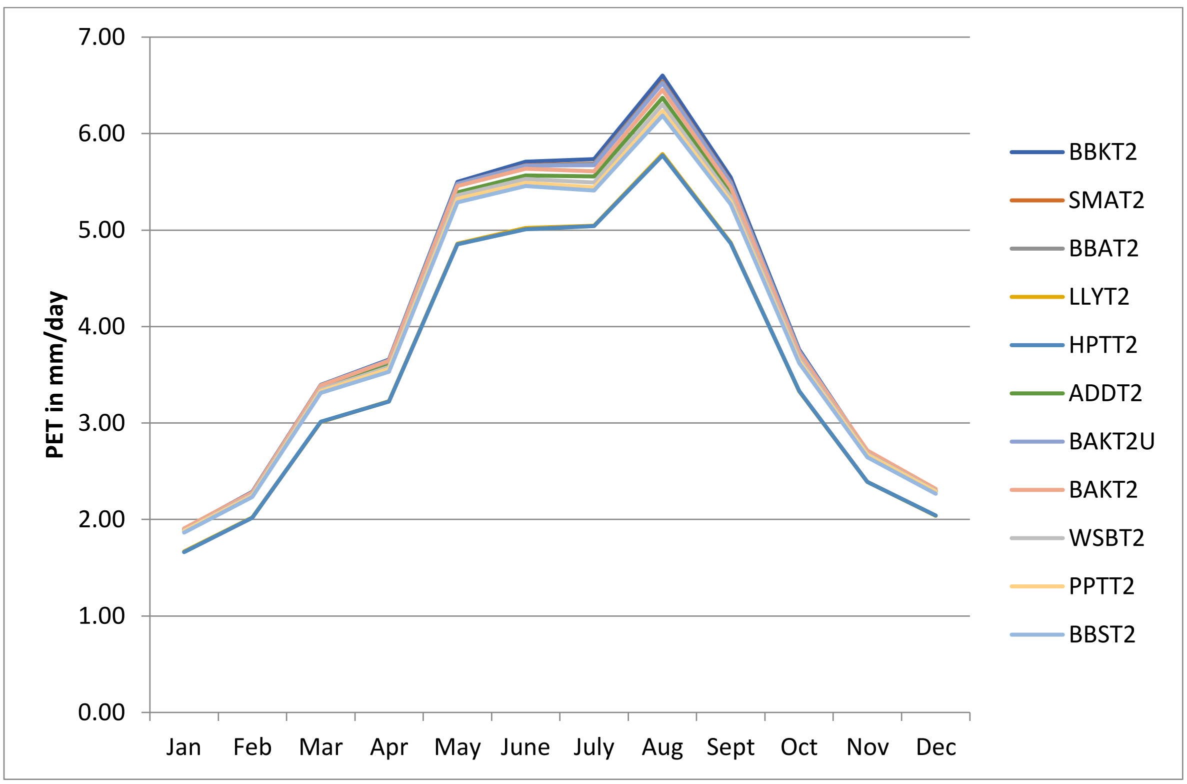
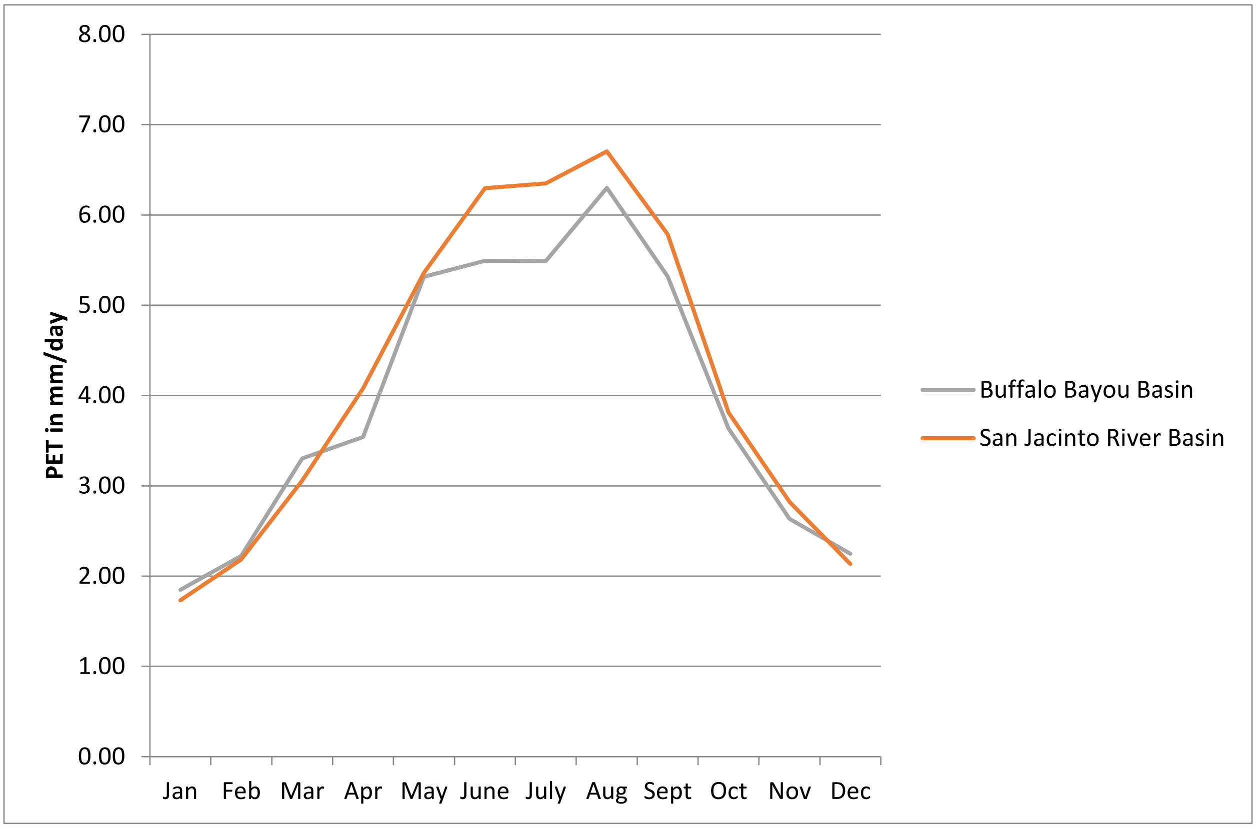


Figure 9. Final Average PET Curves by River Basin



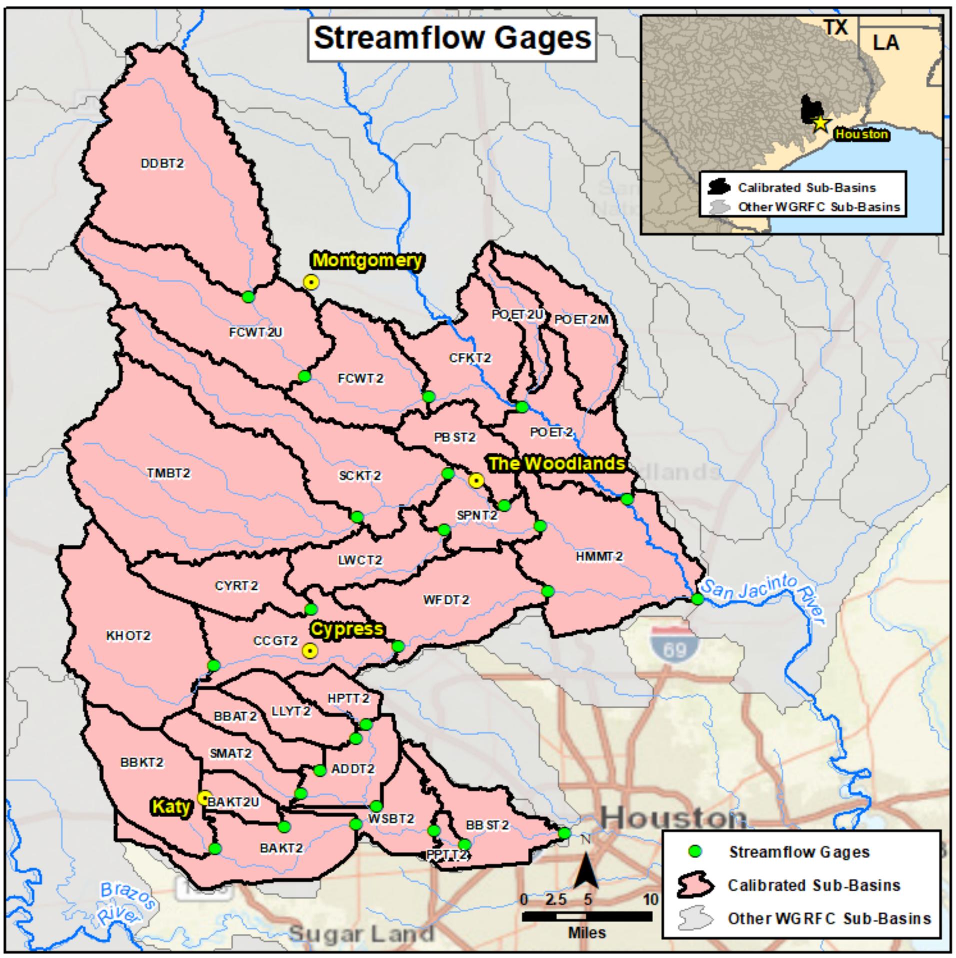
3.4 Streamflow Data

The retrieval of historical observed streamflow data was necessary for the development of the water balance as well as the calibration of the hydrologic models. For the water balance, historical daily flows were retrieved and converted to a monthly timescale. For some locations, streamflow filling was required to estimate periods of missing data. The purpose of filling data over the evaluation period is to remove potential temporal bias within analysis results that might occur if differing periods of record are considered.

The initial step in the filling process entailed identifying months that contained one or more missing daily values. For months with no more than two consecutive missing daily values, data were filled using linear interpolation between the observed daily values. If a particular month contained a period with more than two consecutive missing daily values, then the total monthly volume was considered missing, and regression techniques or mean annual analysis were employed. The regression techniques involved comparing nearby streamflow stations to develop linear regression relationships. The general method for selecting individual stations or station groups for data filling was to select spatially nearby or topologically relevant stations that give the highest observed data correlation over the common observed period 2000-2018.

Final filled streamflow estimates were used for the water balance analysis only. Streamflow filling was not used to supplement streamflow time series for model calibration purposes. Rather, daily and instantaneous streamflow records were downloaded from either the USGS National Water Information System (NWIS) (USGS 2018), or the Harris County Flood Control District (HCFCD) flood warning website (HCFCD 2018c). All instantaneous data sets were converted to a uniform hourly time step for model calibration. Figure 10 presents a map of the study sub-basins and associated streamflow gage data sources.

Figure 10. Historical Observed Streamflow Gage Locations



Note from Figure 10 that streamflow stations do not exist for two sub-basins (POET2U and POET2M). These sub-basins were calibrated jointly with the downstream local area POET2. In addition, there were not sufficient historical hourly (or higher resolution) streamflow data to warrant conducting a calibration analysis for sub-basins FCWT2U and HMMT2. As a result, SAC-SMA and LAG/K parameters for these sub-basins were specified based on the calibration of nearby sub-basins with similar basin characteristics. For FCWT2U, the LAG/K parameters for routing of flows from the upstream basin DDBT2 were estimated by considering the entire reach from DDBT2 down to FCWT2, then linearly scaling the results based on relative reach lengths (DDBT2 to FCWT2U and FCWT2U to FCWT2). The other two locations with missing data are the outlets of POET2M and POET2U. These basins were calibrated simultaneously with downstream basin POET2. For HMMT2, there were recent observed stage data available, which were used to perform a limited calibration of the routing parameters.

In addition to the missing flow locations, some gages had missing data for key events or limited periods of instantaneous flow records. A summary of the streamflow data retrieved and analyzed is provided in Table 8. The "USGS Peak Data Exist" column denotes locations where reported peak flow values from USGS gages were available to statistically assess the performance of the simulation of high flow events with respect to timing and magnitude.

Table 8. Streamflow Summary

Station ID	Station Name	Basin ID	Mean Annual Flow (cfs)	Highest Recorded Peak (cfs)	Date of Highest Recorded Peak	USGS Peak Data Exist	Instant. Data POR
San Jacinto River Basin							
08067690	Lake Ck nr Dobbin, TX	DDBT2	219	15,400	3/29/2018	n	2018-02 to 2018-10
08067920	Lake Ck at Sendera Ranch Rd nr Conroe, TX	FCWT2	478	55,300	8/28/2017	y	2015-07 to 2018-10
08068090	W Fk San Jacinto Rv Abv Lk Houston nr Porter, TX	POET2	629	131,000	8/29/2017	y	1994-10 to 2018-10
08068450	Panther Br nr Spring, TX	PBST2	62	13,100	6/9/2001	y	1999-10 to 2018-10
08068310/1060	Spring Ck at Kuykendahl, The Woodlands, TX	SCKT2	352	4,360	5/22/2018	n	2018-03 to 2018-10
08068500/1050	Spring Ck nr Spring, TX	SPNT2	383	78,800	10/18/1994	y	1995-10 to 2018-10
08068275/1070	Spring Ck nr Tomball, TX	TMBT2	137	48,900	8/28/2017	y	1999-10 to 2018-10
08068325/1320	Willow Ck nr Tomball, TX	LWCT2	40	11,200	8/28/2017	y	2006-10 to 2018-10
08068780/1220	Little Cypress Ck nr Cypress, TX	CYRT2	28	10,200	4/18/2016	y	1989-05 to 2018-10
08069500/760	W Fk San Jacinto Rv nr Humble, TX	HMMT2	11,362	187,000	5/31/1929;11/26/1940	y	2017-11 to 2018-10
08069000/1120	Cypress Ck nr Westfield, TX	WFDT2	303	31,500	8/28/2017	y	1989-05 to 2018-10
08068800/1160	Cypress Ck at Grant Rd nr Cypress, TX	CCGT2	163	21,000	4/19/2016	y	2007-10 to 2018-10
08068720/1180	Cypress Ck at Katy-Hockley Rd nr Hockley, TX	KHOT2	56	12800	8/28/2017	y	1989-05 to 2018-10
08068000	W Fk San Jacinto Rv nr Conroe, TX	CFKT2	502	122000	8/29/2017	y	1990-10 to 2018-10
08067650	W Fk San Jacinto Rv bl Lk Conroe nr Conroe, TX	LCTT2 (u/s of CFKT2)	884	75400	8/28/2017	y	2007-10 to 2018-10

(continued)

Table 8. Streamflow Summary (continued)

Station ID	Station Name	Basin ID	Mean Annual Flow (cfs)	Highest Recorded Peak (cfs)	Date of Highest Recorded Peak	USGS Peak Data Exist	Instant. Data POR
Buffalo Bayou Basin							
2130	Horsepen Creek at Trailside Drive	HPTT2	258	11,334	4/18/2016	n	2012-08 to 2018-10
08072760/2120	Langham Ck at W Little York Rd nr Addicks, TX	LLYT2	43	16,000	4/18/2016	y	2001-12 to 2018-10
08072730/2160	Bear Ck nr Barker, TX	BBAT2	38	20,400	4/28/2009	y	1993-10 to 2018-10
08073100/2110	Langham Ck at Addicks Res Outflow nr Addicks, TX	ADDT2	350	7,320	8/30/2017	y	2013-03 to 2018-10
08072680	S Mayde Ck at Heathergold Dr nr Addicks, TX	SMAT2	103	12,200	8/28/2017	y	2015-10 to 2018-10
2020	Mason Creek at Prince Cr Dr abv Barker	BAKT2U	210	39,412	5/1/2009	n	2000-01 to 2018-10
08073600/2270	Buffalo Bayou at W Belt Dr, Houston, TX	WSBT2	494	14,600	8/31/2017	y	1990-10 to 2018-10
08072300/2030	Buffalo Bayou nr Katy, TX	BBKT2	58	17,900	8/28/2017	y	1990-10 to 2018-10
08073700	Buffalo Bayou at Piney Point, TX	PPTT2	547	15,000	8/31/2017	y	1991-10 to 2018-10
08074000/2240	Buffalo Bayou at Houston, TX	BBST2	1,740	40,000	12/9/1935	y	1990-11 to 2018-10
08072600/2010	Buffalo Bayou at State Hwy 6 nr Addicks, TX	BAKT2	249	5,150	4/18/2016	y	2010-08 to 2018-10

3.5 Water Balance Analysis

An average annual water volume balance was computed for the study sub-basins over the period 2000 to 2017 to aid in model calibration and gain/loss modeling and for an overall consistency check of the observed data. The water balance analysis is useful in identifying potential problems in the observed data, the mean areal precipitation estimates, or the PET values. The water balance analysis is also useful for identifying and estimating the magnitudes of gains/losses or diversions within the sub-basins. Water balance results from each sub-basin are compared to those of nearby sub-basins to help identify inconsistencies. In computing the overall water volume balance, estimates of average annual streamflow, precipitation, and PET were required for each modeled sub-basin. The following sub-sections describe both the initial water balance used to identify potential issues before model calibration, and the final water balance that incorporates updates based on calibrated configurations including updates to PET and the addition of operations or model parameters utilized to model gains/losses or diversions.

3.5.1 Initial Water Balance Results

The initial water balance results are provided in Table 9. The analysis incorporates the precipitation from the MAPX data described in Section 3.2, initial PET estimates described in Section 3.3.1, and the monthly filled streamflow data described in Section 3.4.

The value labeled "QME Total" was estimated from the complete or filled streamflow records. This value represents the average annual total runoff discharge volume over the entire upstream drainage area. For the headwater sub-basins, this volume is equivalent to the local discharge volume accumulated.

Two additional parameters that are useful for comparison within the water balance analysis are the actual evapotranspiration (AET) and the runoff coefficient (ROC). AET volume is a derived term estimated as the precipitation minus the local runoff volume. The ROC is also a derived term and is equal to the ratio Local Runoff/MAPX. This value is an estimate of the portion of precipitation that becomes runoff and is observed at the stream gage site. ROC values inconsistent with those of nearby sub-basins may indicate possible gains/losses or diversions into/out of the sub-basin, poor streamflow records, or issues with MAP datsets. Problems with data can often be identified by investigation of the ratio between AET and PET. In general, one would expect values of this ratio to be relatively consistent or show some kind of trend across a river basin. The AET/PET Ratio provides a check for the computed PET values and can be employed together with ROC values to identify problems with the flow or MAP volumes.

Table 9. Initial Water Balance Results Based on Annual Volumes (2000 – 2017)

Sub-basin	Local Area [sq-mi]	Total Area [sq-mi]	MAPX Local [in]	QME Total [cfsd]	Losses (+) Gains (-) [cfsd]	Local Runoff [cfsd]	Local Runoff [in]	ROC	AET [in]	PET [in]	AET/PET	Basin Type
San Jacinto River Basin												
DDBT2	155	155	47.5	42	0	42	3.7	0.08	43.9	64.7	0.68	HW
FCWT2U	101	256	48.8	181	0	139	18.8	0.39	30.0	63.7	0.47	LA
FCWT2	59	315	50.2	223	0	42	9.6	0.19	40.5	63.6	0.64	LA
CFKT2	57	828	50.0	502	0	-7	-1.7	-0.03	51.6	61.5	0.84	LA
POET2U	19	19	49.4	24	0	24	17.3	0.35	32.1	64.5	0.50	HW
POET2M	44	44	50.0	56	0	56	17.3	0.34	32.8	63.3	0.52	HW
POET2	64	955	51.3	634	0	52	11.0	0.21	40.3	64.6	0.62	LA
PBST2	35	35	52.3	62	0	62	24.1	0.46	28.2	63.4	0.45	HW
TMBT2	187	187	50.3	137	0	137	10.0	0.20	40.3	63.9	0.63	HW
SCKT2	111	299	51.4	297	0	159	19.5	0.38	32.0	63.6	0.50	LA
LWCT2	40	40	52.6	41	0	41	13.8	0.26	38.8	64.3	0.60	HW
SPNT2	32	406	53.3	383	0	-17	-7.0	-0.13	60.3	64.4	0.94	LA
CYRT2	42	42	50.7	29	0	29	9.2	0.18	41.4	64.1	0.65	HW
KHOT2	104	104	46.8	57	0	57	7.5	0.16	39.3	62.7	0.63	HW
CCGT2	63	209	51.7	162	0	133	28.6	0.55	23.1	63.4	0.36	LA
WFDT2	70	280	53.7	303	0	141	27.3	0.51	26.5	63.9	0.41	LA
HMMT2	105	1746	55.2	1969	0	649	83.7	1.52	-28.5	63.8	-0.45	LA

Table 9. Initial Water Balance Results Based on Annual Volumes (2000 – 2017) (continued)

Sub-basin	Local Area [sq-mi]	Total Area [sq-mi]	MAPX Local [in]	QME Total [cfsd]	Losses (+) Gains (-) [cfsd]	Local Runoff [cfsd]	Local Runoff [in]	ROC	AET [in]	PET [in]	AET/PET	Basin Type
Buffalo Bayou Basin												
HPTT2	13	13	53.6	22	0	22	22.4	0.42	31.2	64.4	0.48	HW
LLYT2	26	26	51.9	42	0	42	21.3	0.41	30.6	63.2	0.48	HW
BBAT2	23	23	49.2	38	0	38	22.4	0.46	26.8	63.2	0.42	HW
SMAT2	28	28	49.2	42	0	42	20.1	0.41	29.1	63.2	0.46	HW
ADDT2	34	125	52.8	209	0	66	25.9	0.49	26.9	63.2	0.43	LA
BAKT2U	15	15	50.7	25	0	25	22.4	0.44	28.3	62.5	0.45	HW
BBKT2	61	61	49.1	65	0	65	14.5	0.29	34.7	63.4	0.55	HW
BAKT2	58	134	51.7	208	0	118	27.6	0.53	24.1	62.0	0.39	LA
WSBT2	31	290	53.9	494	0	78	34.3	0.64	19.6	63.0	0.31	LA
PPTT2	6	297	55.1	519	0	25	52.7	0.96	2.4	63.0	0.04	LA
BBST2	41	338	56.5	778	0	259	85.8	1.52	-29.3	62.3	-0.47	LA

The initial water balance results revealed some minor inconsistencies with AET/PET ratios in both river basins, with one negative AET/PET ratio in each (HMMT2 in San Jacinto and BBST2 in Buffalo Bayou). The majority of the sub-basins in this project's scope, however, showed consistent results, with nearly every non-negative AET/PET ratio falling within one standard deviation of the average. In the San Jacinto basin, there were two sub-basins (SPNT2 and CFKT2) with negative ROC values, while the Buffalo Bayou basin had none. The initial water balance results were used to help identify the sub-basins where diversion or gain/loss modeling techniques (such as CHANLOSS, LOOKUP, or the SAC-SMA model SIDE parameter) should be tested and possibly incorporated into the calibrated models.

3.5.2 Final Water Balance Results

To arrive at the final water balance, which was used as a validation and consistency check of particular adjustments made during the model calibration phase, the PET input data were revised to account for vegetative/land cover influences. Additionally, identified diversions and gains/losses had to be incorporated into the final calculations. Adjustments to the PET estimates, described in Section 3.3.2, reflect modifications to the sub-basin specific PET curves which were made during the model calibration analysis. Adjustments to the PET curves were made with consideration of typical regional patterns and of monthly volume bias output from the STAT-QME operation, as described previously. The final water balance results are provided in Table 10.

Table 10. Final Water Balance Results Based on Annual Volumes (2000 – 2017)

Sub-basin	Local Area [sq-mi]	Total Area [sq-mi]	MAPX Local [in]	QME Total [cfsd]	Losses (+) Gains (-) [cfsd]	Local Runoff [cfsd]	Local Runoff [in]	ROC	AET [in]	PET [in]	AET/PET	Basin Type
San Jacinto River Basin												
DDBT2	155	155	47.5	42	0	42	3.7	0.08	43.9	64.4	0.68	HW
FCWT2U	101	256	48.8	181	0	139	18.8	0.39	30.0	67.9	0.44	LA
FCWT2	59	315	50.2	223	0	42	9.6	0.19	40.5	66.2	0.61	LA
CFKT2	57	828	50.0	502	0	-7	-1.7	-0.03	51.6	64.6	0.80	LA
POET2U	19	19	49.4	24	0	24	17.3	0.35	32.1	59.5	0.54	HW
POET2M	44	44	50.0	56	0	56	17.3	0.34	32.8	59.9	0.55	HW
POET2	64	955	51.3	634	0	52	11.0	0.21	40.3	57.8	0.70	LA
PBST2	35	35	52.3	62	0	62	24.1	0.46	28.2	55.7	0.51	HW
TMBT2	187	187	50.3	137	0	137	10.0	0.20	40.3	68.1	0.59	HW
SCKT2	111	299	51.4	297	0	159	19.5	0.38	32.0	60.4	0.53	LA
LWCT2	40	40	52.6	41	0	41	13.8	0.26	38.8	66.7	0.58	HW
SPNT2	32	406	53.3	383	0	-17	-7.0	-0.13	60.3	52.7	1.14	LA
CYRT2	42	42	50.7	29	0	29	9.2	0.18	41.4	60.1	0.69	HW
KHOT2	104	104	46.8	57	14	71	9.3	0.20	37.6	53.3	0.70	HW
CCGT2	63	209	51.7	162	0	133	28.6	0.55	23.1	55.8	0.41	LA
WFDT2	70	280	53.7	303	0	141	27.3	0.51	26.5	56.2	0.47	LA
HMMT2	105	1746	55.2	1969	0	649	83.7	1.52	-28.5	57.9	-0.49	LA

Table 10. Final Water Balance Results Based on Annual Volumes (2000 – 2017) (continued)

Sub-basin	Local Area [sq-mi]	Total Area [sq-mi]	MAPX Local [in]	QME Total [cfsd]	Losses (+) Gains (-) [cfsd]	Local Runoff [cfsd]	Local Runoff [in]	ROC	AET [in]	PET [in]	AET/PET	Basin Type
Buffalo Bayou Basin												
HPTT2	13	13	53.6	22	0	22	22.4	0.42	31.2	51.9	0.60	HW
LLYT2	26	26	51.9	42	-1	40	20.6	0.40	31.3	52.0	0.60	HW
BBAT2	23	23	49.2	38	-9	28	16.8	0.34	32.5	58.6	0.55	HW
SMAT2	28	28	49.2	42	-3	39	18.8	0.38	30.4	57.7	0.53	HW
ADDT2	34	125	52.8	209	0	66	25.9	0.49	26.9	57.7	0.47	LA
BAKT2U	15	15	50.7	25	0	25	22.4	0.44	28.3	58.6	0.48	HW
BBKT2	61	61	49.1	65	0	65	14.5	0.29	34.7	59.0	0.59	HW
BAKT2	58	134	51.7	208	0	118	27.6	0.53	24.1	58.3	0.41	LA
WSBT2	31	290	53.9	494	0	78	34.3	0.64	19.6	57.4	0.34	LA
PPTT2	6	297	55.1	519	-11	14	29.8	0.54	25.2	57.0	0.44	LA
BBST2	41	338	56.5	778	177	435	144.4	2.56	-87.9	56.6	-1.55	LA

The final water balance results show improved consistency between sub-basins in both major basins. Within the San Jacinto basin, evaluation during the calibration analysis appeared to indicate that the negative runoff coefficients calculated for sub-basins CFKT2 and SPNT2 are likely a result of inconsistencies in observed streamflow volumes upstream of the gage (e.g., observed releases from Lake Conroe in the case of CFKT2). Investigation of these sub-basins did not reveal any significant diversions or sources of potential gains/losses; therefore, no diversion or gain/loss modeling was implemented. Although not large in terms of average annual volume, the Cypress Creek overflow, which occurs during large flood events, impacts sub-basins KHOT2 (San Jacinto), and LLYT2, BBAT2, and SMAT2 (Buffalo Bayou). These impacts are reflected in the final water balance as gains/losses. Additional description of the modeling of the Cypress Creek overflow is provided in Section 4.7.

Table 11 provides a summary of the identified diversions and gains/loss that were incorporated into the sub-basin models. The summary includes the volume of the diversion or gain/loss and the modeling method used. For sub-basin BBST2, a significant loss was found to be needed during the model calibration analysis; however, the water balance indicated a gain should be required. There is a high degree of uncertainty in the streamflow filling process for the upstream releases from Addicks and Barker Reservoirs; therefore, the most recent observed data (not the entire filled period from 2000-2017) was used during model calibration to evaluate the water balance at this location.

Table 11. Summary of Diversion and Gain/Loss Modeling

Sub-basin	Diversion/Loss (+) Return/Gain (-) [cfsd]	Diversion/Loss (+) Return/Gain (-) [cmsd]	Operation/Parameter Used in Model
KHOT2	13.5	0.382	LOOKUP
LLYT2	-1.4	-0.038	LOOKUP
BBAT2	-9.4	-0.267	LOOKUP
SMAT2	-2.7	-0.076	LOOKUP
PPTT2	-10.7	-0.300	CHANLOSS
BBST2	176.6	5.000	CHANLOSS

4. HYDROLOGIC MODEL CALIBRATION

This section presents a discussion of the primary hydrologic models calibrated for this study, followed by a summary of calibration results for each river basin and a detailed write-up of each sub-basin. The primary models (described in Sections 4.1 through 4.3) calibrated include streamflow routing using the Lag/K method (LAG/K), the Sacramento Soil Moisture Accounting Model (SAC-SMA), and the Unit Hydrograph (UNIT-HG) method. These models and their associated parameters are used in sequence to produce a streamflow simulation that can be calibrated to improve the match with historical observations. Once the calibrated parameters are incorporated in the operational forecast system, it should allow for enhanced performance in forecasting streamflow with respect to hydrologic conditions. RTI also calibrated CHANLOSS and LOOKUP operations to capture associated reach gains and losses.

In general, RTI utilized the Interactive Calibration Program (ICP) to provide an efficient model calibration environment. After completion of the model calibration analysis, all operations and parameters were configured in a CHPS/FEWS standalone for ease of transfer to the operational forecast system and for model visualization by WGRFC. A primary focus of each sub-basin calibration was on achieving peak flows at an hourly time-step.

The discussion of each river basin in Sections 4.5 and 4.6 includes a map of the calibrated sub-basins and summary tables of the LAG/K and SAC-SMA parameters, as well as tables summarizing the statistics of the final calibrated simulations. Overview maps of each individual sub-basin are also provided in Appendix B for reference.

4.1 Streamflow Routing using the Lag/K Method

Flow routing from upstream areas was performed for each of the 14 modeled local area sub-basins using the LAG/K model. The LAG/K model has been used by the NWS for decades as a practical method of storage routing between flow points. A primary benefit of the LAG/K operation is the flexibility to define both the lag (flow travel time) and k (wave attenuation) independently and dynamically for varying flow levels.

Historical observed streamflow data were obtained from the USGS and the HCFCD and converted as necessary to create 1-hour interval time series, as previously described in Section 3.4. To enable this analysis, model calibration input files (for use in NWSRFS) were constructed which perform the following functions:

- Read in the observed downstream and upstream time series of flow rates (historical observations as recorded by the river gages).
- Route the upstream time series using the LAG/K operation with the specified parameter values.

- Create a daily average time series from the routed upstream time series (MEAN-Q operation).
- Create a daily average time series (if necessary) from the downstream QIN time series (MEAN-Q operation).
- Plot routed upstream and the downstream hourly (QIN) time series (PLOT-TS operation) for visual comparison.
- Perform a statistical comparison of the correlation coefficient between the routed upstream daily average and the downstream daily average time series (STAT-QME operation).
- Progressively check improvements in the daily STAT-QME with the hourly STAT-Q (run outside of ICP) correlation coefficient.

The analysis procedure consisted of varying the LAG/K parameters and examining the effects through visual comparison (PLOT-TS) and tracking the associated correlation coefficient (STAT-QME). Initially, a run was made using a guess of constant parameter values based on a plot of the times series with no LAG/K operation in place. Following iteration (trial) number 1, which employed the estimated Lag and K values, individual events (the exact number of which depended on the amount of historical observations on record, but typically 50+ in number) were examined and peak timing discrepancies were recorded. Based on these discrepancies, a new set of variable or constant Lag parameters was estimated. The daily STAT-QME was used as an initial check that could be easily read from ICP, but STAT-Q was utilized to check the hourly correlation coefficient as refinements became more tuned.

Following the initial assessment of the variable Lag parameters, the K parameter was expanded to incorporate variable characteristics and wave attenuation as needed. Subsequent adjustments of both the variable Lag and variable K parameters were made based on visual comparison and based on attempting to improve the resultant correlation. Event-by-event analysis was repeated one to two times for each analyzed reach. Final adjustments were made using this detailed analysis. The analysis was considered complete when the visual comparison showed accurate peak timing performance and when no improvements to the correlation results could be identified.

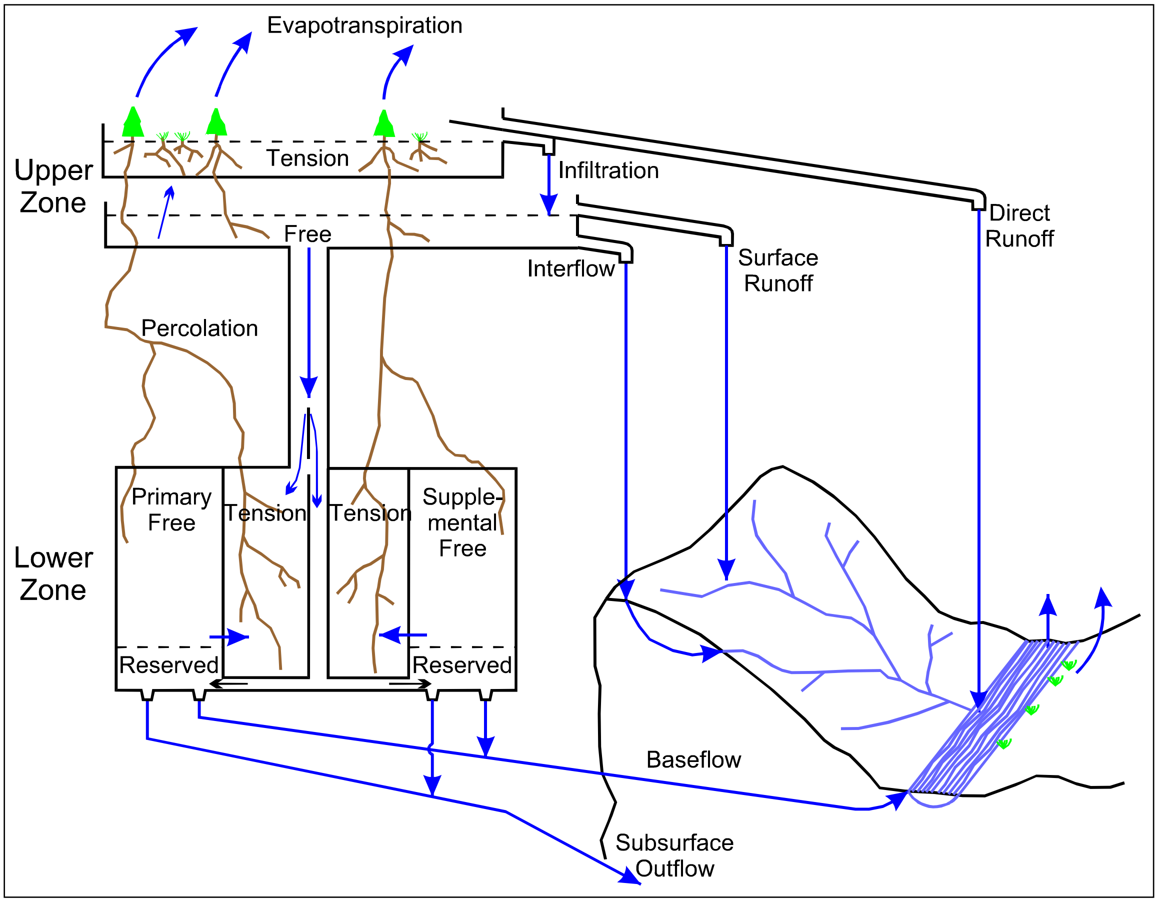
Final adjustments were made to some of the LAG/K parameters based on the full simulation with the SAC-SMA and UNIT-HG models. These changes primarily resulted in sub-basins where high observed flows were missing but could be assessed by routing the simulated flows. Summary tables of the final calibrated LAG/K parameter sets are provided in subsequent sections (Sections 4.5 and 4.6).

In addition to the routing of upstream flows through the downstream sub-basin, the LAG/K operation was used to attenuate local runoff in a few sub-basins where the UNIT-HG model was insufficient for modeling the behavior of very high flood runoff events. Routing modeling was also required to accurately simulate the timing of incoming flows from the Cypress Creek overflow, which contributes to the Addicks Reservoir inflows through the headwater sub-basins LLYT2, BBAT2, and SMAT2. Further discussion of the Cypress Creek overflow modeling is provided in Section 4.7.

4.2 SAC-SMA Model Description

The Sacramento Soil Moisture Accounting (SAC-SMA) is a conceptually-based lumped rainfall-runoff model which utilizes precipitation and evapotranspiration data as inputs. Within an operational flood forecasting system, SAC-SMA can be used to simulate the runoff response based on observed and forecasted precipitation. The simulated runoff can then be used as input to models that simulate the conveyance of this runoff through the basin and receiving channels. The SAC-SMA model represents soil moisture characteristics such that applied moisture is distributed properly in various depths and energy states in the soil; rational percolation characteristics are maintained; and streamflow is simulated effectively (NWS 2006). Flow is modeled based on direct runoff (impervious surfaces), surface runoff, interflow, and baseflows which contain two recession rates (primary and supplementary). Figure 11 provides a conceptual schematic of these processes.

Figure 11. SAC-SMA Conceptual Diagram



There are 20 conceptually based parameters in the SAC-SMA model that can affect either timing or volume of a simulated hydrograph. Calibration of the model involves adjusting these parameters to produce simulated responses to align with observed historical streamflows based on observed historical precipitation inputs. Once calibrated, the model can be used to forecast streamflows based on real-time and forecasted precipitation.

The SAC-SMA model was calibrated for each of the 28 study sub-basins utilizing ICP. The original parameters for each sub-basin were retrieved from the WGRFC CHPS/FEWS operational forecast system as the initial starting point. Calibrations were focused on the hourly simulations produced using the PLOT-TS interface within ICP. Each sub-basin underwent an initial calibration effort, peer review, and senior review. The senior review involved conducting a regionalization analysis of basin parameters with land cover and soil characteristics previously described in Section 3.1, as well as any trends observed across basins.

To the extent possible, parameters were confined to the typical ranges defined by Anderson (Anderson 2002 Table 7-5-3), given in Table 12. Exceptions included higher than normal values of PCTIM due to the high density of development in the sub-basins dominated by urban/sub-urban areas. Summary tables of the final SAC-SMA parameter sets are provided in subsequent sections (Sections 4.5 and 4.6).

Table 12. Typical range of values for SAC-SMA model parameters (Anderson 2002 Table 7-5-3)

Parameter	Description	Lower Limit	Upper Limit
LZPK	Fractional daily primary withdrawal rate	0.001	0.015
LZSK	Fractional daily supplemental withdrawal rate	0.03	0.20
LZFPM	Lower zone primary free water capacity (mm)	40	600
LZFSM	Lower zone supplemental free water capacity (mm)	15	300
UZTWM	Upper zone tension water capacity (mm)	25	125
LZTWM	Lower zone tension water capacity (mm)	75	300
UZK	Fractional daily upper zone free water withdrawal rate	0.2	0.5
UZFWM	Upper zone free water capacity (mm)	10	75
PFREE	Fraction of percolated water going directly to lower zone free water storage	0.0	0.5
PCTIM	Minimum impervious area (decimal fraction)	0.0	0.05
ADIMP	Additional impervious area (decimal fraction)	0.0	0.20
ZPERC	Maximum percolation rate coefficient	20	300
REXP	Percolation equation exponent	1.4	3.5
RIVA	Riparian vegetation area (decimal fraction)	0.0	0.2

During the initial calibration effort, daily statistics were reviewed from the STAT-QME which could be easily read from ICP and RTI's internal calibration database tool. However, statistics from the hourly STAT-Q operation were utilized as refinements became more tuned. The calibrations incorporated a combination of both manual and automatic optimizer techniques utilizing the OPT3 operation. A summary table of the final STAT-Q statistics is given for each basin in Sections 4.5 and 4.6.

4.3 Unit Hydrograph Model Development

A traditional unit hydrograph (UH) is defined as the streamflow response that results from one unit (usually inch or mm) of runoff (rainfall excess) generated uniformly over a sub-basin at a uniform rate for a specified time period. The following assumptions are important to note:

1. The total volume generated represents one unit of runoff depth over the entire sub-basin. A common misconception is that the UH represents one unit of precipitation depth. The precipitation depth required to generate one unit of runoff is usually greater than one unit of precipitation depth – often significantly greater.
2. Runoff occurs uniformly over the entire sub-basin. Historical events that result from precipitation that is more spatially uniform are generally better for UH development analysis than are events that are localized.
3. Runoff rate is constant. Historical events with temporally uniform rainfall distribution are better suited for UH development analysis than are events generated from precipitation that varies significantly over time.
4. UH "duration" is defined by the duration of the rainfall excess that generates the runoff. For example, a 1-hour duration rainfall event would stipulate a 1-hour unit hydrograph.

Functionally, the UH developed for the UNIT-HG operation fulfills the same purpose as a traditional UH model – it is intended to describe the timing and movement of a unit of runoff volume generated within a sub-basin by an event from the initial time of rainfall excess to the time at which a runoff response at the sub-basin outlet is no longer evident. In the traditional definition, the movement of the runoff volume represented by the UH occurs as overland flow, fast-response flow within the soil layers (i.e., interflow), and streamflow within the stream channel network; however, because the SAC-SMA runoff model includes baseflow and interflow components, the UNIT-HG operation describes only the overland and streamflow portions of the sub-basin outlet flow accumulation. Techniques for UH development are similar to traditional methods, but, in sub-basins where the baseflow and interflow components are large, it is important to account only for overland and stream channel effects. In general, a UH developed for the UNIT-HG operation should peak more quickly and have a shorter recession period than a traditional UH derived for the same sub-basin.

RTI used manual and automatic geographic information system (GIS) techniques to develop UH's for all defined sub-basins. Manual analysis involved a review of the available 1-hour streamflow data to identify events from which a UH could be estimated. In picking events, the following criteria were generally applied:

- An event should be isolated from other events. Ideally, there should be several dry days before and after the precipitation event. The shape of the event hydrograph should be smooth and continuous, with minimal interference from other events evident.
- An event should be free from obvious measurement noise.
- "Medium-sized" events are preferred for analysis.
- Events from every season should be selected (if possible).
- Multiple-peaking events typically should not be used because they are indicative of non-constant runoff rates. In limited cases, however, the basin characteristics may stipulate that multiple peaks are indicative of runoff response and are, therefore, appropriate.

Analysis of selected events began with the separation of the baseflow and interflow components from the event hydrograph. To accomplish this, each event was examined individually and the baseflow plus interflow portion of the hydrograph was estimated by using the following steps:

- Plot the recession portion of the event hydrograph (i.e., all points on the observed hydrograph that occur after the peak) on a semi-log scale (log Q vs. time).
- Locate the point on this curve at which the curve becomes approximately linear. This is designated as the inflection point.
- The linear portion of the curve is then extended from the inflection point backwards in time to the time of the peak using the best fit line of the following recession equation:

$$Q_t = Q_0 e^{-\alpha t}$$

where: Q_t = flow at time t
Q_0 = flow at the point of inflection
α = recession constant (fitted parameter)

- The recession portion of the baseflow can now be computed using the above equation and the derived value of the "α" parameter.

Once the baseflow and interflow components were identified, the fast runoff derived from each event could be estimated. From the fast runoff component, initial UHs of varying duration were derived. The S-curve method (Linsley et al. 1982) was employed to estimate the duration. The event duration was adjusted until a smooth S-curve was produced. Once the duration of the event was determined, the initial 1-hour unit hydrograph was computed based on the S-curve method.

For the modeled local areas and any headwater sub-basins that lacked sufficient streamflow data, UHs could not be derived directly from past runoff events due to missing, insufficient, or poor data. For these instances a GIS procedure was used to derive the initial UNIT-HG ordinates. The procedure involves developing Flow Accumulation (FAC) and Flow Direction (FDR) grids from a 30-meter Digital Elevation Model (DEM) from the National Hydrography Dataset (NHD). Specifics of the procedure include the following:

1. Derive a flow accumulation grid (FAC) and flow direction grid (FDR) for the project area from the DEM.
2. Obtain field measurements (from the USGS or other source) for the river's cross-sectional area, roughness, and slope at the sub-basin outlet. If none are available, select a nearby gage that appears to share similar characteristics as the desired location. Choose up to about 30 field measurements for analysis.
3. Estimate the upstream and downstream elevations of the river at each end of the basin from the DEM as well as the total stream length. Enter these into the analysis spreadsheet.
4. Calculate an average/representative hydraulic radius and Manning's n from the field measurements. A hydraulic radius corresponding to a 1 km^2 drainage area is also required (assumed to be 0.1m for this project).
5. Run RTI's GIS-based GeoTool using the sub-basin boundary, DEM, FAC, FDR, Manning's n, and hydraulic radius parameters. In general terms, the GeoTool estimates how long effective precipitation within the DEM takes to reach the sub-basin outlet after falling on each 30m x 30m cell by calculating slopes, hydraulic properties, velocities, and flow times for each cell.
6. Verify that the results are physically reasonable by examining the raster outputs of GeoTool.
7. Create a histogram of the resultant flow times. Define the bins of the histogram to be equal to the desired ordinate interval of the final unit hydrograph; the value of the (unfinalized) hydrograph at each ordinate is then the sum of the cells within each bin multiplied by the average flow of runoff per cell. For this project the interval was 60 minutes.
8. Verify that the total number of cells in the histogram corresponds to the total known sub-basin drainage area. Make manual adjustments to each interval as necessary.
9. Route the unit hydrograph, adjust hydrograph duration as needed, and obtain final UH ordinates.
10. Confirm the total volume of the final UH is roughly equal to an effective precipitation event of unit depth distributed uniformly over the sub-basin. When the final UH is acceptable it is utilized as the initial input to the calibration deck.

Unlike the starting LAG/K and SAC-SMA parameters, all initial UNIT-HG ordinates were developed from either the manual or GIS procedure, rather than retrieved from operational CHPS/FEWS forecast system. This is primarily because many of the previous UNIT-HG models were defined at 6-hour rather than 1-hour ordinates, or in some cases, new sub-basins were subdivided from previously larger extents.

During calibration with the LAG/K and SAC-SMA models, many of the initial UNIT-HG ordinates were modified. A plot comparing the initial and final calibrated UNIT-HG ordinates is presented for each sub-basin in Appendix C.

4.4 Model Calibration Review Process

RTI's model calibration analysis included a thorough review process to ensure that the final models perform well under a wide range of hydrologic conditions and that the specified parameter sets are appropriate for the basin characteristics and properly reflect the limitations of the available historical data. The review process included both internal review steps, conducted by RTI's modeling team, and external review steps, conducted by WGRFC staff. For the internal review, the individual sub-basin model calibrations were reviewed in two phases. The first phase was the peer review, where modeling team members evaluate the initial sub-basin calibrations of fellow team members. This feedback is used to refine model parameters as appropriate and to discuss findings with the team, so that modeling issues are addressed consistently. The second phase of the internal review process was conducted immediately prior to submittal of the models to the WGRFC. This phase was the final senior review of all models, conducted by a very experienced modeler. The emphasis of this review was on parameter consistency across the study area and ensuring that the overall calibration objectives have been achieved. Minor parameter adjustments were made as a result of this review.

Once the internal review was complete and the final models had been imported to and configured in the standalone calibration CHPS/FEWS, the files were transferred to the WGRFC via RTI's ftp server. These files were posted on February 1, 2019 and downloaded by the WGRFC for their review. The WGRFC performed an extensive review of the models and provided RTI with comments on February 13, 2019. In response to these comments, RTI performed adjustments to the models and submitted a revised version of the standalone calibration CHPS/FEWS to the WGRFC via the ftp server on February 19, 2019. As a final step, the WGRFC reviewed the revised models and provided RTI with approval of acceptance on March 5, 2019.

4.5 Calibration Results for the San Jacinto River Basin

The sub-basins within the San Jacinto River basin that were included in this study are highlighted in Figure 12. Summaries of the calibrated parameters from the LAG/K and SAC-SMA operations are provided in Tables 13 – 15. A summary of the total flow simulation statistics (generated using the STAT-Q tool) is provided in Table 16. Local flow statistics are given in Table 17. These statistics were calculated by comparing the simulated local flow to a calculated "observed" time series (i.e., the difference between the total observed flow and the routed upstream flows) using the STAT-QME operation. Table 18 shows the model performance for the recent major flood events for sub-basins with peak flow data available from the USGS. In addition to these performance data (taken from the PEAKFLOW operation), hourly hydrograph plots (generated in ICP) showing simulated and observed for these events are provided in Appendix D.

As indicated in Tables 13 and 14, in addition to the typically required routing of upstream flows through the modeled sub-basins, three sub-basins required additional routing of local runoff to capture attenuation effects at high flow ranges that could not be replicated by the static UNIT-HG model. These three sub-basins (KHOT2, CCGT2, and WFDT2) generally have a large number of agricultural berms, detention ponds, and wetlands areas that impact the timing of the local runoff during flooding. The use of the LAG/K operation to simulate these effects significantly improved the timing and magnitude of the simulated flood peaks.

In addition to the applied local runoff routing, sub-basin KHOT2 required the modeling of overflow from Cypress Creek into the Buffalo Bayou watershed. Further description of the modeling of the Cypress Creek overflow is provided in Section 4.7. Although this overflow occurs relatively infrequently, it has a major impact during the largest flood events on the timing and magnitude of peaks for KHOT2 and the volume of inflows into Addicks reservoir. More information on the impacts and frequency of the Cypress Creek overflow is available from the HCFCD (2015).

In the San Jacinto basin, two sub-basins (POET2U and POET2M) are ungaged and two sub-basins (FCWT2U and HMMT2) had insufficient data to support a full calibration analysis. For the ungaged sites, RTI calibrated the models jointly with the downstream local area (POET2). Because POET2U and POET2M are very similar in characteristics, the same SAC-SMA parameters were applied to both sub-basins. These parameters were varied from the downstream local area (POET2) based on soils information and through analysis of the total flow simulation of the larger flood events. Similarly, sub-basin FCWT2U in the Lake Creek watershed was analyzed in conjunction with the downstream local area (FCWT2). SAC-SMA parameters for FCWT2U were assigned by considering the final parameter sets for both the upstream (DDBT2) and downstream (FCWT2) sub-basins, as well as through analysis of the total flow simulation of the largest available observed events at FCWT2. For sub-basin HMMT2, where no reliable streamflow readings were available (only very limited stage data were available during the calibration analysis period), the final SAC-SMA parameters were assigned based on the final parameter sets of the nearby calibrated sub-basins, with consideration of the basin characteristics.

As shown in Table 15, relatively high values of UZFWM are specified in most sub-basins. The simulation of the largest flood event peaks proved very sensitive to this parameter, which primarily controls the proportion of runoff modeled as surface runoff (vs. interflow). Setting this value high generally limits the frequency of events where the simulated peak is primarily driven by surface runoff. In addition, four sub-basins have PCTIM values significantly higher than the upper limit defined by Anderson (see Table 12). These values indicate that direct runoff is very high and often is a significant driver of the timing and magnitude of the peaks (which for direct runoff is controlled by the UNIT-HG model). The need for a high PCTIM value is likely due to the high degree of urban/suburban development in these sub-basins, which can be seen in the sub-basin maps provided in Appendix B.

The final calibrated models generally perform well over the defined calibration periods, as evidenced from the total flow simulation statistics provided in Table 16. From this table, the level of correlation between the simulated and observed hourly data is high. The calculated R values are greater than 0.88 in all but one case. In this case (sub-basin DDBT2), the modeled period is extremely short (Oct 2018 – Jan 2019). The local flow statistics given in Table 17 also indicate that the final models produce simulated local runoff that correlates generally well when compared to the estimated observed flows. This correlation is lower for the local areas (such as SPNT2 and POET2) where the local drainage area is relatively small compared to the total drainage area. Finally, from Table 18 and Appendix D, the final calibrated models generally simulated the largest recent flood events very well. In particular, the models were able to produce peaks with timing and magnitude similar to those recorded during Hurricane Harvey, with an average discharge ratio of 1.08 for the San Jacinto sub-basins where data from the USGS are available. Overall, the final models should provide the WGRFC with a significantly improved capacity to forecast the timing and magnitude of flooding in the modeled areas.

Figure 12. Calibrated Sub-basins in the San Jacinto River Basin

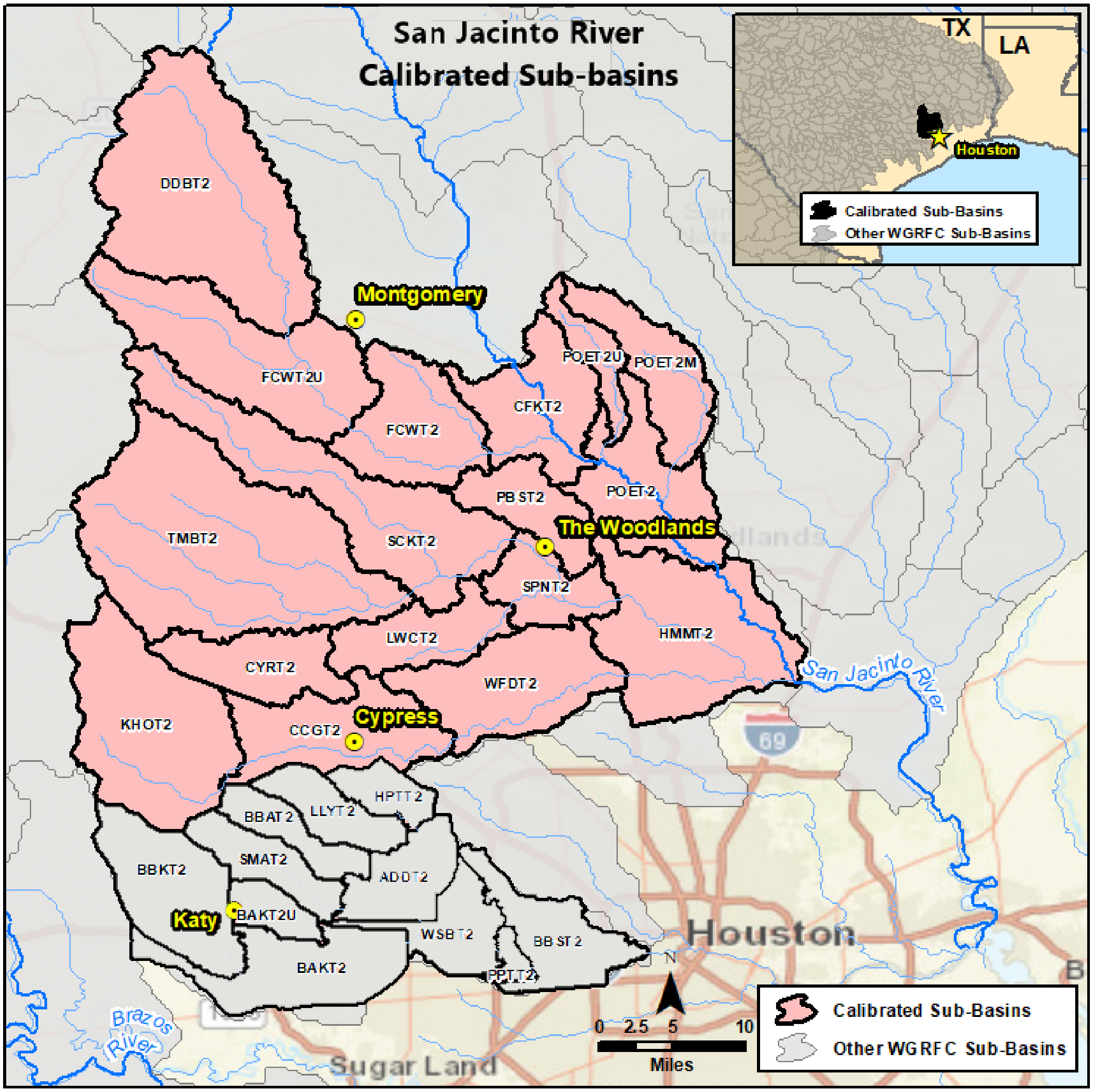


Table 13. Summary of Lag/Q Pairs for Modeled Reaches in the San Jacinto River Basin

Routing from	Routing to	Lag Parameters							
		Lag1 (hr)	Q1 (cfs)	Lag2 (hr)	Q2 (cfs)	Lag3 (hr)	Q3 (cfs)	Lag4 (hr)	Q4 (cfs)
DDBT2	FCWT2U	10	350	16	1700	10	5000	4	15000
DDBT2	FCWT2U	(cont.)		2	25000				
FCWT2U	FCWT2	14	350	25	1700	14	5000	5	15000
FCWT2U	FCWT2	(cont.)		4	25000				
FCWT2	CFKT2	4	3500	18	7000	6	20000		
LCTT2	CFKT2	4	3500	5	7000	4	35000		
CFKT2	POET2	8							
POET2U	POET2	9							
POET2M	POET2	6							
TMBT2	SCKT2	11	3000	9	3100				
SCKT2	SPNT2	10	2100	15	4000	8	38000	11	50000
PBST2	SPNT2	2	3500	4	7000				
LWCT2	SPNT2	4	3500	6	7000				
KHOT2	CCGT2	6	1750	10	3000				
CYRT2	CCGT2	3	1750	5	3000				
CCGT2	WFDT2	7	700	6	3000	11	6000	0	15000
POET2	HMMT2	6	3000	5	8000				
SPNT2	HMMT2	5							
WFDT2	HMMT2	5							
Local Runoff	KHOT2	0							
Local Runoff	CCGT2	0							
Local Runoff	WFDT2	0							

Table 14. Summary of K/Q Pairs for Modeled Reaches in the San Jacinto River Basin

Routing from	Routing to	K Parameters							
		K1 (hr)	Q1 (cfs)	K2 (hr)	Q2 (cfs)	K3 (hr)	Q3 (cfs)	K4 (hr)	Q4 (cfs)
DDBT2	FCWT2U	10	1700	5	5000	4	15000	2	25000
FCWT2U	FCWT2	14	1700	7	5000	5	15000	4	25000
FCWT2	CFKT2	3	3500	5	7000				
LCTT2	CFKT2	3	3500	5	7000				
CFKT2	POET2	1	3500	8	10000	1	25000		
POET2U	POET2	1	3500	6	10000	1	25000		
POET2M	POET2	1	3500	8	10000	1	25000		
TMBT2	SCKT2	10							
SCKT2	SPNT2	0							
PBST2	SPNT2	5							
LWCT2	SPNT2	2							
KHOT2	CCGT2	8	1750	5	3000				
CYRT2	CCGT2	4	1000	20	3000	4	4000		
CCGT2	WFDT2	2	3000	10	6000	50	25000		
POET2	HMMT2	3	3000	5	8000				
SPNT2	HMMT2	1							
WFDT2	HMMT2	0							
Local Runoff	KHOT2	24	1765	12	3530	3	5297		
Local Runoff	CCGT2	0	35	12	1775	24	2700	42	3550
Local Runoff	CCGT2	(cont.)		48	7100				
Local Runoff	WFDT2	0	500	1	2000	3	4000	6	6000
Local Runoff	WFDT2	(cont.)		20	10000				

Table 15. Calibrated SAC-SMA Parameters for Modeled Sub-basins in the San Jacinto River Basin

NWS Basin ID	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
DDBT2	1.0	1.0	25	30	0.50	0.020	0.000	0.015	300	2.0	175	15	35	0.20	0.002	0.05	0.30	0.00	3.07
FCWT2U	1.0	1.0	75	35	0.45	0.020	0.000	0.000	300	2.5	250	15	45	0.18	0.002	0.10	0.30	0.00	2.79
FCWT2	1.0	1.0	75	75	0.50	0.005	0.000	0.000	285	2.4	300	30	110	0.20	0.005	0.05	0.30	0.00	6.55
CFKT2	1.0	1.0	75	50	0.50	0.020	0.000	0.000	250	2.0	250	30	100	0.20	0.005	0.05	0.30	0.00	6.50
POET2U	1.0	1.0	25	75	0.40	0.005	0.040	0.020	75	2.0	150	20	50	0.15	0.003	0.05	0.30	0.00	3.15
POET2M	1.0	1.0	25	75	0.40	0.005	0.040	0.020	75	2.0	150	20	50	0.15	0.003	0.05	0.30	0.00	3.15
POET2	1.0	1.0	20	75	0.40	0.005	0.040	0.020	150	2.5	250	60	300	0.08	0.002	0.10	0.30	0.00	5.40
PBST2	1.0	1.0	35	60	0.35	0.180	0.150	0.000	120	2.0	75	30	90	0.17	0.005	0.35	0.30	0.00	5.55
TMBT2	1.0	1.0	50	40	0.50	0.015	0.000	0.005	120	2.5	220	25	50	0.17	0.003	0.05	0.30	0.00	4.40
SCKT2	1.0	1.0	50	65	0.40	0.010	0.000	0.020	100	2.4	215	30	100	0.15	0.010	0.05	0.30	0.00	5.50
LWCT2	1.0	1.0	50	75	0.40	0.050	0.040	0.000	150	2.0	200	15	30	0.15	0.008	0.15	0.30	0.00	2.49
SPNT2	1.0	1.0	40	50	0.50	0.150	0.020	0.000	120	2.5	100	25	50	0.20	0.010	0.20	0.30	0.00	5.50
CYRT2	1.0	1.0	65	60	0.40	0.010	0.015	0.005	150	2.0	230	15	30	0.15	0.020	0.05	0.30	0.00	2.85
KHOT2	1.0	1.0	65	75	0.50	0.005	0.020	0.025	220	2.6	200	20	30	0.20	0.010	0.05	0.30	0.00	4.30
CCGT2	1.0	1.0	40	75	0.50	0.090	0.050	0.000	230	2.0	250	20	120	0.20	0.002	0.35	0.30	0.00	4.24
WFDT2	1.0	1.0	25	50	0.50	0.300	0.100	0.000	100	2.5	100	40	150	0.15	0.010	0.10	0.30	0.00	7.50
HMMT2	1.0	1.0	20	75	0.40	0.040	0.060	0.020	150	2.5	250	50	225	0.12	0.006	0.10	0.30	0.00	7.35

Table 16. Total Flow Simulation Statistics (from STAT-Q) for Modeled Sub-basins in the San Jacinto River Basin

NWS Basin ID	Calibration Period	% Bias	Abs. % Bias	Obs. Q_{mean} (CMS)	Sim. Q_{mean} (CMS)	Obs. std (CMS)	Sim. std (CMS)	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
DDBT2	2018-10-01 to 2019-01-31	12.17	84.84	3.95	4.43	21.92	23.3	5.552	5.264	412.6	16.29	0.742	0.448	0.698	0.86	0.70
FCWT2U	n/a	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
FCWT2	2015-11-01 to 2018-10-31	6.16	34.57	10.66	11.32	64.33	62.0	6.032	5.474	153.80	16.40	0.967	0.935	0.932	-0.70	1.00
CFKT2	2015-11-01 to 2018-10-31	4.83	31.31	13.54	14.19	76.53	84.1	5.653	5.925	127.20	17.22	0.981	0.949	0.893	0.86	0.89
POET2U	n/a	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
POET2M	n/a	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
POET2	2007-10-01 to 2018-10-31	-4.51	17.45	18.36	17.53	80.89	77.5	4.406	4.422	82.76	15.19	0.983	0.965	0.942	0.39	1.03
PBST2	2000-01-01 to 2018-10-31	-2.49	45.40	1.77	1.72	8.44	7.8	4.780	4.547	210.30	3.72	0.898	0.806	0.833	0.10	0.97
TMBT2	2008-01-01 to 2018-10-31	-0.05	40.48	3.98	3.98	38.17	37.3	9.589	9.362	225.80	8.99	0.972	0.945	0.948	0.02	1.00
SCKT2	2018-03-01 to 2018-10-31	-2.87	31.91	4.88	4.74	13.99	16.6	2.868	3.507	102.50	5.00	0.961	0.872	0.809	1.04	0.81
LWCT2	2006-10-01 to 2018-10-31	1.30	42.90	1.07	1.09	6.61	7.4	6.172	6.796	221.10	2.37	0.948	0.872	0.850	0.15	0.85
SPNT2	2005-01-01 to 2018-10-31	-4.51	23.56	10.86	10.37	51.24	51.5	4.718	4.960	97.60	10.60	0.979	0.957	0.975	0.75	0.98
CYRT2	2000-01-01 to 2018-11-30	0.13	50.89	0.83	0.84	5.74	7.4	6.888	8.813	341.10	2.85	0.935	0.755	0.730	0.23	0.73
KHOT2	2000-01-01 to 2018-11-30	1.27	60.08	1.57	1.59	7.05	7.6	4.487	4.761	226.70	3.56	0.884	0.745	0.822	0.26	0.82
CCGT2	2001-09-01 to 2018-11-30	2.57	29.32	3.94	4.04	16.16	16.6	4.100	4.096	127.80	5.04	0.953	0.903	0.930	0.18	0.93
WFDT2	2000-01-01 to 2018-11-30	0.71	25.66	8.65	8.71	28.63	29.1	3.311	3.335	88.79	7.68	0.965	0.928	0.951	0.37	0.95
HMMT2	2018-02-01 to 2018-10-31	-12.72	17.05	64.01	55.87	108.00	102.6	1.687	1.836	28.91	18.51	0.989	0.971	0.939	5.83	1.04

Table 17. Local Flow Simulation Statistics (from STAT-QME) for Modeled Sub-basins in the San Jacinto River Basin

NWS Basin ID	Calibration Period	Sim. Q_{mean} (CMS)	Obs. Q_{mean} (CMS)	Annual % Bias	R	DRMS Error (CMS)	DRMS Ratio	Best Fit A	Best Fit B	High Flow Bias %
FCWT2U	n/a	--	--	--	--	--	--	--	--	--
FCWT2	2015-11-01 to 2018-10-31	2.58	4.48	-42.4	0.856	13.0	2.90	1.45	1.18	-20.31
CFKT2	2015-11-01 to 2018-10-31	2.65	5.07	-47.8	0.977	5.7	1.13	2.06	1.14	-76.00
POET2	2007-10-01 to 2018-10-31	1.40	3.51	-60.1	0.573	13.0	3.71	1.89	1.16	-66.83
SCKT2	2018-03-01 to 2018-10-31	1.57	2.23	-29.4	0.687	3.2	1.44	0.67	0.99	-56.18
SPNT2	2005-01-01 to 2018-10-31	1.54	2.45	-36.9	0.565	7.7	3.13	1.54	0.59	-36.26
CCGT2	2001-09-01 to 2018-11-30	2.15	2.23	-3.4	0.862	4.8	2.15	0.61	0.75	-10.15
WFDT2	2000-01-01 to 2018-11-30	3.86	3.85	0.2	0.937	4.3	1.11	0.30	0.96	-12.49
HMMT2	2018-02-01 to 2018-10-31	2.42	9.71	-75.1	0.894	12.6	1.30	3.05	2.75	-71.59

Table 18. Simulated Peak Comparison (from PEAKFLOW) for Recent Large Events for Modeled Sub-basins in the San Jacinto River Basin

NWS Basin ID	Obs. Q_{peak} (CFS)	Date of Obs. Q_{peak}	Sim. Q_{peak} (CFS)	Date of Sim. Q_{peak}	Timing Error (days)	Discharge Error (CFS)	Discharge Ratio (Sim/Obs)	Notes
FCWT2	55,444	8/28/2017	49,794	8/28/2017	0	-5,650	0.90	Hurricane Harvey
FCWT2	37,434	5/27/2016	52,972	5/27/2016	0	15,538	1.42	Memorial Day Flood
CFKT2	122,189	8/29/2017	120,776	8/29/2017	0	-1,413	0.99	Hurricane Harvey
CFKT2	58,975	5/28/2016	60,035	5/28/2016	0	1,059	1.02	Memorial Day Flood
POET2	122,189	8/29/2017	120,776	8/29/2017	0	-1,413	0.99	Hurricane Harvey
POET2	55,797	5/29/2016	62,154	5/28/2016	1	6,357	1.11	Memorial Day Flood Simulated peaks 13 hours early.
PBST2	12,501	8/28/2017	11,724	8/28/2017	0	-777	0.94	Hurricane Harvey
PBST2	8,122	4/18/2016	6,992	4/18/2016	0	-1,130	0.86	Tax Day Flood
TMBT2	48,734	8/28/2017	53,678	8/28/2017	0	4,944	1.10	Hurricane Harvey
TMBT2	45,556	5/27/2016	35,668	5/28/2016	-1	-9,888	0.78	Memorial Day Flood Simulated has double peak; first peak timing matches observed.
LWCT2	11,195	8/28/2017	11,619	8/28/2017	0	424	1.04	Hurricane Harvey
LWCT2	6,498	4/18/2016	5,862	4/18/2016	0	-636	0.90	Tax Day Flood
SPNT2	78,399	8/28/2017	75,573	8/28/2017	0	-2,825	0.96	Hurricane Harvey
SPNT2	60,035	5/28/2016	49,794	5/28/2016	0	-10,241	0.83	Memorial Day Flood
CYRT2	9,146	8/28/2017	13,702	8/27/2017	1	4,556	1.50	Hurricane Harvey; observed peak is noisy, true timing hard to evaluate.
CYRT2	10,206	4/18/2016	8,970	4/18/2016	0	-1,236	0.88	Tax Day Flood
KHOT2	12,784	8/28/2017	12,572	8/28/2017	0	-212	0.98	Hurricane Harvey
KHOT2	9,959	4/18/2016	11,477	4/18/2016	0	1,519	1.15	Tax Day Flood
CCGT2	17,516	8/28/2017	25,568	8/28/2017	0	8,052	1.46	Hurricane Harvey; observed data very noisy.
CCGT2	21,012	4/19/2016	15,079	4/18/2016	1	-5,933	0.72	Tax Day Flood; simulated peaks 4 hours early.
WFDT2	31,501	8/28/2017	32,843	8/28/2017	0	1,342	1.04	Hurricane Harvey
WFDT2	14,514	4/18/2016	20,306	4/19/2016	-1	5,792	1.40	Tax Day Flood; observed is double-peaked, simulated peaks 16 hours late.

4.6 Calibration Results for the Buffalo Bayou Basin

The sub-basins within the Buffalo Bayou basin that were included in this study are highlighted in Figure 13. Summaries of the calibrated parameters from the LAG/K and SAC-SMA operations are provided in Tables 19 – 21. A summary of the total flow simulation statistics (generated using the STAT-Q tool) is provided in Table 22. Local flow statistics are given in Table 23. These statistics were calculated by comparing the simulated local flow to a calculated "observed" time series (i.e., the difference between the total observed flow and the routed upstream flows) using the STAT-QME operation. Table 24 shows the model performance for the recent major flood events for sub-basins with peak flow data available from the USGS. In addition to these performance data (taken from the PEAKFLOW operation), hourly hydrograph plots (generated in ICP) showing simulated and observed for these events are provided in Appendix D.

As indicated in Tables 19 and 20, in addition to the typically required routing of upstream flows through the modeled sub-basins, two sub-basins required additional routing of local runoff to capture attenuation effects at high flow ranges that could not be replicated by the static UNIT-HG model. One of these two sub-basins (BBKT2) has several agricultural berms and small detention ponds that impact the timing of the local runoff during flooding. The other sub-basin (BBST2) contains a very large natural preserve area with woody wetlands that may act to attenuate runoff during large events where flows significantly exceed bank full conditions in the bayou. The use of the LAG/K operation to simulate these effects significantly improved the timing and magnitude of the simulated flood peaks. In addition to the applied local runoff routing, sub-basins LLYT2, BBAT2, and SMAT2 receive inflows from the previously mentioned Cypress Creek overflow (describe further in Section 4.7). These inflows required the use of a LAG/K operation to match the observed timing and magnitude observed at the sub-basin outlets during overflow conditions.

In the Buffalo Bayou basin, two sub-basins (HPTT2 and BAKT2U) have only stage data from the HCFCD available. To enable calibration of these sites, RTI acquired rating curves from the HCFCD to translate the recorded stages to discharge. Testing of the provided rating curves demonstrated that they likely over-estimate streamflow values during low-flow periods. Accordingly, RTI ignored low flow periods during the calibration analysis for these sub-basins. To specify the baseflow parameters for HPTT2 and BAKT2U, nearby sub-basins with similar basin characteristics were used for guidance. For the local areas at Addicks and Barker Reservoirs (ADDT2 and BAKT2), historical inflow data were provided by the USACE Galveston District. RTI reviewed these data and performed quality control over the calibration analysis period. For both reservoirs, the inflow volumes provided by the USACE indicate a very high incoming baseflow contribution between events that could not be matched without artificially introducing volume (e.g., through a CHANLOSS). After a thorough review, RTI concluded that these high baseflow volumes were likely a data issue. Therefore, similar to HPTT2 and BAKT2U, the calibration effort focused only on the flood events, with baseflow parameters being estimated from nearby sub-basins with similar characteristics.

As shown in Table 21, relatively high values of UZFWM are specified in most sub-basins. The simulation of the largest flood event peaks proved very sensitive to this parameter, which primarily controls the proportion of runoff modeled as surface runoff (vs. interflow). Setting this value high generally limits the frequency of events where the simulated peak is primarily driven by surface runoff. In addition, all but one of the modeled sub-basins have PCTIM values significantly higher than the upper limit defined by Anderson (see Table 12). These values indicate that direct runoff is very high and often is a significant driver of the timing and magnitude of the peaks (which for direct runoff is controlled by the UNIT-HG model). The need for a high PCTIM value is likely due to the high degree of urban/suburban development in these sub-basins, which can be seen in the sub-basin maps provided in Appendix B.

The final calibrated models generally perform well over the defined calibration periods, as evidenced from the total flow simulation statistics provided in Table 22. From this table, the level of correlation between the simulated and observed hourly data is high. The calculated R values are greater than 0.83 in all cases. The local flow statistics given in Table 23 also indicate that the final models produce simulated local runoff that correlates generally well when compared to the estimated observed flows, with correlation coefficients (R) at or above 0.7 in all cases. Finally, from Table 24 and Appendix D, the final calibrated models generally simulated the largest recent flood events very well. In particular, the models were able to produce peaks with timing and magnitude similar to those recorded during the Tax Day Flood, with an average discharge ratio of 0.98 for the Buffalo Bayou sub-basins where data from the USGS are available. This value omits sub-basin BBKT2, which had an unusually low recorded peak for this event relative to the other nearby sub-basins. Overall, the final models should provide the WGRFC with a significantly improved capacity to forecast the timing and magnitude of flooding in the modeled areas.

Figure 13. Calibrated Sub-basins in the Buffalo Bayou Basin

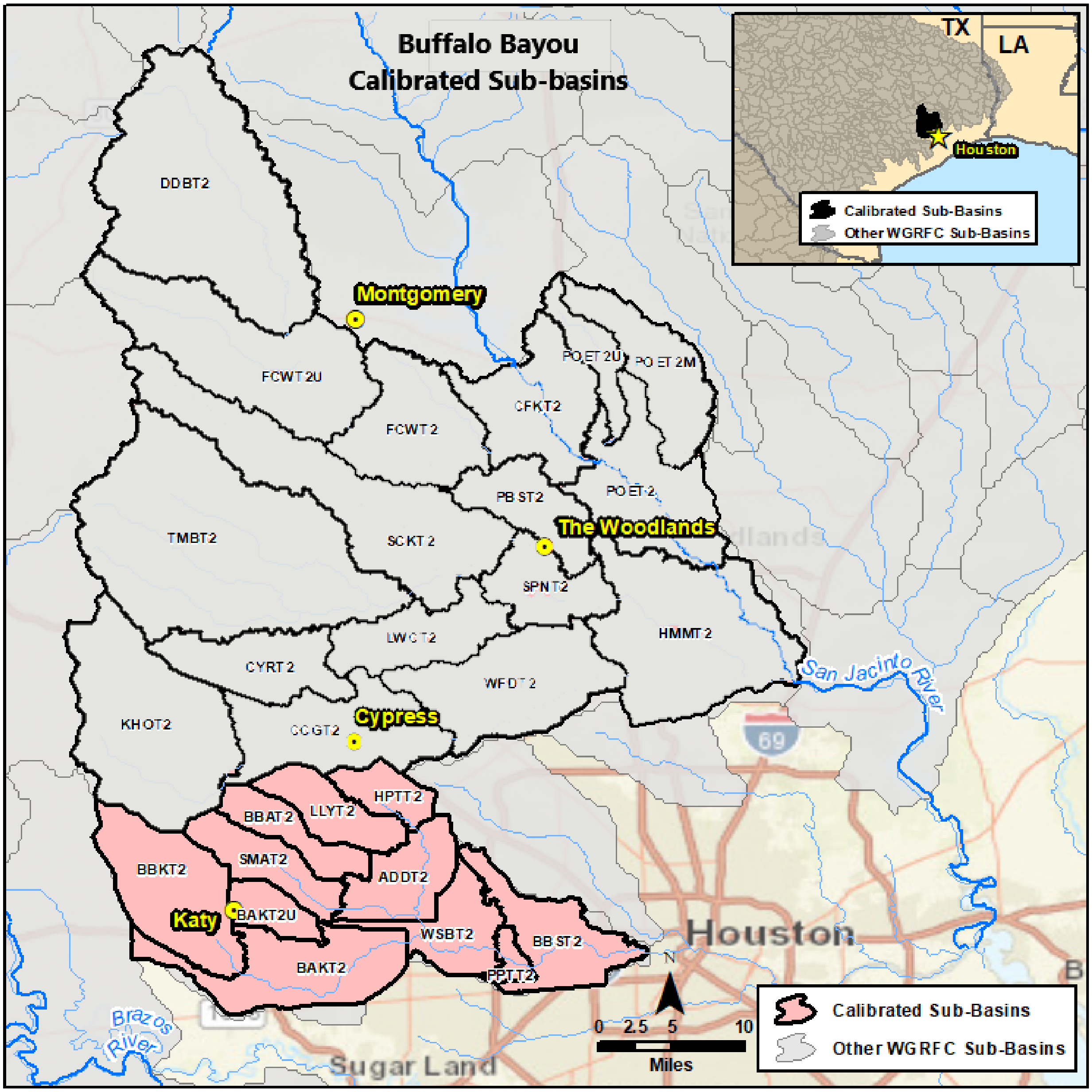


Table 19. Summary of Lag/Q Pairs for Modeled Reaches in the Buffalo Bayou Basin

Routing from	Routing to	Lag Parameters							
		Lag1 (hr)	Q1 (cfs)	Lag2 (hr)	Q2 (cfs)	Lag3 (hr)	Q3 (cfs)	Lag4 (hr)	Q4 (cfs)
HPTT2	ADDT2	2	900	2	1800	1	10000		
LLYT2	ADDT2	2	900	2	1800	1	10000		
BBAT2	ADDT2	2	900	2	1800	1	10000		
SMAT2	ADDT2	2	900	2	1800	1	10000		
BBKT2	BAKT2	4	900	4	1800	2	10000		
BAKT2U	BAKT2	2	900	2	1800	1	10000		
ADDT2	WSBT2	2	900	2	1800	1	10000		
BAKT2	WSBT2	2	900	2	1800	1	10000		
WSBT2	PPTT2	1							
PPTT2	BBST2	6	1750	0	3500				
Local Runoff	BBKT2	0							
Local Runoff	BBST2	0							
Cypr Ck Overflow	LLYT2	9							
Cypr Ck Overflow	BBAT2	3							
Cypr Ck Overflow	SMAT2	6							

Table 20. Summary of K/Q Pairs for Modeled Reaches in the Buffalo Bayou Basin

Routing from	Routing to	K Parameters							
		K1 (hr)	Q1 (cfs)	K2 (hr)	Q2 (cfs)	K3 (hr)	Q3 (cfs)	K4 (hr)	Q4 (cfs)
HPTT2	ADDT2	2	900	0	1800				
LLYT2	ADDT2	2	900	0	1800				
BBAT2	ADDT2	2	900	0	1800				
SMAT2	ADDT2	2	900	0	1800				
BBKT2	BAKT2	4	900	0	1800				
BAKT2U	BAKT2	2	900	0	1800				
ADDT2	WSBT2	2	900	0	1800				
BAKT2	WSBT2	2	900	0	1800				
WSBT2	PPTT2	1	1750	2	3500	4	10000		
PPTT2	BBST2	0	1750	3	3500	2	10000		
Local Runoff	BBKT2	0	500	3	2500	6	5000	9	7500
Local Runoff	BBKT2	(cont.)		16	10000	20	20000		
Local Runoff	BBST2	0	5000	16	10000				
Cypr Ck Overflow	LLYT2	36							
Cypr Ck Overflow	BBAT2	84	1060	18	1766	6	3530		
Cypr Ck Overflow	SMAT2	6							

Table 21. Calibrated SAC-SMA Parameters for Modeled Sub-basins in the Buffalo Bayou Basin

NWS Basin ID	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
HPTT2	1.0	1.0	50	60	0.50	0.150	0.030	0.000	200	2.5	150	20	250	0.15	0.002	0.15	0.30	0.00	3.50
LLYT2	1.0	1.0	45	75	0.40	0.150	0.100	0.000	280	3.0	120	20	400	0.10	0.001	0.25	0.30	0.00	2.40
BBAT2	1.0	1.0	30	40	0.50	0.100	0.050	0.000	300	3.5	220	15	60	0.20	0.004	0.30	0.30	0.00	3.24
SMAT2	1.0	1.0	30	75	0.50	0.070	0.050	0.000	285	3.2	250	25	100	0.20	0.004	0.25	0.30	0.00	5.40
ADDT2	1.0	1.0	40	70	0.50	0.130	0.100	0.050	200	3.0	200	20	75	0.15	0.002	0.20	0.30	0.00	3.15
BAKT2U	1.0	1.0	20	75	0.50	0.150	0.010	0.000	300	3.5	125	20	250	0.15	0.001	0.20	0.30	0.00	3.25
BBKT2	1.0	1.0	25	65	0.50	0.020	0.010	0.000	300	2.0	200	20	45	0.10	0.002	0.20	0.30	0.00	2.09
BAKT2	1.0	1.0	30	75	0.45	0.160	0.100	0.020	200	3.0	150	25	50	0.13	0.004	0.30	0.30	0.00	3.45
WSBT2	1.0	1.0	25	75	0.50	0.350	0.010	0.000	300	3.5	125	20	50	0.15	0.001	0.30	0.30	0.00	3.05
PPTT2	1.0	1.0	25	75	0.50	0.500	0.005	0.000	210	2.0	100	30	75	0.15	0.002	0.30	0.30	0.00	4.65
BBST2	1.0	1.0	30	75	0.50	0.300	0.020	0.000	250	2.0	150	30	50	0.15	0.004	0.30	0.30	0.00	4.70

Table 22. Total Flow Simulation Statistics (from STAT-Q) for Modeled Sub-basins in the Buffalo Bayou Basin

NWS Basin ID	Calibration Period	% Bias	Abs. % Bias	Obs. Q_{mean} (CMS)	Sim. Q_{mean} (CMS)	Obs. std (CMS)	Sim. std (CMS)	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
HPTT2	2014-05-01 to 2018-11-30	n/a	--	--	--	--	--	--	--	--	--	--	--	--	--	--
LLYT2	2001-12-01 to 2018-11-30	-0.06	54.11	1.20	1.20	6.77	7.4	5.643	6.190	345.00	4.14	0.834	0.626	0.761	0.29	0.76
BBAT2	2000-01-01 to 2018-11-30	-0.86	64.19	0.93	0.92	5.38	5.4	5.807	5.895	321.00	2.98	0.848	0.694	0.843	0.15	0.84
SMAT2	2015-10-01 to 2018-10-31	-11.06	53.13	2.42	2.15	15.28	14.8	6.319	6.859	356.70	8.63	0.836	0.681	0.807	0.56	0.87
ADDT2	2000-01-01 to 2018-10-31	n/a	--	--	--	--	--	--	--	--	--	--	--	--	--	--
BAKT2U	2015-05-01 to 2018-09-30	n/a	--	--	--	--	--	--	--	--	--	--	--	--	--	--
BBKT2	2009-01-01 to 2018-11-30	-8.27	49.87	1.81	1.66	9.33	10.3	5.147	6.206	232.30	4.21	0.913	0.796	0.826	0.44	0.83
BAKT2	2000-01-01 to 2018-09-30	n/a	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WSBT2	2008-01-01 to 2018-09-30	-5.87	30.15	13.96	13.14	23.89	23.7	1.711	1.807	67.21	9.38	0.923	0.846	0.917	1.76	0.93
PPTT2	2001-10-01 to 2018-11-30	0.07	6.23	15.23	15.24	25.34	25.1	1.664	1.644	13.90	2.12	0.997	0.993	0.985	-0.14	1.01
BBST2	2013-01-01 to 2018-11-30	1.03	12.62	57.42	58.02	68.98	60.9	1.201	1.050	31.19	17.91	0.970	0.933	0.856	-6.31	1.10

Table 23. Local Flow Simulation Statistics (from STAT-QME) for Modeled Sub-basins in the Buffalo Bayou Basin

NWS Basin ID	Calibration Period	Sim. Q_{mean} (CMS)	Obs. Q_{mean} (CMS)	Annual % Bias	R	DRMS Error (CMS)	DRMS Ratio	Best Fit A	Best Fit B	High Flow Bias %
ADDT2	2000-01-01 to 2018-10-31	1.13	4.00	-71.8	0.699	6.97	1.74	3.15	0.75	-56.55
BAKT2	2000-01-01 to 2018-09-30	2.40	5.06	-52.5	0.896	6.73	1.33	2.75	0.96	-36.09
WSBT2	2008-01-01 to 2018-09-30	4.39	6.67	-34.2	0.914	6.35	0.95	2.89	0.86	-31.00
PPTT2	2001-10-01 to 2018-11-30	0.91	1.55	-41.3	0.719	2.03	1.31	0.91	0.71	-46.07
BBST2	2013-01-01 to 2018-11-30	8.87	11.66	-24.0	0.870	13.39	1.15	2.54	1.03	-7.58

Table 24. Simulated Peak Comparison (from PEAKFLOW) for Recent Large Events for Modeled Sub-basins in the Buffalo Bayou Basin

NWS Basin ID	Obs. Q_{peak} (CFS)	Date of Obs. Q_{peak}	Sim. Q_{peak} (CFS)	Date of Sim. Q_{peak}	Timing Error (days)	Discharge Error (CFS)	Discharge Ratio (Sim/Obs)	Notes
LLYT2	9,005	8/27/2017	17,551	8/27/2017	0	8,546	1.95	Hurricane Harvey; double-peaked event, impacted by Cypress Creek overflow.
LLYT2	15,998	4/18/2016	15,433	4/18/2016	0	-565	0.96	Tax Day Flood
BBAT2	15,715	8/27/2017	19,176	8/28/2017	-1	3,461	1.22	Hurricane Harvey; observed data extremely noisy.
BBAT2	13,702	4/18/2016	12,184	4/18/2016	0	-1,519	0.89	Tax Day Flood
SMAT2	12,219	8/28/2017	15,998	8/27/2017	1	3,779	1.31	Hurricane Harvey; double-peaked event, impacted by Cypress Creek overflow.
SMAT2	9,782	4/18/2016	10,171	4/18/2016	0	388	1.04	Tax Day Flood
BBKT2	17,905	8/28/2017	18,823	8/28/2017	0	918	1.05	Hurricane Harvey
BBKT2	5,650	4/18/2016	12,925	4/18/2016	0	7,275	2.29	Tax Day Flood; observed peak shows large amount of attenuation not replicated in simulation.
BBST2	36,374	8/28/2017	29,947	8/27/2017	1	-6,427	0.82	Hurricane Harvey; observed data extremely noisy.
BBST2	15,715	4/18/2016	16,068	4/18/2016	0	353	1.02	Tax Day Flood

4.7 Model Development for the Cypress Creek Overflow

During large flood events, there is a known natural trans-basin rerouting of flow from the headwaters of Cypress Creek, in the San Jacinto River basin, into the headwaters of Buffalo Bayou, impacting both the peak magnitude and timing at KHOT2 and the volume of inflows into Addicks Reservoir. Known as the Cypress Creek overflow, this transfer of flow presented a unique modeling challenge. As mentioned previously, further information on the Cypress Creek overflow is available from the HCFCD (2015). The modeling challenges included identifying and replicating: 1) the conditions involved in triggering the overflow; 2) the apportionment of the overflow into the Buffalo Bayou headwaters; and, 3) the timing of the additional inflow to Addicks Reservoir. These challenges are complex due to the fact that the volumes and apportionments of the overflow change depending on the size and spatial characteristics of the flood event.

To model the Cypress Creek overflow, RTI's modeling team consulted with the WGRFC and determined that we would look for a modeling solution that was not overly-burdensome computationally, but would adequately meet the following goals to improve: 1) the accuracy of the simulation of inflow volume into Addicks Reservoir; 2) the peak magnitude and timing of flood events at KHOT2; and, 3) the simulation of secondary peaks (that are a result of the overflow) at the Buffalo Bayou headwaters. In addition, as part of the desired modeling simplicity, we wanted to avoid the creation of any external time series that would need to be transferred between modeled sub-basins and tracked in the operational CHPS/FEWS. A final goal was to conserve runoff volume (i.e., no artificial adjustment of volume to match observations of particular events).

In light of these modeling objectives, the derived modeling solution included the addition of a LOOKUP operation, multiple WEIGH-TS operations, and LAG/K operations to route the simulated overflow through the Buffalo Bayou headwaters. Based on the HCFCD overflow report and inspection of the available historical observed streamflow records, it was determined that the impacted sub-basins include KHOT2 (the source of the overflow) and Buffalo Bayou headwaters LLYT2, BBAT2, and SMAT2 (which receive the overflow). The table in the developed LOOKUP operation was specified by reviewing the available peak flow data at KHOT2 and iteratively adjusting table values to reduce the simulated peaks and improve the matching of the historical observations. The overflow was assumed to be the observed reduction in peaks evident in the larger flood events (and reported on by the HCFCD). The final LOOKUP operation used to calculate the overflow time series was copied into the receiving sub-basin models to avoid the need for an external time series. To apportion the overflow between the receiving sub-basins, WEIGH-TS operations were used. Using data from the HCFCD report, the approximate average apportionment over all reported overflow events was used: 70% of the total overflow to sub-basin BBAT2, 20% to SMAT2, and 10% to LLYT2. This fixed apportionment ensures that the runoff volume is conserved; however, it is a simplification that generally reduces the accuracy of the model.

Sample hydrographs showing the simulations of the impacted sub-basins without and with the overflow modeling for recent flood events are given in Appendix E.

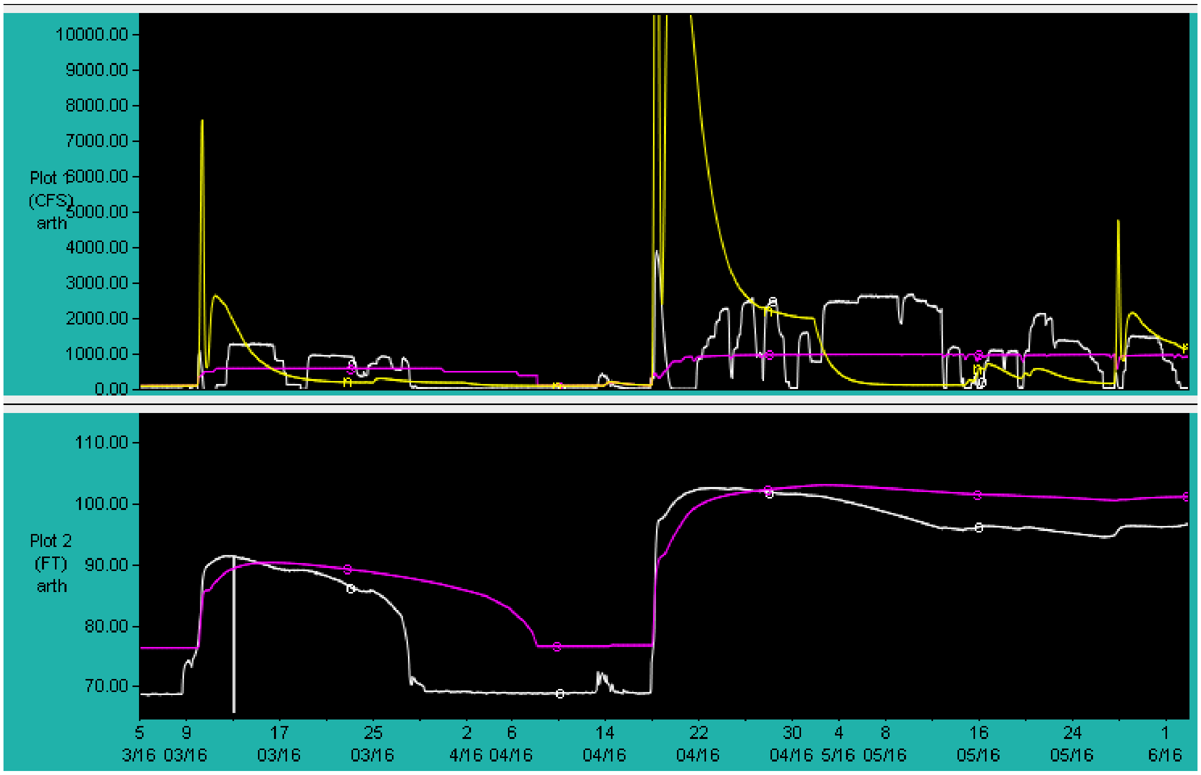
4.8 Evaluation of Existing Reservoir Models

To assist the WGRFC in assessing the performance of their current operational forecasting system, RTI performed an evaluation of the existing models (RES-J) of Addicks and Barker Reservoirs in ICP using collected historical datasets. The following is a summary of our findings.

Overall, the Addicks Reservoir RES-J model performs satisfactorily for the recent major flood events. The simulated baseline pool elevation tended to be higher than observed, with the simulation averaging around 76.5 ft with the observed around 69.0 ft. Many events result in under-simulated releases, though the peak pool elevations are often close to the observed. The model releases between 500 – 1,000 cfs continuously during most events, whereas the actual operations typically release at a higher rate over a shorter time. The RES-J simulation of Addicks Reservoir for the Tax Day Flood (and a smaller antecedent event) is shown in Figure 14.

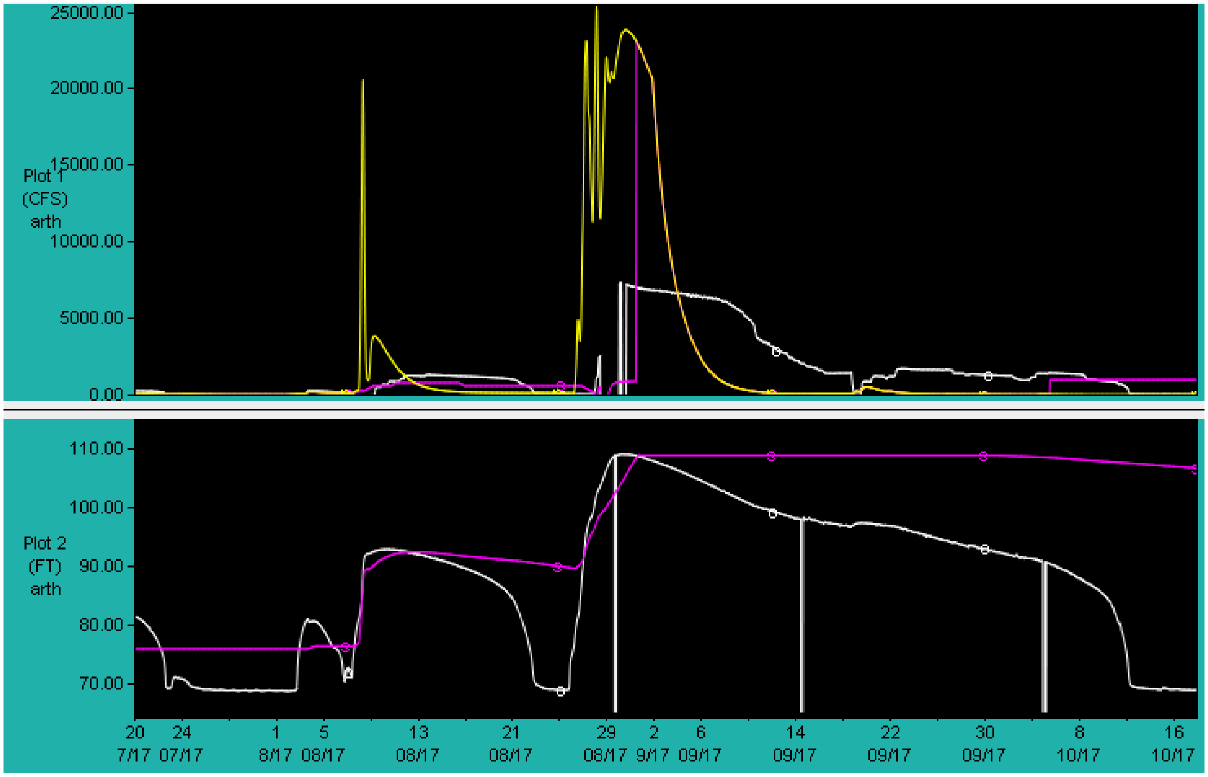
The modeling of Hurricane Harvey (shown in Figure 15) indicated that the maximum reservoir pool elevation is matched well; however, the simulated releases differ from the observed significantly. The observed release data are missing when the pool elevation is at its maximum, but, when data are available, they indicate a maximum release around 7,200 cfs. The RES-J model limits releases to 1,000 cfs – this limit may need to be increased using the observed Hurricane Harvey operations as a guide.

Figure 14. Addicks Reservoir RES-J Model Performance for the Tax Day Flood



(Purple Line = Simulated, White Line = Observed, Yellow Line = Inflows)

Figure 15. Addicks Reservoir RES-J Model Performance for Hurricane Harvey

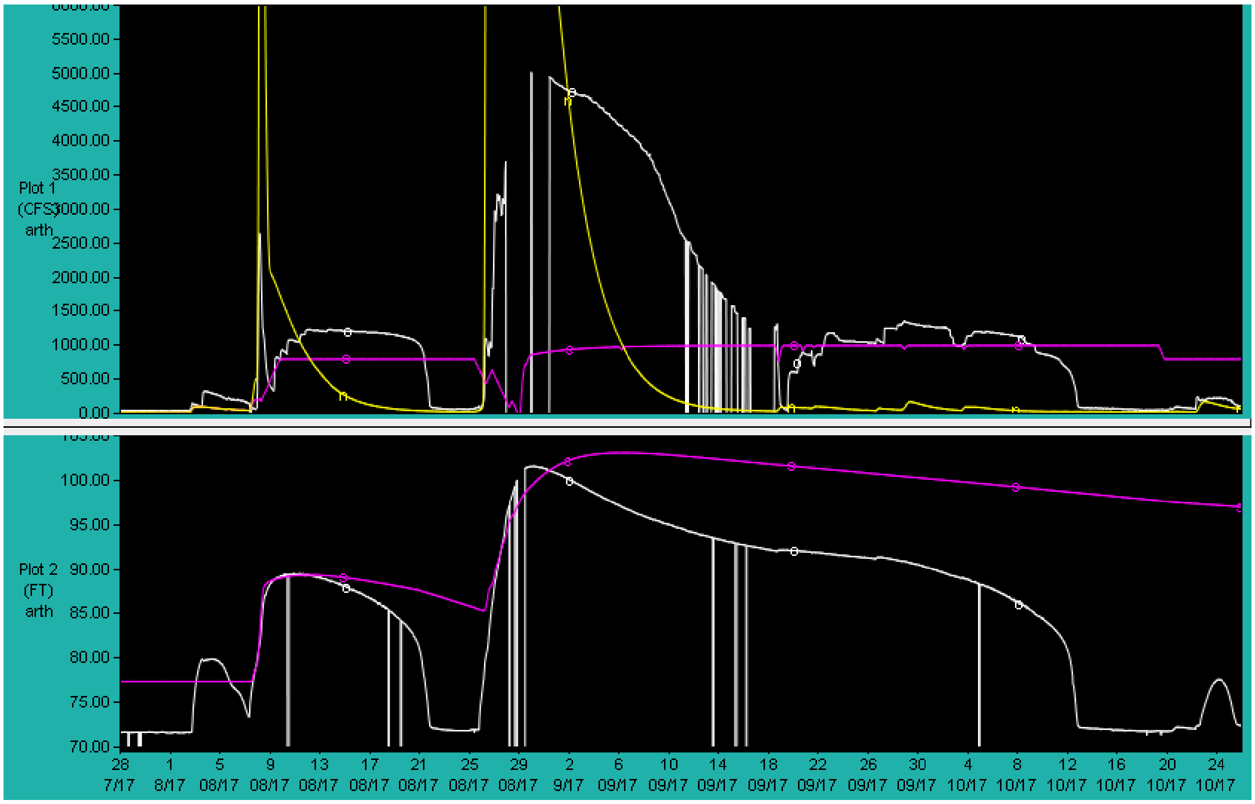


(Purple Line = Simulated, White Line = Observed, Yellow Line = Inflows)

The Barker Reservoir RES-J model performs similarly to Addicks. Baseline pool elevations are still over-simulated at times, though much less often than at Addicks. Medium-sized events are often under-simulated: the model releases a maximum of around 800 cfs, whereas the actual operations peak between 1,000 and 2,000 cfs.

The simulation of the recent large flood events indicates that the Barker Reservoir model tends to under-predict releases. The actual peak release at Barker for the Tax Day Flood event was over 5,000 cfs, whereas the model releases only 800 cfs. For Hurricane Harvey (see Figure 16), the actual peak release is unknown due to missing data, but the observed values that are available indicate a release of around 5,000 cfs for a prolonged period. This event was large enough to push the model up to 1,000 cfs, which is the largest release specified in the existing RES-J model. It may be beneficial to recalibrate the model for very high elevations using the two large observed events for guidance.

Figure 16. Barker Reservoir RES-J Model Performance for Hurricane Harvey



(Purple Line = Simulated, White Line = Observed, Yellow Line = Inflows)

5. CONCLUSIONS

Over the course of this study, RTI completed several tasks in support of TWDB's effort to improve flood forecasting for 28 sub-basins in the Houston metropolitan area in southeastern Texas. This project was performed in cooperation with the NWS-WGRFC. Prior to the hydrologic model calibration analysis, potential evapotranspiration estimates were derived using a simplified Penman-Montieth method, historical observed time series datasets were quality controlled, historical precipitation estimates were compared to the PRISM model to assess temporal bias, and a water balance analysis was conducted. Basin characteristics data were also collected and summarized by sub-basin.

Based on results of the data analysis, a model calibration period of 2000 – 2018 was selected, contingent upon observed streamflow availability for each sub-basin. In addition to parameterizing the SAC-SMA runoff and LAG/K routing models, the conducted calibration analysis included development of unit hydrograph (UNIT-HG) models using both manual analysis of historical event hydrographs and GIS-based techniques. Based on water balance results and investigations of hydrogeologic features and water control operations within the study area, diversions and water gains/losses were accounted for in the models using channel loss (CHANLOSS), LOOKUP, and WEIGH-TS operations. Toward the end of the model calibration analysis, the initial PET curves were refined based on preliminary monthly simulation volume bias results. The final step of the calibration analysis was to review the specified SAC-SMA parameters for all sub-basins to ensure that values are consistent regionally. Outlying parameter values were tested for simulation sensitivity and adjusted to ensure consistent model performance.

Following completion of the calibration analysis and the finalization of all model parameter values, the developed models were transferred into the WGRFC CHPS configuration to allow for easy updating of the existing forecast system. In addition to transferring the models into CHPS, the final calibrated PET curves were compared to the historical daily potential evaporation (PE) time series data to derive PE adjustment factors for use in the SAC-SMA operation.

The final calibrated models greatly improve the simulation of the recent historical flood peaks in the region. As part of the model evaluation process, the peak flow operation was used, where available, to evaluate how well the models replicate the highest yearly instantaneous streamflow at USGS stream gage locations. Within the San Jacinto River basin, the average peak flow discharge ratio for Hurricane Harvey was 1.08. For the sub-basins within the Buffalo Bayou basin, the model simulations produced an average discharge ratio of 0.98 for the Tax Day Flood. Over all the modeled sub-basins, comparing the simulations to the hourly observations over the calibration period yields total flow correlation values of 0.742 to 0.997 and volume bias values of -12.7% to 12.2%. These statistics demonstrate the ability of the calibrated models to accurately and consistently replicate the timing and magnitude of the flood peaks.

Overall, the calibrated hydrologic models should significantly enhance the WGRFC's capability to predict the timing of flood events by providing a simulation at a 1-hour time step. The prediction of peak magnitudes and reservoir inflows should also be significantly improved with fully calibrated model parameters as well as the accounting for the impacts of the Cypress Creek overflow during large flood events. Finally, the results for this study provide the WGRFC with models for newly established forecast points, allowing for more accurate information at more locations.

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Appendix A:
Annual Mean Areal Precipitation comparison with PRISM

Basin	Data	Year																	
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
San Jacinto River																			
DDBT2	PRISM	45.1	52.1	58.5	44.1	63.3	40.5	50.1	54.3	43.7	49.8	31.8	23.4	44.1	37.8	46.1	72.8	66.0	63.2
	MAPX	46.4	53.4	56.6	42.8	54.0	35.9	44.9	50.2	37.1	44.4	30.5	21.2	40.2	37.4	51.4	76.9	68.9	63.0
	% Diff	3%	2%	-3%	-3%	-15%	-11%	-10%	-8%	-15%	-11%	-4%	-9%	-9%	-1%	11%	6%	4%	0%
FCWT2U	PRISM	43.8	53.6	61.3	40.8	61.8	38.0	48.8	54.1	48.5	52.8	31.7	24.2	46.7	38.3	45.7	68.8	73.8	67.2
	MAPX	43.1	56.4	59.4	41.1	54.5	34.7	44.1	49.5	43.2	47.5	31.5	21.5	44.2	37.7	51.4	73.1	77.3	68.3
	% Diff	-1%	5%	-3%	1%	-12%	-9%	-10%	-9%	-11%	-10%	0%	-11%	-5%	-2%	12%	6%	5%	2%
FCWT2	PRISM	40.2	56.6	55.7	46.3	62.7	36.1	52.9	54.7	61.3	46.7	34.3	23.6	44.1	41.4	45.5	64.1	78.0	68.9
	MAPX	40.9	64.1	51.4	43.7	54.9	33.7	49.5	51.4	54.5	45.8	32.9	20.3	43.8	41.9	49.8	70.6	81.1	72.9
	% Diff	2%	13%	-8%	-5%	-12%	-7%	-6%	-6%	-11%	-2%	-4%	-14%	-1%	1%	10%	10%	4%	6%
CFKT2	PRISM	36.8	59.8	58.7	43.5	63.6	35.0	56.5	53.0	63.4	47.8	34.5	26.1	45.8	42.1	45.7	57.1	71.6	66.8
	MAPX	41.4	70.8	52.7	45.5	54.0	31.2	49.0	50.8	53.7	46.5	34.2	23.0	44.0	43.3	52.0	64.0	76.0	67.6
	% Diff	13%	18%	-10%	5%	-15%	-11%	-13%	-4%	-15%	-3%	-1%	-12%	-4%	3%	14%	12%	6%	1%
POET2U	PRISM	36.7	59.3	58.2	39.8	67.4	34.6	57.7	51.1	60.8	50.3	34.8	26.4	45.9	41.5	44.6	58.0	69.3	67.6
	MAPX	40.6	70.6	54.2	42.2	56.1	30.4	49.1	50.8	49.8	48.9	33.0	22.8	43.8	44.6	50.4	62.8	73.2	65.4
	% Diff	11%	19%	-7%	6%	-17%	-12%	-15%	-1%	-18%	-3%	-5%	-14%	-5%	7%	13%	8%	6%	-3%
POET2M	PRISM	38.7	60.3	58.2	42.4	66.0	36.0	56.5	55.2	57.4	51.2	34.4	25.4	47.1	43.6	45.7	59.4	65.3	66.8
	MAPX	42.4	69.3	55.1	44.7	57.5	33.0	50.6	53.9	49.3	51.0	33.3	22.1	46.0	44.1	49.5	63.8	70.0	65.2
	% Diff	10%	15%	-5%	5%	-13%	-8%	-10%	-2%	-14%	0%	-3%	-13%	-2%	1%	8%	8%	7%	-2%
POET2	PRISM	39.2	61.0	60.8	47.6	64.1	36.8	54.5	59.1	59.6	52.3	36.3	26.5	44.5	44.4	48.3	59.5	67.2	67.4
	MAPX	45.6	69.7	55.6	45.2	54.8	32.2	47.8	57.7	55.5	52.7	34.9	22.8	44.4	45.7	52.6	65.8	71.4	69.6
	% Diff	16%	14%	-9%	-5%	-15%	-12%	-12%	-2%	-7%	1%	-4%	-14%	0%	3%	9%	10%	6%	3%
PBST2	PRISM	38.5	59.9	59.8	46.7	64.6	38.3	53.6	58.0	63.3	47.5	36.4	27.2	46.7	41.7	43.1	57.6	71.2	64.4
	MAPX	45.5	77.4	52.8	44.4	56.4	34.3	48.1	56.4	58.7	47.6	36.5	24.0	47.8	44.6	51.3	66.1	79.5	70.7
	% Diff	18%	29%	-12%	-5%	-13%	-10%	-10%	-3%	-7%	0%	0%	-12%	2%	7%	19%	15%	12%	10%
TMBT2	PRISM	39.9	54.8	57.6	42.8	63.0	36.2	51.3	56.8	51.9	48.8	33.6	23.3	48.9	41.8	45.9	67.7	78.6	69.2
	MAPX	45.0	60.7	53.5	40.2	54.4	33.0	47.5	52.7	48.3	48.1	32.9	20.4	47.1	39.5	50.9	73.4	81.4	75.6
	% Diff	13%	11%	-7%	-6%	-14%	-9%	-7%	-7%	-7%	-2%	-2%	-13%	-4%	-5%	11%	8%	3%	9%

Basin	Data	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
		Year																	
San Jacinto River																			
SCKT2	PRISM	39.2	56.3	59.7	45.8	64.5	37.3	51.9	55.0	57.6	50.6	33.7	24.4	47.5	41.3	45.4	66.1	78.6	66.9
	MAPX	43.4	65.9	55.9	43.5	57.0	34.7	48.7	52.1	54.2	50.3	33.0	21.3	46.6	41.2	51.3	72.1	81.8	72.5
	% Diff	11%	17%	-6%	-5%	-12%	-7%	-6%	-5%	-6%	-1%	-2%	-13%	-2%	0%	13%	9%	4%	8%
LWCT2	PRISM	38.3	59.6	57.3	47.0	67.8	38.5	60.8	57.6	57.0	47.4	35.9	25.9	48.2	43.8	46.6	64.4	75.9	71.4
	MAPX	42.7	69.0	50.4	43.5	61.2	35.0	56.5	56.5	55.7	50.2	34.4	23.1	47.8	44.6	50.3	69.8	78.7	77.8
	% Diff	11%	16%	-12%	-7%	-10%	-9%	-7%	-2%	-2%	6%	-4%	-11%	-1%	2%	8%	8%	4%	9%
SPNT2	PRISM	38.0	60.0	60.2	48.3	67.8	40.1	58.2	61.0	60.0	50.6	35.8	27.8	48.1	44.7	45.1	64.6	72.6	69.8
	MAPX	43.8	73.5	54.2	45.5	59.6	35.5	51.2	59.4	58.6	52.4	37.2	24.9	48.3	46.1	50.3	69.5	75.3	73.8
	% Diff	15%	23%	-10%	-6%	-12%	-11%	-12%	-2%	-2%	4%	4%	-11%	1%	3%	12%	8%	4%	6%
CYRT2	PRISM	40.8	57.1	56.9	43.8	65.1	35.0	56.6	56.7	46.7	45.5	33.9	23.3	48.4	41.0	44.9	63.2	76.7	71.2
	MAPX	42.2	62.7	54.3	43.0	58.0	30.9	54.2	54.4	45.1	46.5	33.3	21.1	47.2	39.5	49.6	70.0	80.9	78.8
	% Diff	3%	10%	-5%	-2%	-11%	-12%	-4%	-4%	-3%	2%	-2%	-9%	-3%	-4%	11%	11%	5%	11%
KHOT2	PRISM	41.9	55.7	55.3	42.2	62.7	34.4	48.4	57.3	36.5	42.5	30.1	20.1	45.4	42.2	43.4	63.6	69.8	72.6
	MAPX	42.8	56.8	51.8	37.7	52.9	29.9	44.5	52.1	34.5	42.1	29.0	17.3	41.4	40.1	47.2	70.4	72.9	79.0
	% Diff	2%	2%	-6%	-11%	-16%	-13%	-8%	-9%	-6%	-1%	-4%	-14%	-9%	-5%	9%	11%	4%	9%
CCGT2	PRISM	42.0	59.6	55.5	41.7	63.5	38.9	60.5	56.4	47.8	48.7	36.8	25.5	50.5	41.1	47.8	61.7	77.9	73.3
	MAPX	42.9	61.0	52.5	40.6	56.4	35.6	55.4	56.0	44.6	46.9	36.2	23.6	48.4	41.3	52.6	69.9	82.5	84.0
	% Diff	2%	2%	-5%	-3%	-11%	-9%	-8%	-1%	-7%	-4%	-2%	-7%	-4%	0%	10%	13%	6%	15%
WFDT2	PRISM	40.3	61.1	60.9	52.1	65.4	40.6	60.5	63.3	53.2	48.3	38.1	25.3	47.2	40.0	48.7	65.9	73.1	75.7
	MAPX	44.9	74.1	55.3	47.2	56.5	36.1	56.3	60.6	52.5	49.6	37.8	22.7	46.2	42.8	53.3	71.1	78.6	81.9
	% Diff	11%	21%	-9%	-10%	-14%	-11%	-7%	-4%	-1%	3%	-1%	-10%	-2%	7%	9%	8%	8%	8%
HMMT2	PRISM	40.1	62.1	63.7	53.7	67.2	39.9	58.9	67.2	58.6	52.0	40.4	27.5	45.9	43.7	53.8	70.3	70.8	76.7
	MAPX	44.5	72.0	59.5	50.5	55.7	34.8	54.2	65.1	58.1	53.7	41.6	24.0	43.2	44.4	57.7	75.9	74.9	83.7
	% Diff	11%	16%	-7%	-6%	-17%	-13%	-8%	-3%	-1%	3%	3%	-13%	-6%	2%	7%	8%	6%	9%

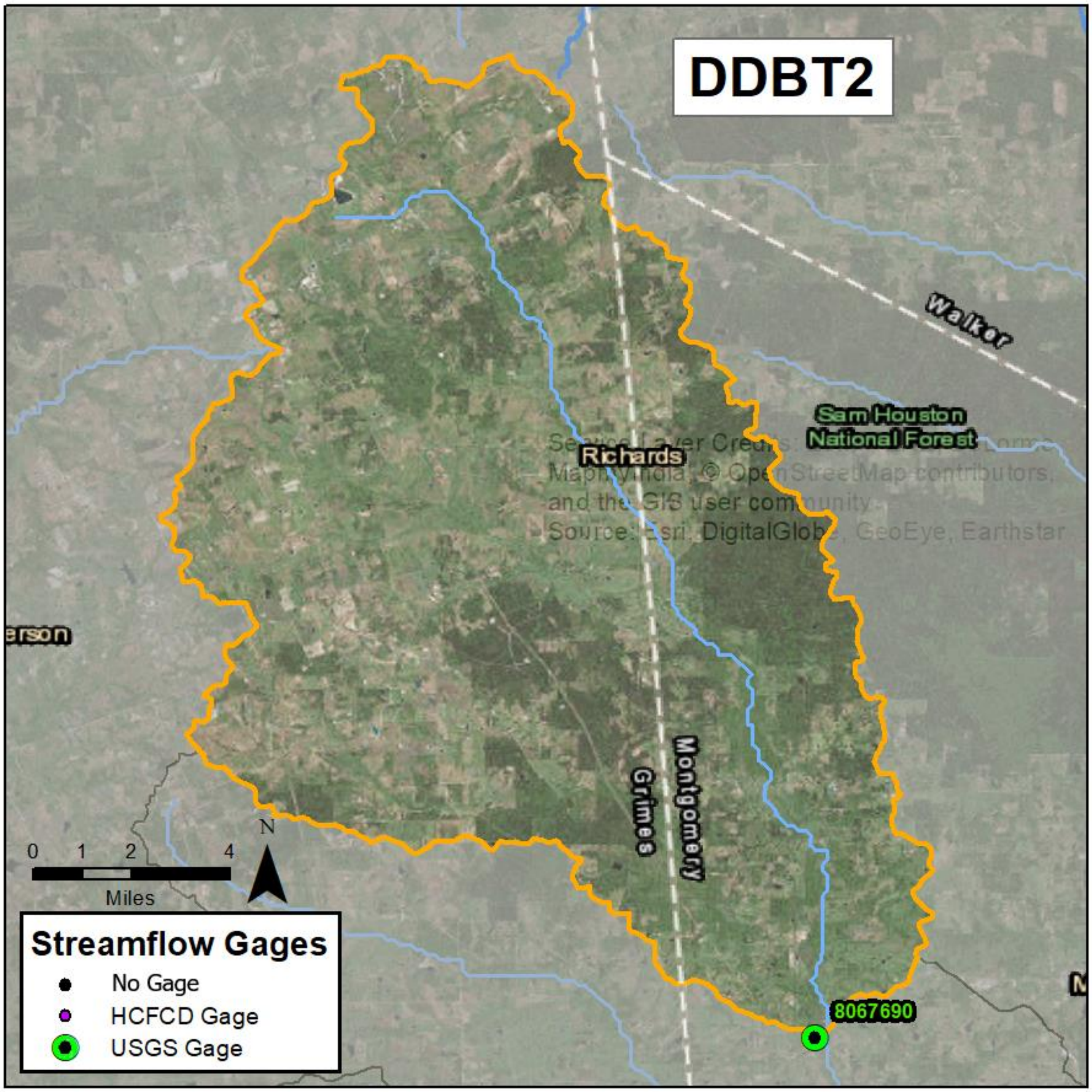
Basin	Data	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Buffalo Bayou																			
HPTT2	PRISM	41.8	60.0	59.5	44.3	63.9	42.7	56.4	59.3	47.1	50.0	40.9	25.5	49.4	40.4	48.3	63.1	73.6	78.4
	MAPX	45.3	58.0	62.3	47.8	57.2	40.7	53.6	59.8	44.3	47.0	41.0	24.3	48.1	42.0	53.0	70.6	79.4	89.7
	% Diff	9%	-3%	5%	8%	-10%	-5%	-5%	1%	-6%	-6%	0%	-5%	-3%	4%	10%	12%	8%	14%
LLYT2	PRISM	42.0	58.1	60.6	47.3	64.4	40.0	52.4	58.8	42.6	48.6	37.9	23.3	48.7	43.0	48.0	62.8	72.0	79.7
	MAPX	44.0	56.1	60.9	46.4	56.6	38.0	49.5	58.5	40.6	45.9	37.7	21.8	46.8	42.9	52.5	70.6	75.1	90.8
	% Diff	5%	-3%	0%	-2%	-12%	-5%	-6%	0%	-5%	-6%	0%	-6%	-4%	0%	9%	12%	4%	14%
BBAT2	PRISM	42.3	55.7	59.1	46.9	65.5	37.8	48.7	61.3	41.3	48.6	37.5	22.4	46.2	43.4	48.7	62.3	67.1	81.2
	MAPX	40.8	54.8	54.5	41.2	55.4	34.9	44.2	58.0	37.3	45.1	35.1	20.1	43.6	41.6	51.9	69.4	69.8	88.6
	% Diff	-3%	-2%	-8%	-12%	-15%	-8%	-9%	-5%	-10%	-7%	-6%	-10%	-6%	-4%	7%	11%	4%	9%
SMAT2	PRISM	42.5	54.7	57.5	44.1	68.2	37.4	47.1	62.4	40.8	48.5	37.7	22.2	46.4	42.3	49.4	62.7	63.4	80.7
	MAPX	41.4	57.8	52.4	38.8	57.6	34.9	41.1	59.4	36.4	44.7	35.6	19.8	42.7	40.9	53.2	71.9	68.0	88.9
	% Diff	-3%	6%	-9%	-12%	-16%	-7%	-13%	-5%	-11%	-8%	-6%	-11%	-8%	-3%	8%	15%	7%	10%
ADDT2	PRISM	42.1	58.9	59.4	49.4	66.3	40.1	52.4	63.7	46.3	51.1	42.5	22.8	53.0	40.9	47.9	67.3	68.7	80.9
	MAPX	40.5	55.3	57.2	45.9	59.3	37.9	50.2	62.9	44.0	48.5	42.0	21.2	53.0	40.8	50.9	74.7	74.9	90.8
	% Diff	-4%	-6%	-4%	-7%	-10%	-5%	-4%	-1%	-5%	-5%	-1%	-7%	0%	0%	6%	11%	9%	12%
BAKT2U	PRISM	42.9	54.0	58.6	44.1	69.3	38.4	47.7	65.1	43.7	49.9	40.1	22.4	50.2	40.4	51.4	62.9	60.8	81.1
	MAPX	42.3	61.9	52.7	37.6	57.9	35.2	42.7	62.5	39.6	46.0	38.7	21.0	47.0	39.7	55.3	74.7	66.5	90.6
	% Diff	-1%	15%	-10%	-15%	-16%	-8%	-11%	-4%	-9%	-8%	-3%	-6%	-6%	-2%	8%	19%	9%	12%

Basin	Data	Year 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Buffalo Bayou																			
BBKT2	PRISM	43.0	54.6	58.8	43.6	69.6	37.4	44.4	62.6	39.0	46.1	34.7	21.4	47.1	42.6	47.0	63.4	61.4	78.6
	MAPX	42.2	59.4	54.6	37.2	58.8	34.4	39.8	59.4	36.0	43.4	33.5	19.3	43.4	42.2	51.1	74.7	68.1	86.5
	% Diff	-2%	9%	-7%	-15%	-15%	-8%	-10%	-5%	-8%	-6%	-3%	-10%	-8%	-1%	9%	18%	11%	10%
BAKT2	PRISM	42.0	57.4	63.9	47.0	67.7	39.6	49.6	66.2	42.4	47.8	41.5	19.9	51.8	40.2	49.0	66.7	60.1	84.0
	MAPX	42.1	60.5	56.9	39.9	57.8	38.2	47.1	63.8	39.6	45.9	42.2	19.0	50.9	40.8	53.7	75.3	65.3	92.2
	% Diff	0%	5%	-11%	-15%	-15%	-3%	-5%	-4%	-7%	-4%	2%	-5%	-2%	1%	9%	13%	9%	10%
WSBT2	PRISM	43.5	63.1	59.0	53.0	67.6	41.0	54.4	69.4	47.8	54.9	45.6	23.8	53.9	40.7	50.8	71.1	64.6	81.7
	MAPX	36.4	59.2	56.5	47.6	60.1	37.7	49.6	65.9	45.3	50.7	48.1	21.6	54.2	42.6	52.4	77.4	69.3	96.0
	% Diff	-16%	-6%	-4%	-10%	-11%	-8%	-9%	-5%	-5%	-8%	5%	-9%	1%	5%	3%	9%	7%	18%
PPTT2	PRISM	45.4	66.9	66.5	51.4	70.3	41.3	53.6	75.7	50.6	52.1	46.5	24.0	54.5	41.7	54.3	73.0	61.2	81.2
	MAPX	36.9	59.0	64.3	47.7	62.1	37.4	49.3	70.4	48.4	49.5	48.8	22.0	55.0	44.6	57.4	78.4	64.9	94.8
	% Diff	-19%	-12%	-3%	-7%	-12%	-9%	-8%	-7%	-4%	-5%	5%	-9%	1%	7%	6%	7%	6%	17%
BBST2	PRISM	47.5	70.2	58.8	50.8	70.8	43.5	57.9	77.6	57.1	52.8	44.6	25.2	54.5	42.8	54.3	80.2	62.7	81.4
	MAPX	39.9	72.2	53.6	45.0	61.9	39.0	52.1	73.3	54.3	51.2	47.4	23.8	55.5	44.8	56.1	85.8	67.9	93.1
	% Diff	-16%	3%	-9%	-11%	-13%	-10%	-10%	-6%	-5%	-3%	6%	-5%	2%	5%	3%	7%	8%	14%

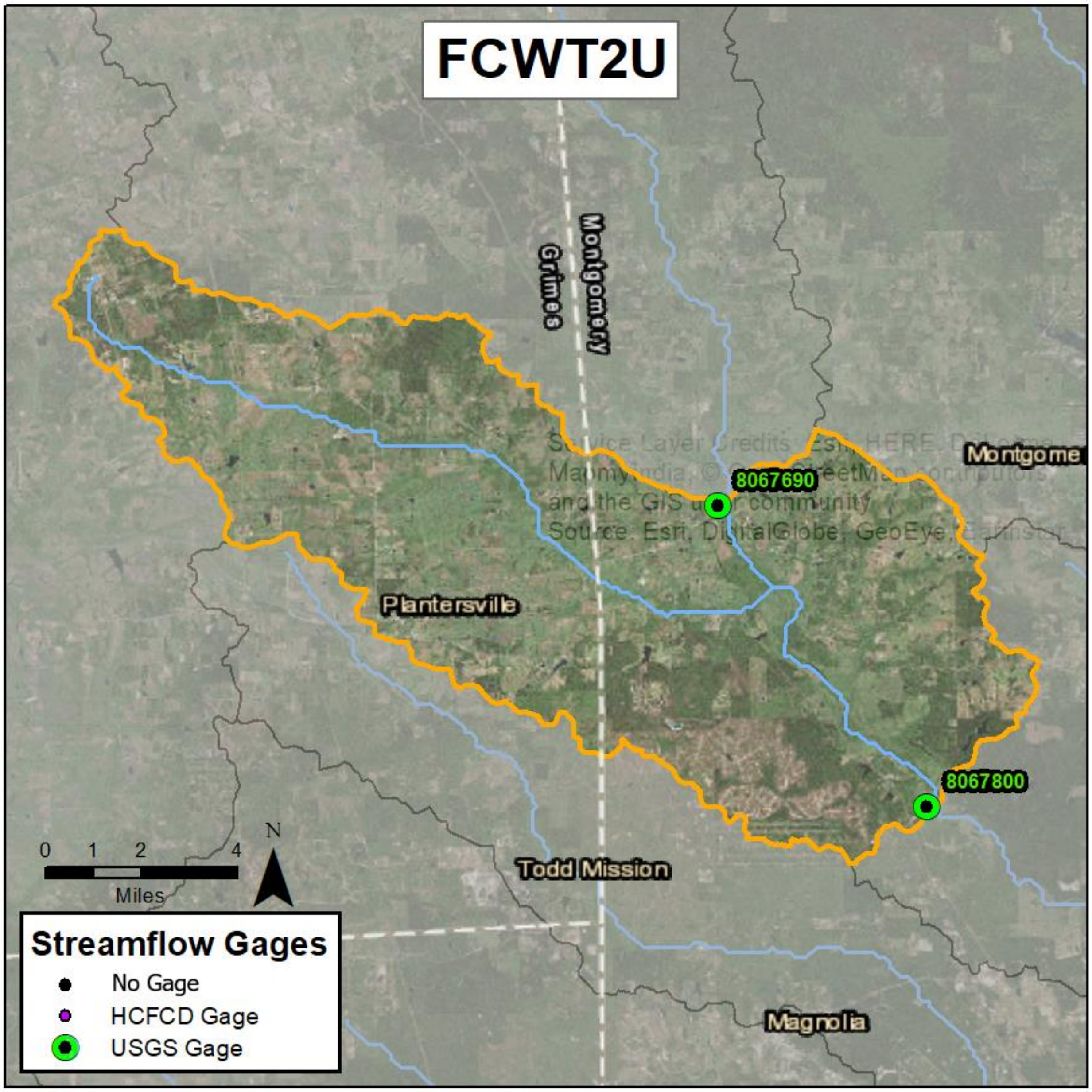
Appendix B:
Sub-basin Maps

San Jacinto Basin

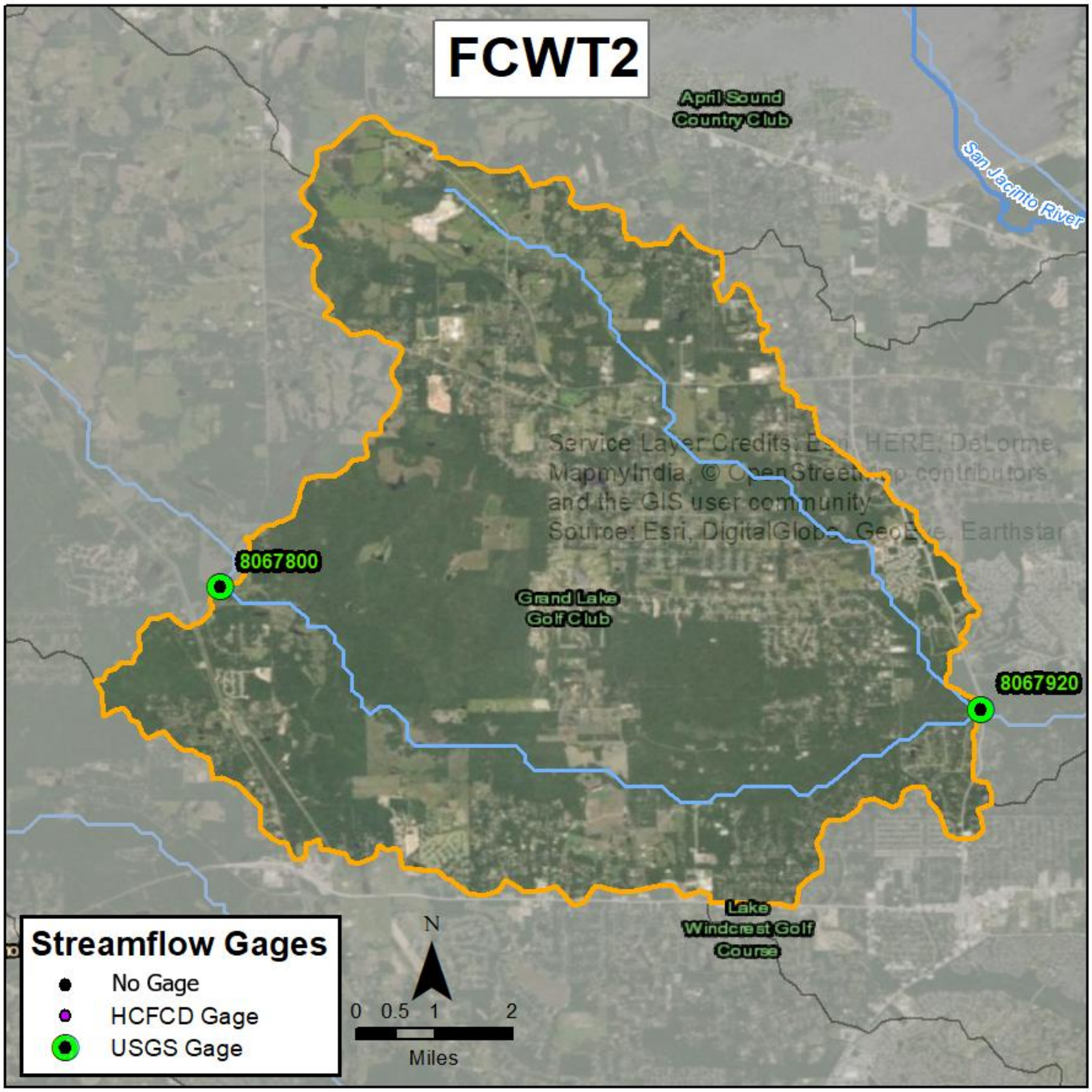
DDBT2 - Lake Ck nr Dobbin, TX



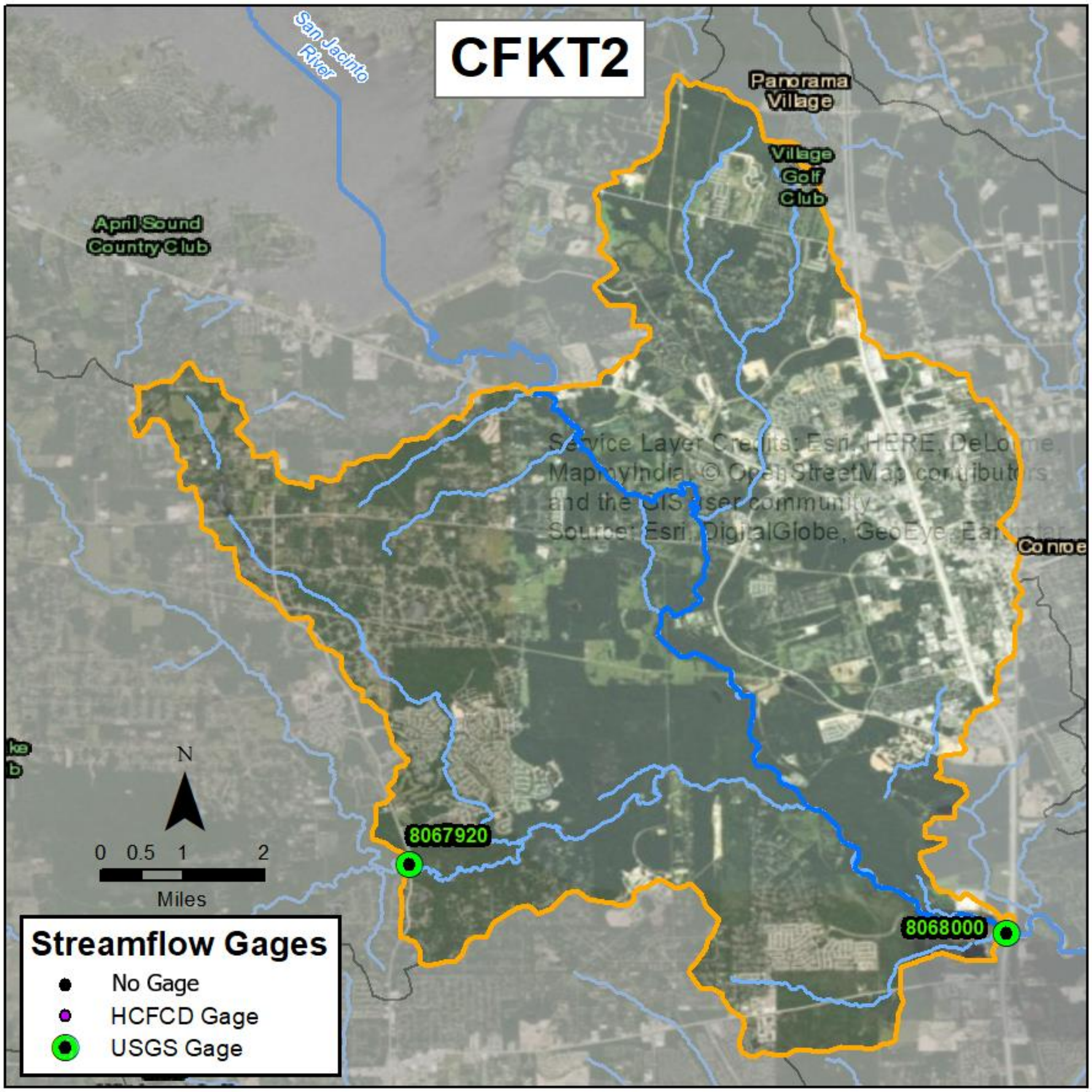
FCWT2U - Lake Ck nr Karen, TX



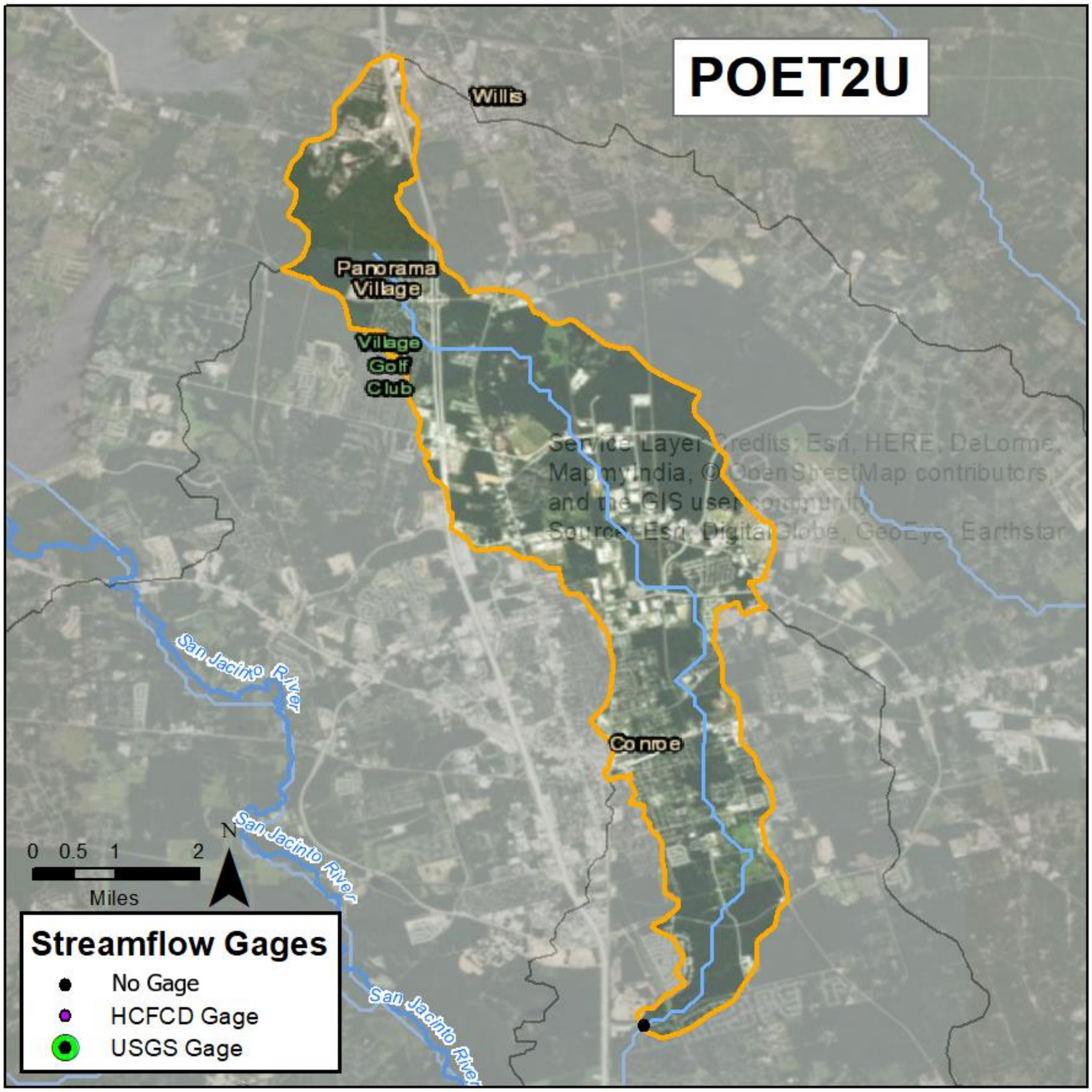
FCWT2 - Lake Ck at Sendera Ranch Rd nr Conroe, TX



CFKT2 - W Fk San Jacinto Rv nr Conroe, TX

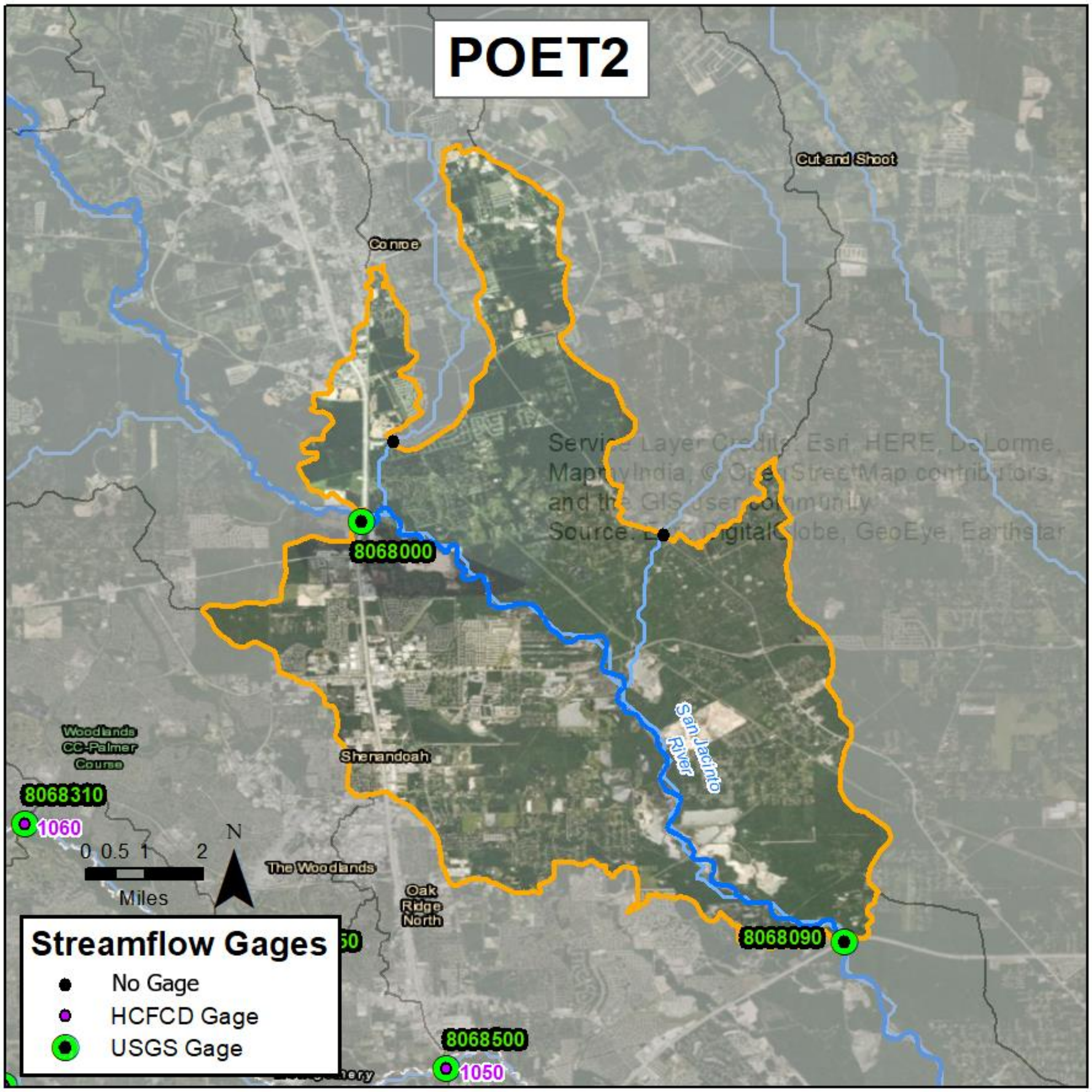


POET2U - Stewarts Creek at Crighton Rd

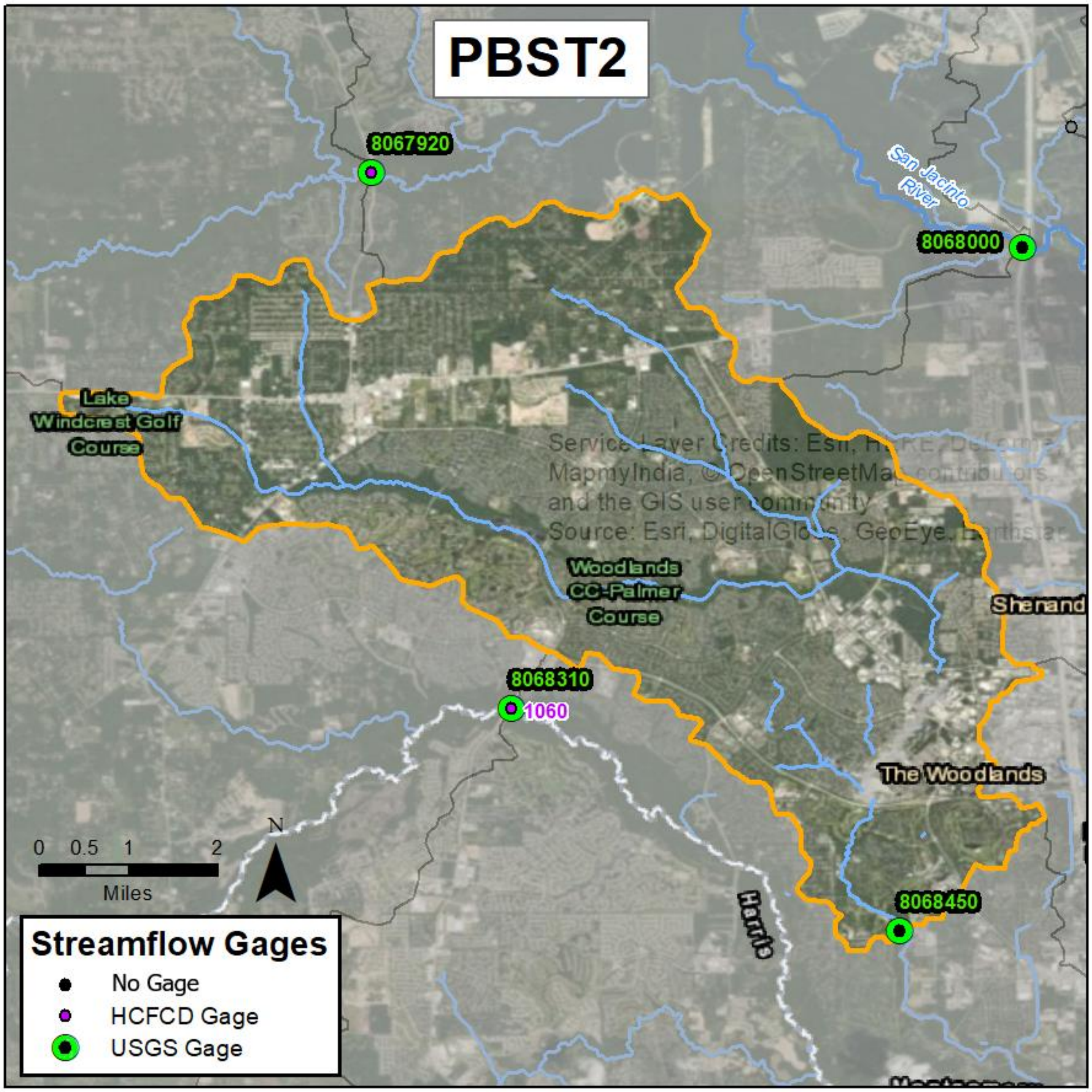


POET2M - Crystal Creek at FM1314

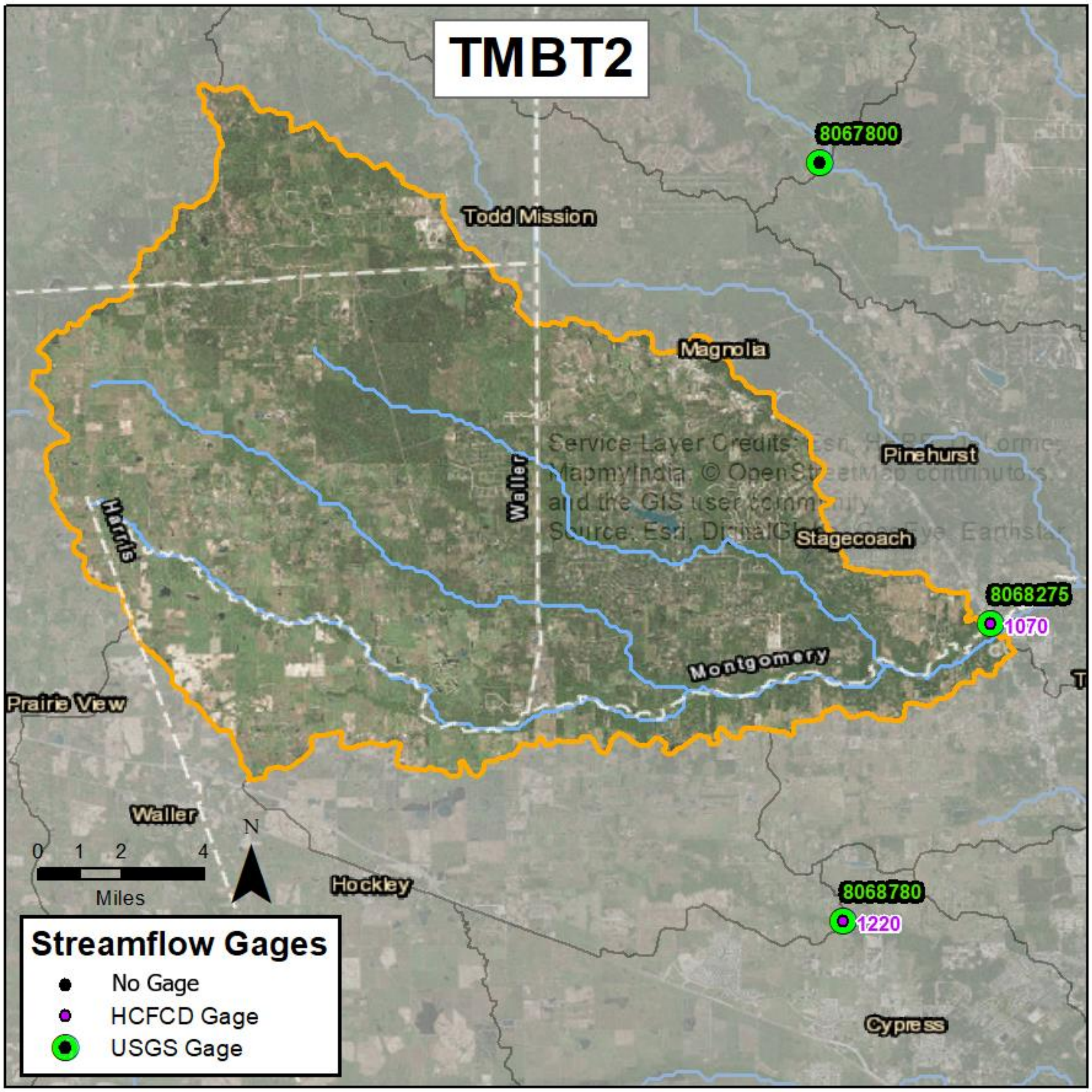
POET2 - W Fk San Jacinto Rv Abv Lk Houston nr Porter, TX



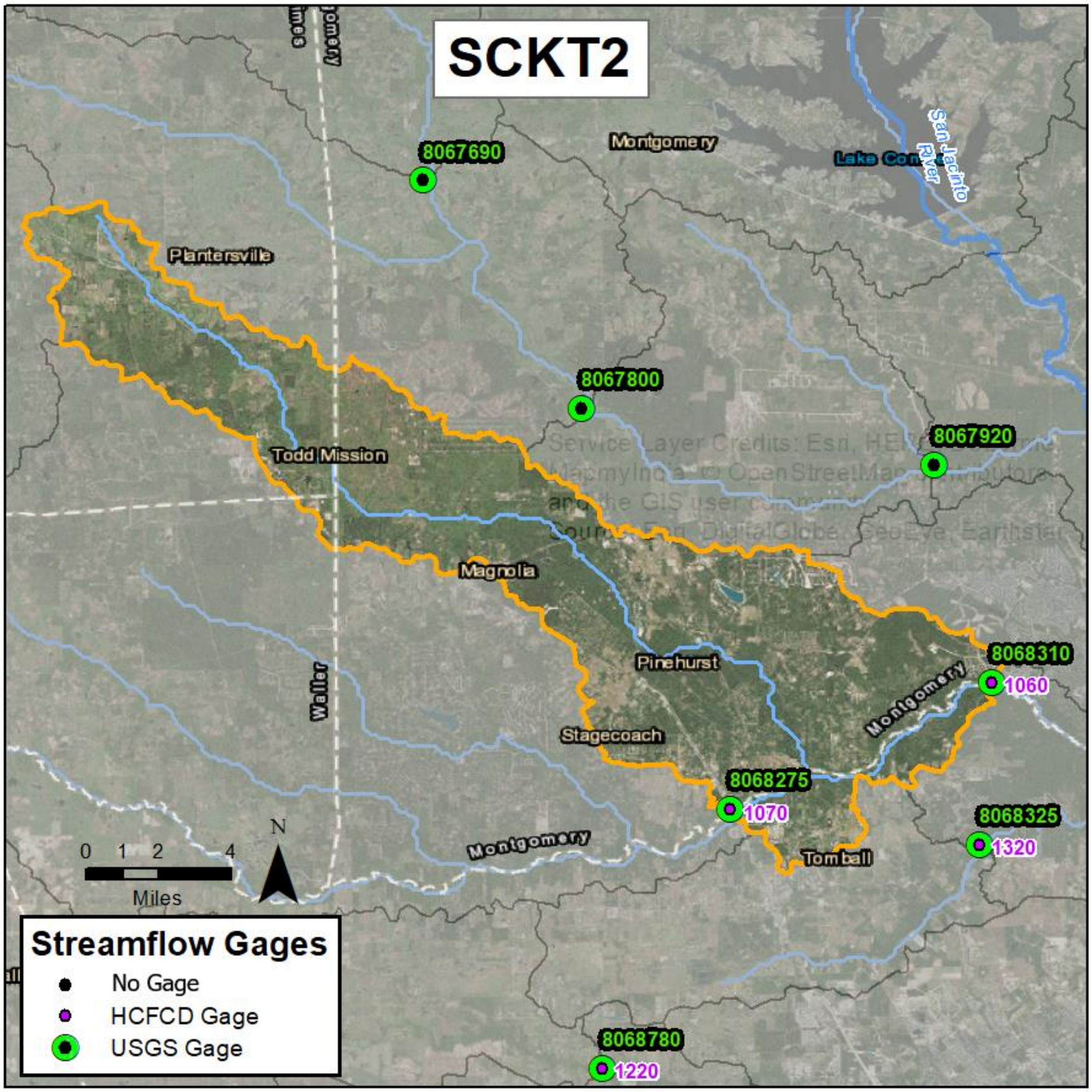
PBST2 - Panther Br nr Spring, TX



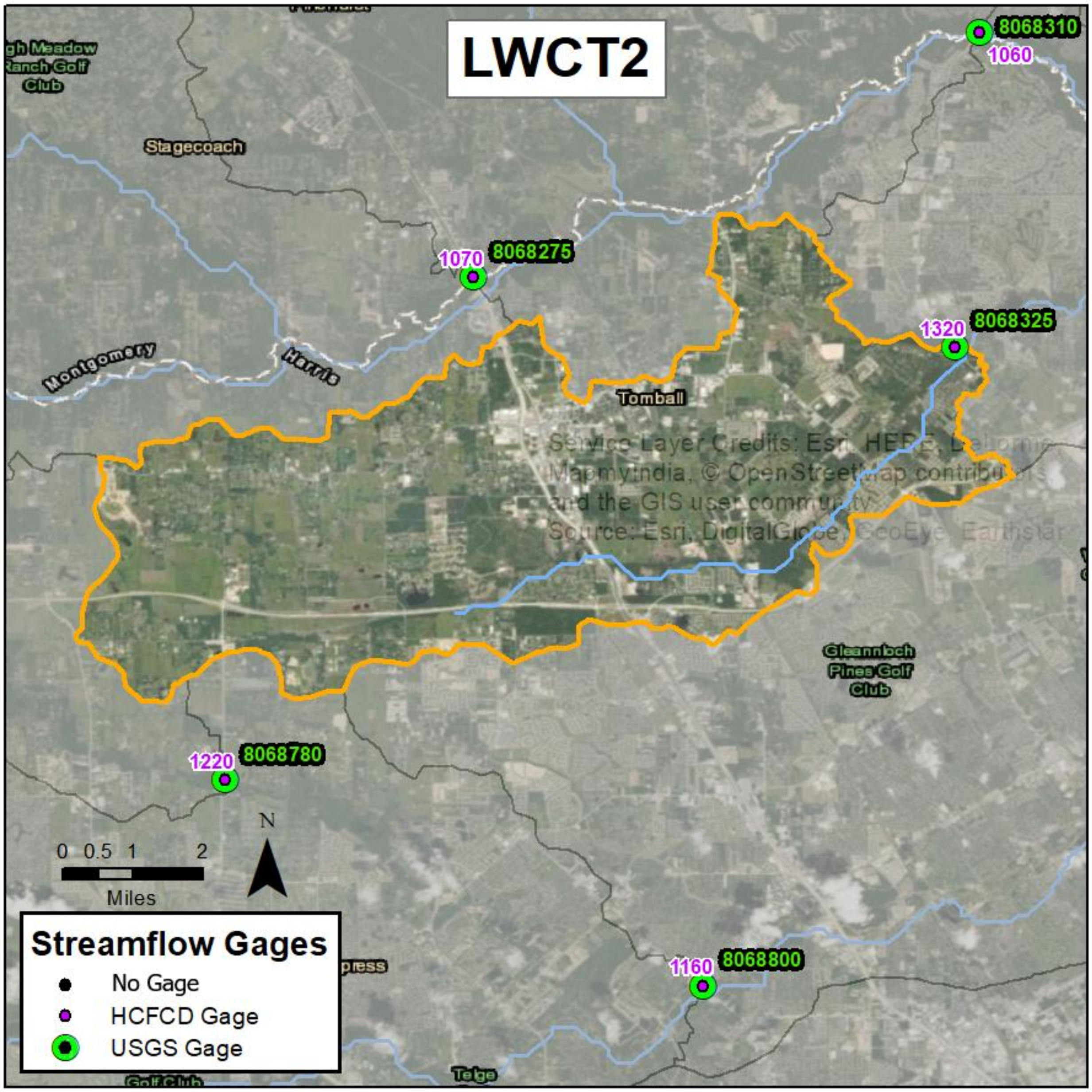
TMBT2 - Spring Ck nr Tomball, TX



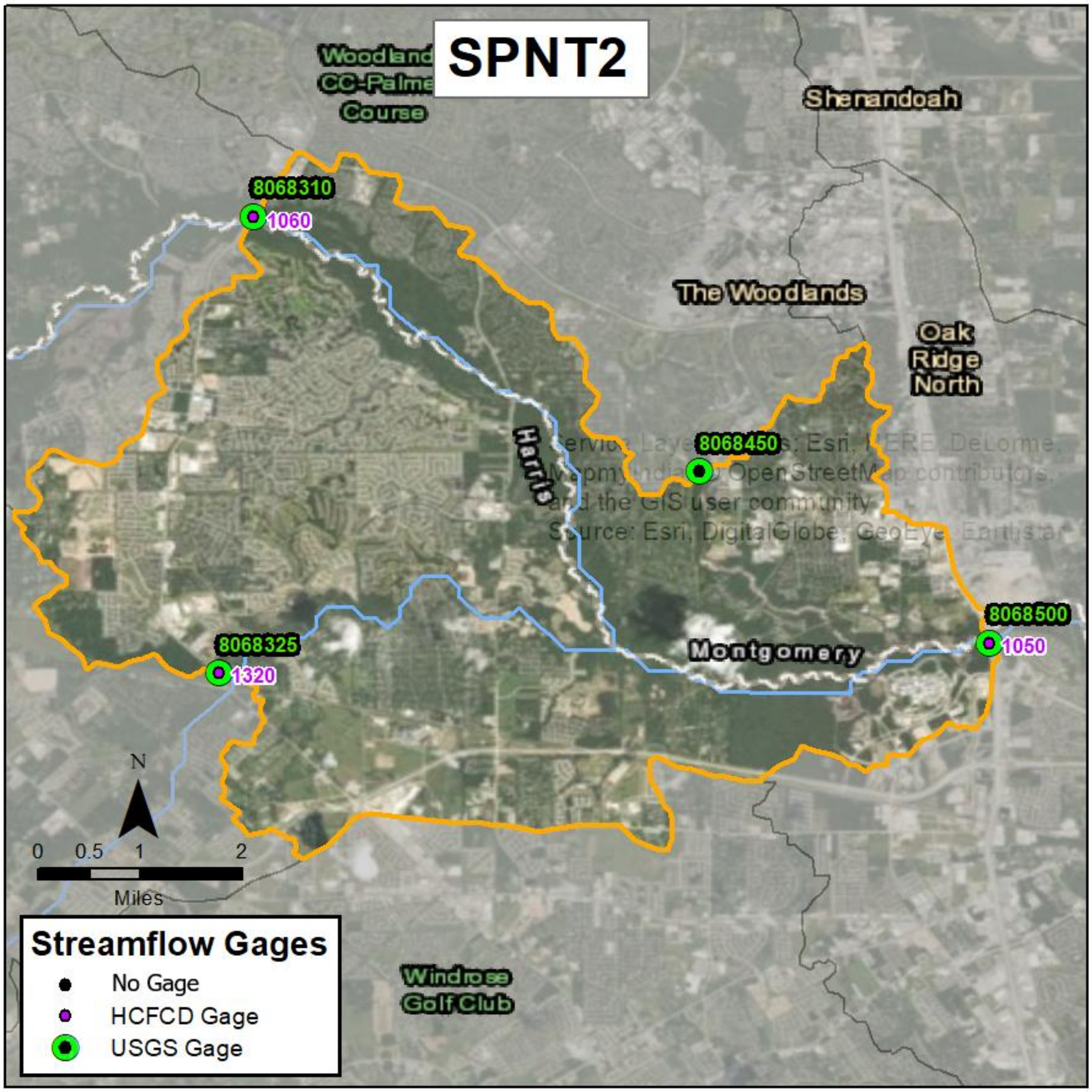
SCKT2 - Spring Ck at Kuykendahl, The Woodlands, TX



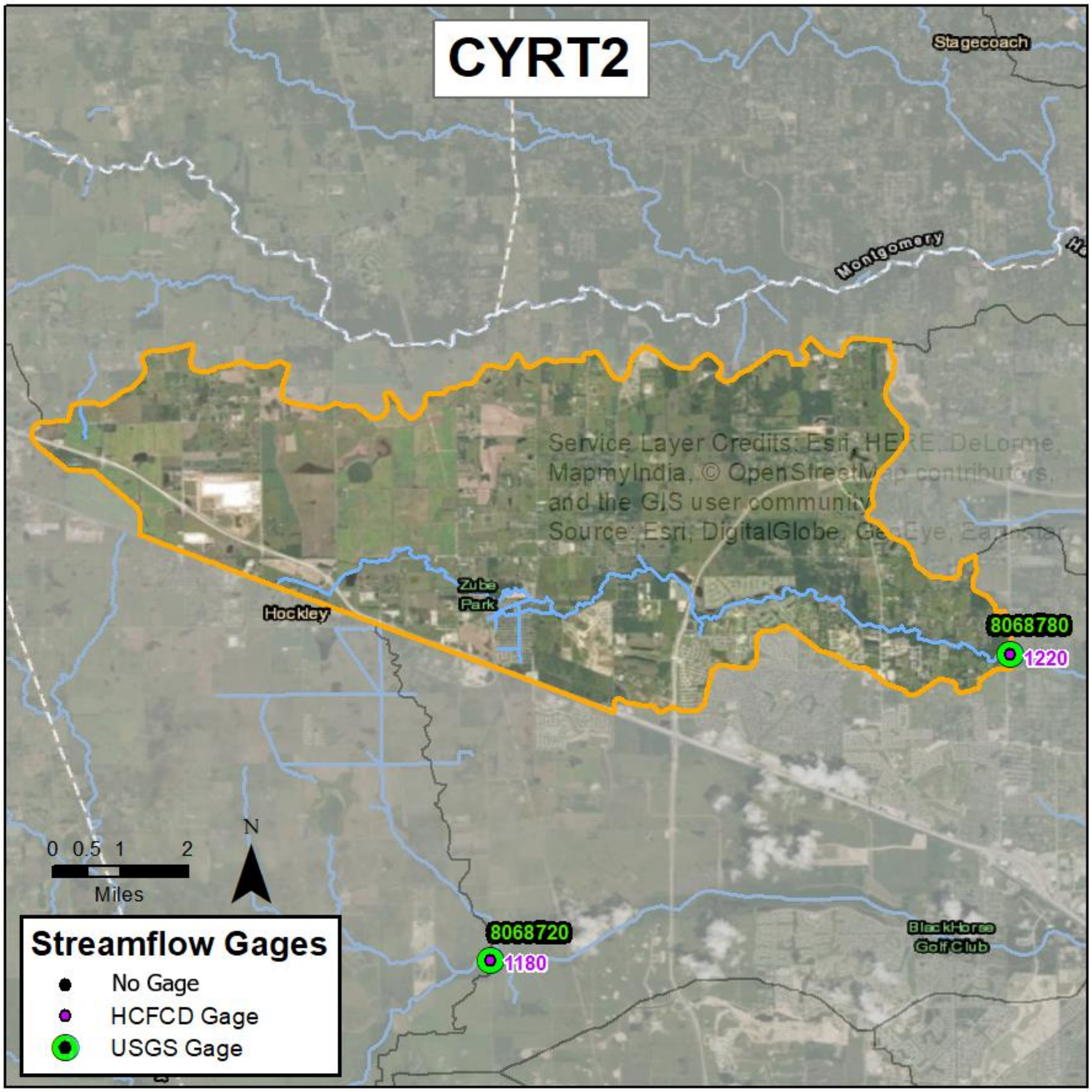
LWCT2 - Willow Ck nr Tomball, TX



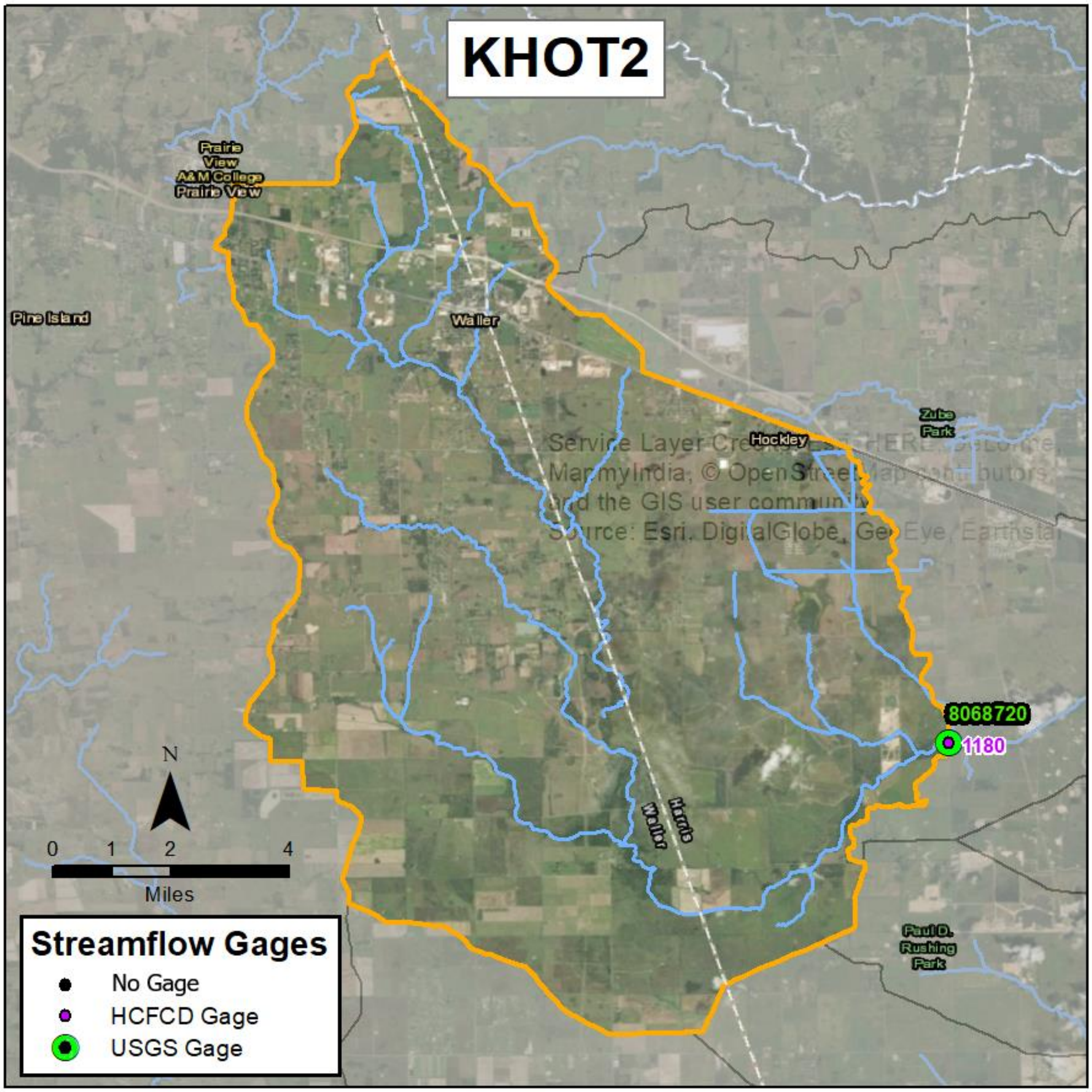
SPNT2 - Spring Ck nr Spring, TX



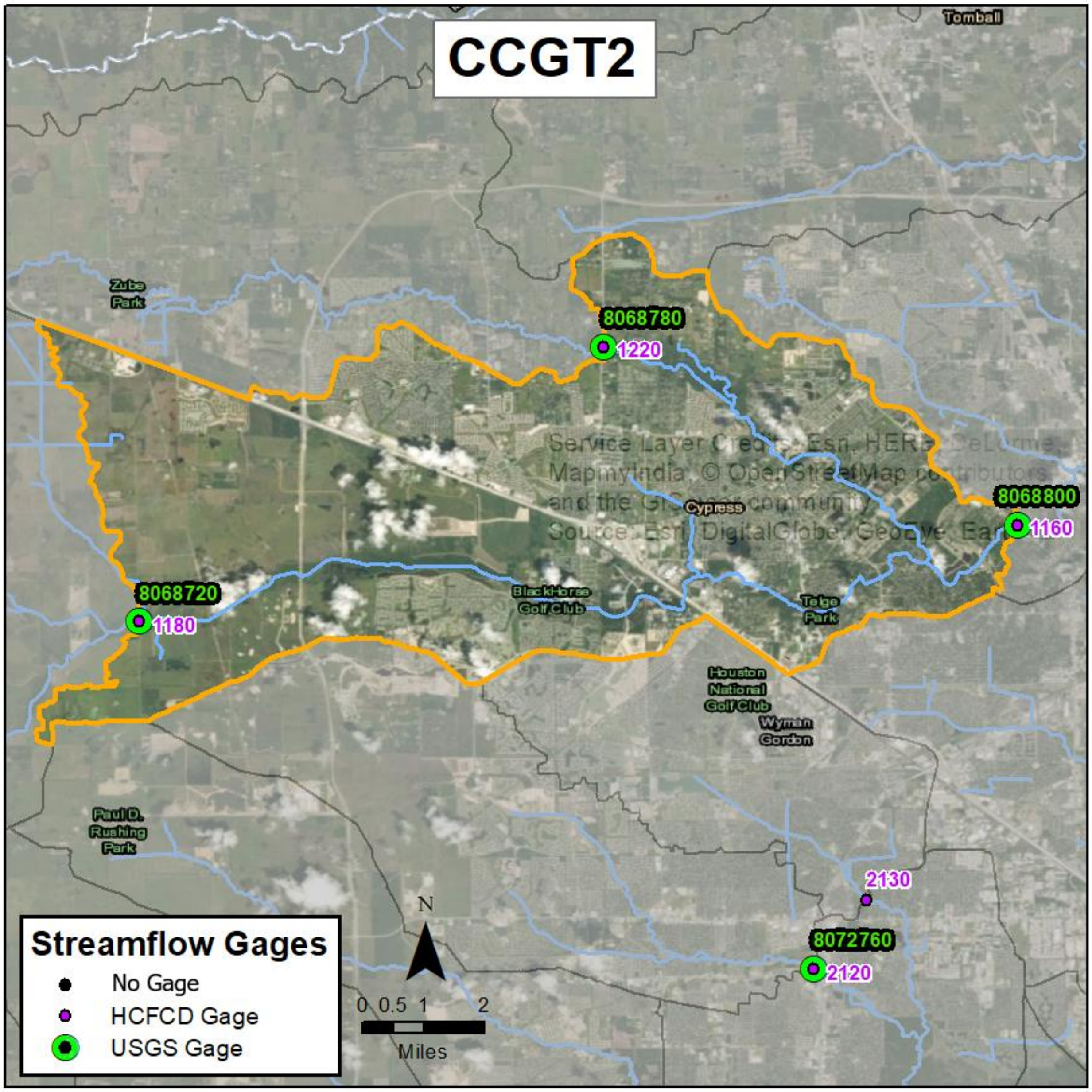
CYRT2 - Little Cypress Ck nr Cypress, TX



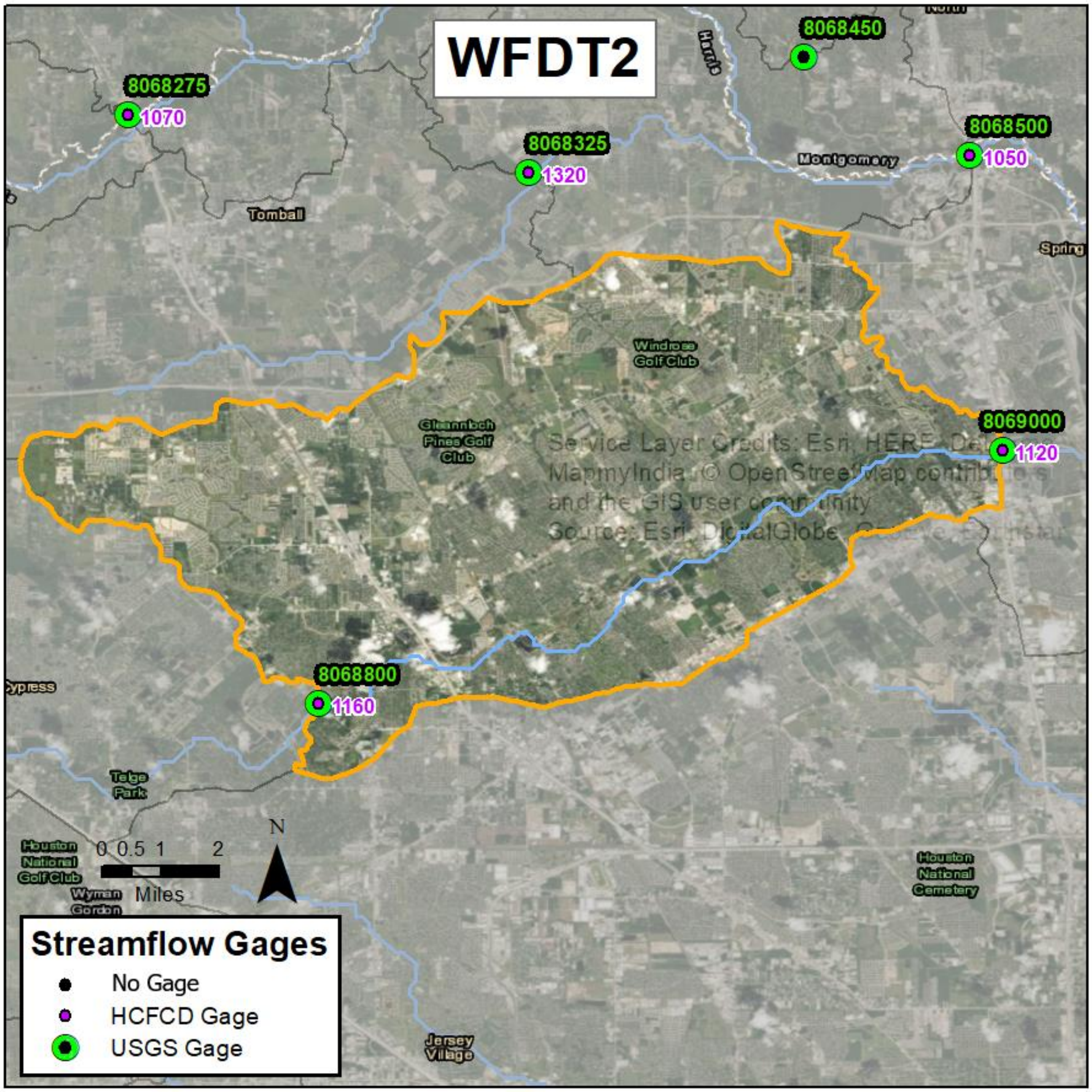
KHOT2 - Cypress Ck at Katy-Hockley Rd nr Hockley, TX



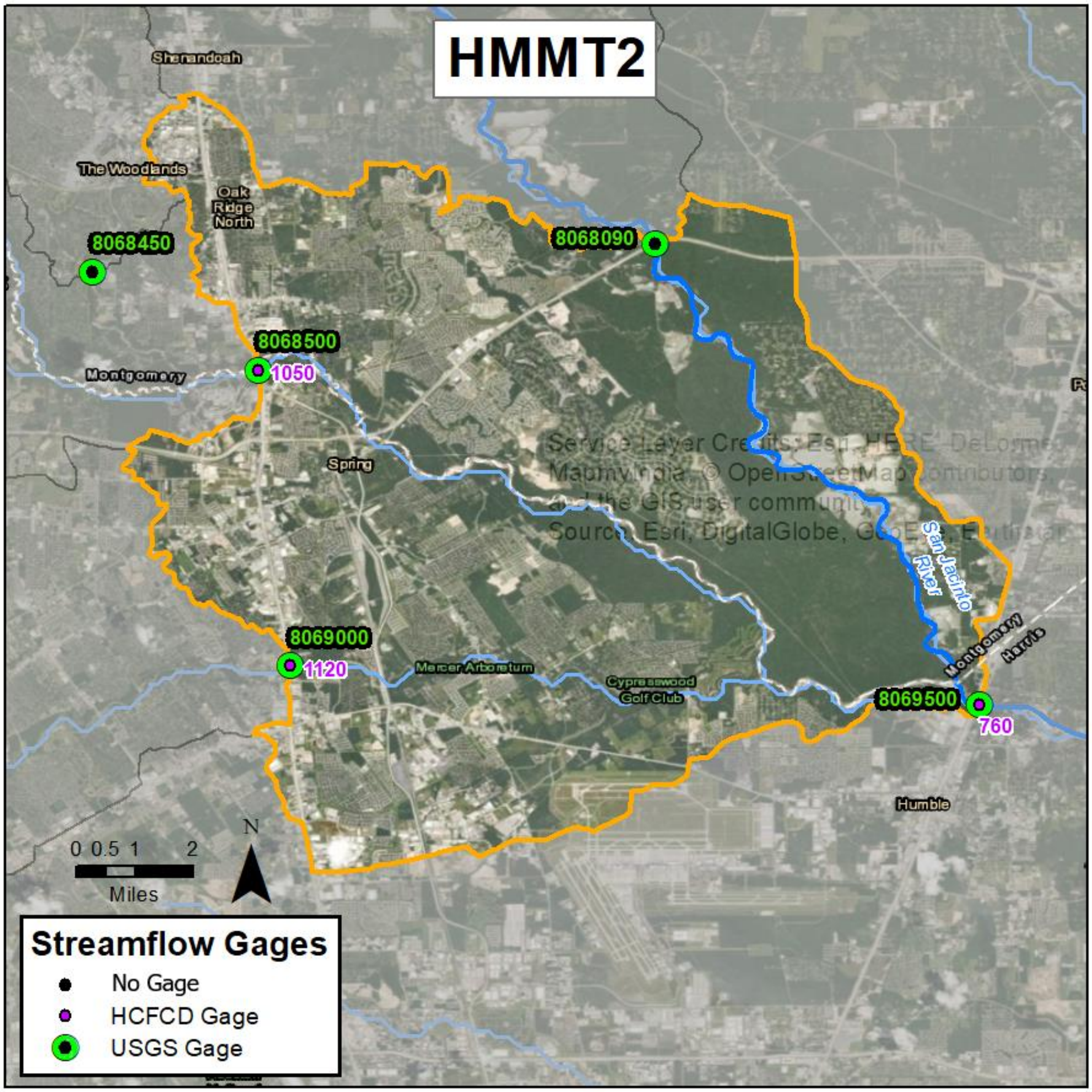
CCGT2 - Cypress Ck at Grant Rd nr Cypress, TX



WFDT2 - Cypress Ck nr Westfield, TX

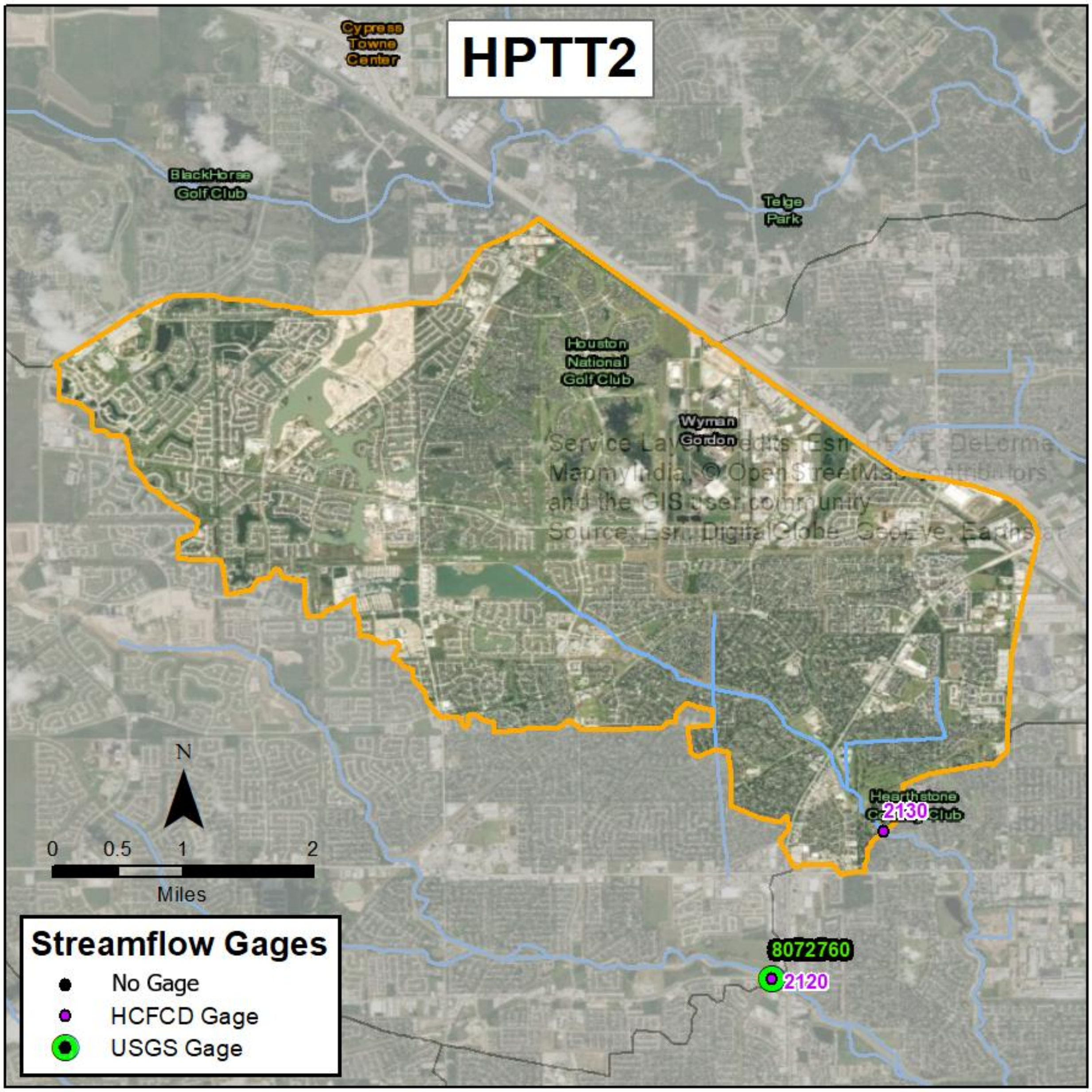


HMMT2 - W Fk San Jacinto Rv nr Humble, TX

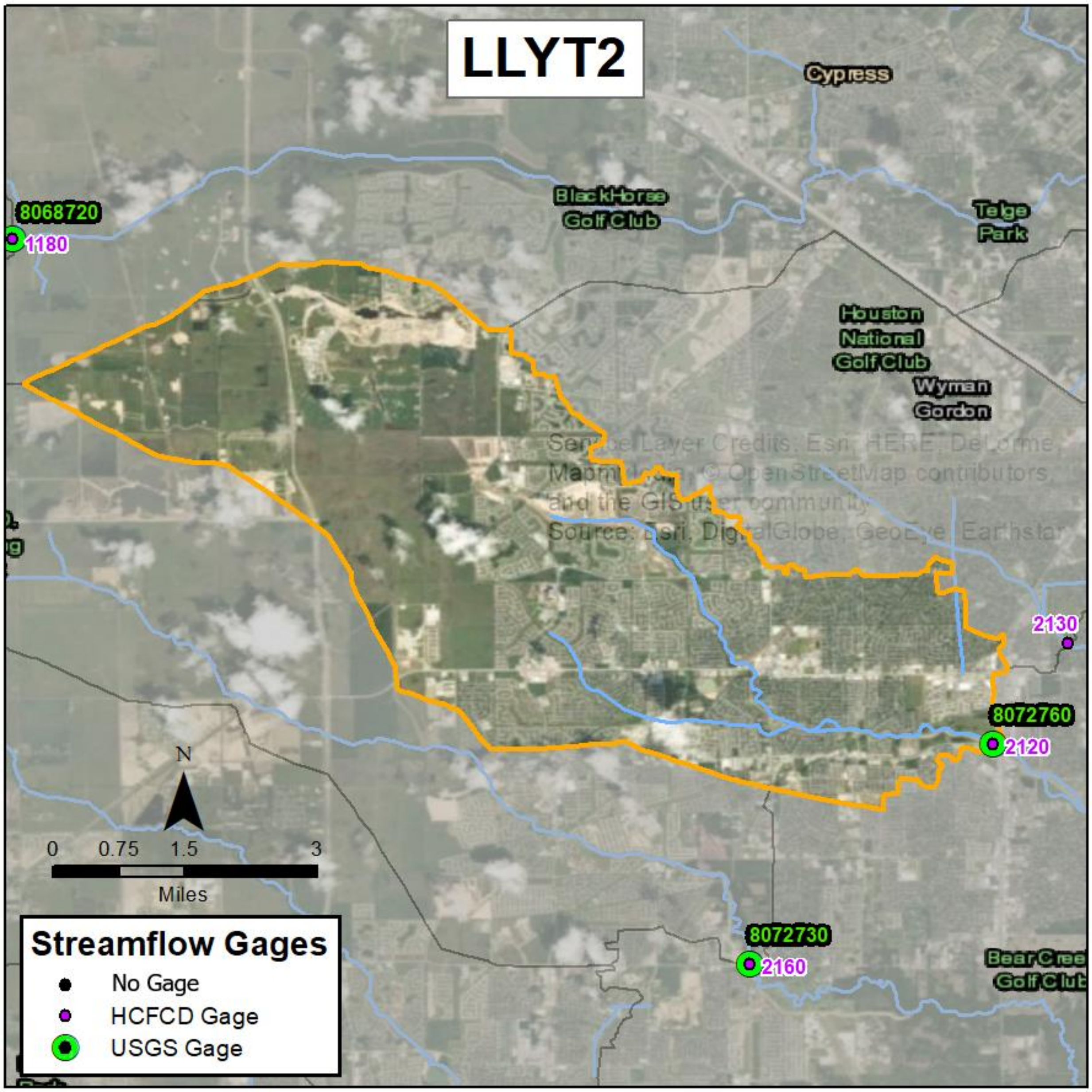


Buffalo Bayou Basin

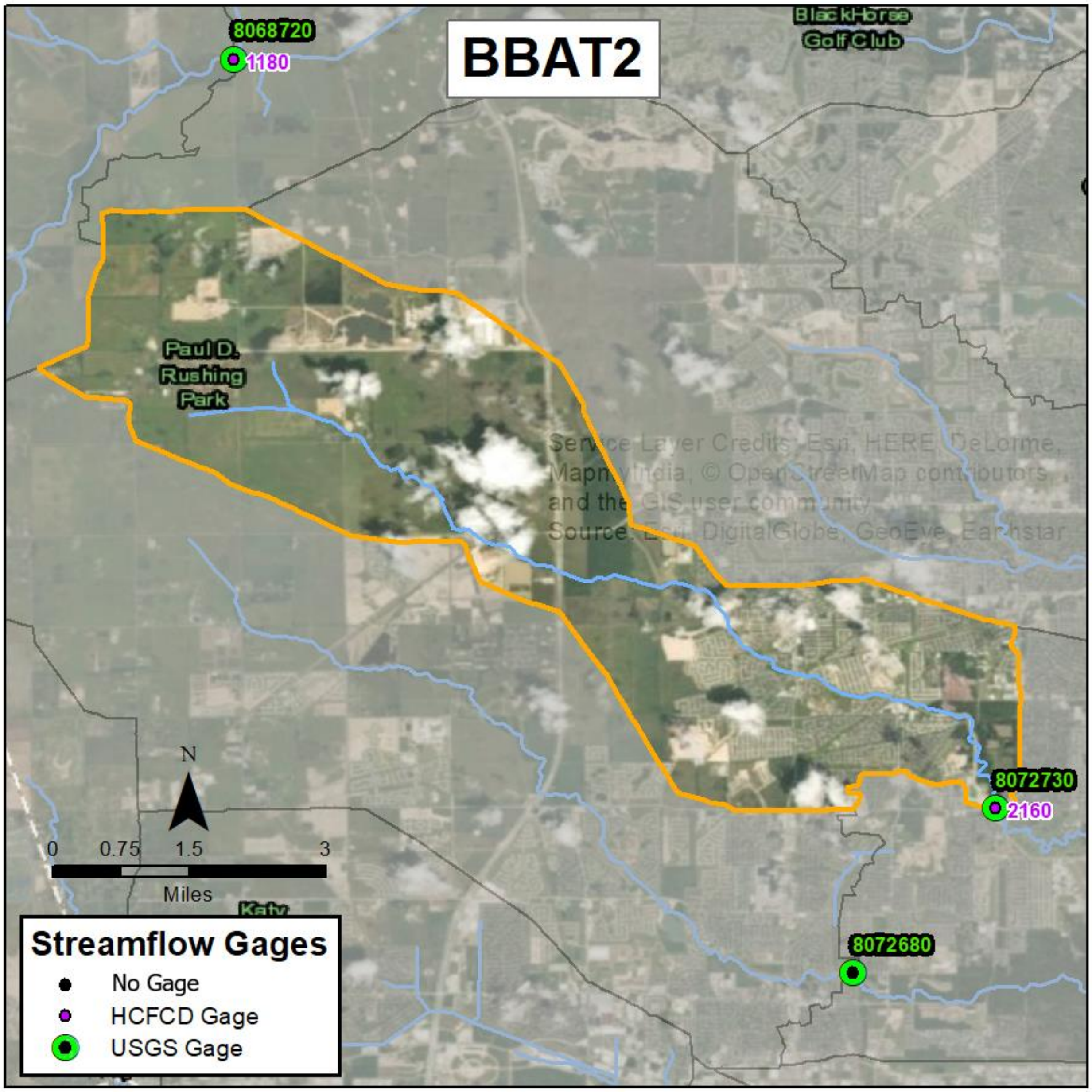
HPTT2 - Horsepen Creek at Trailside Drive



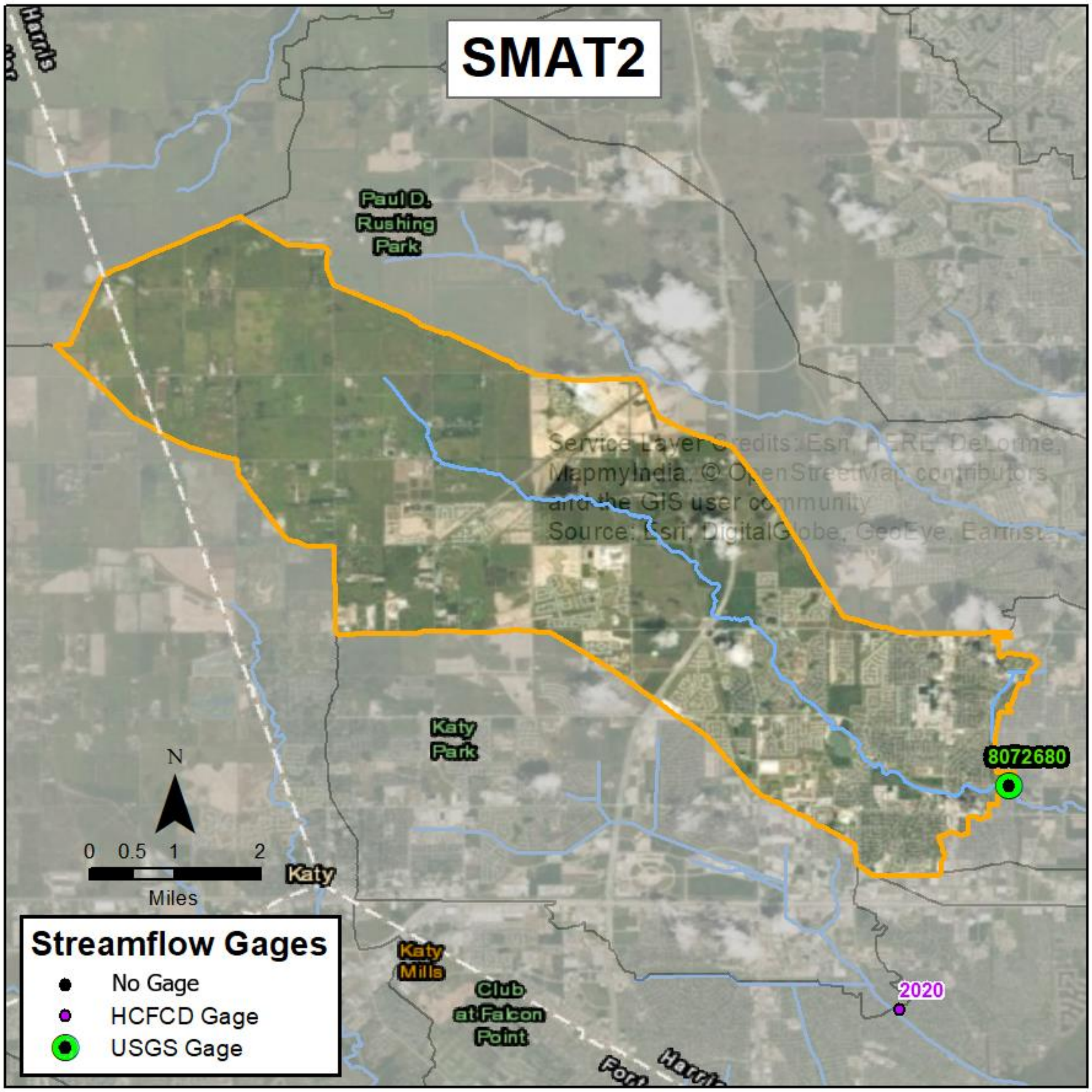
LLYT2 - Langham Ck at W Little York Rd nr Addicks, TX



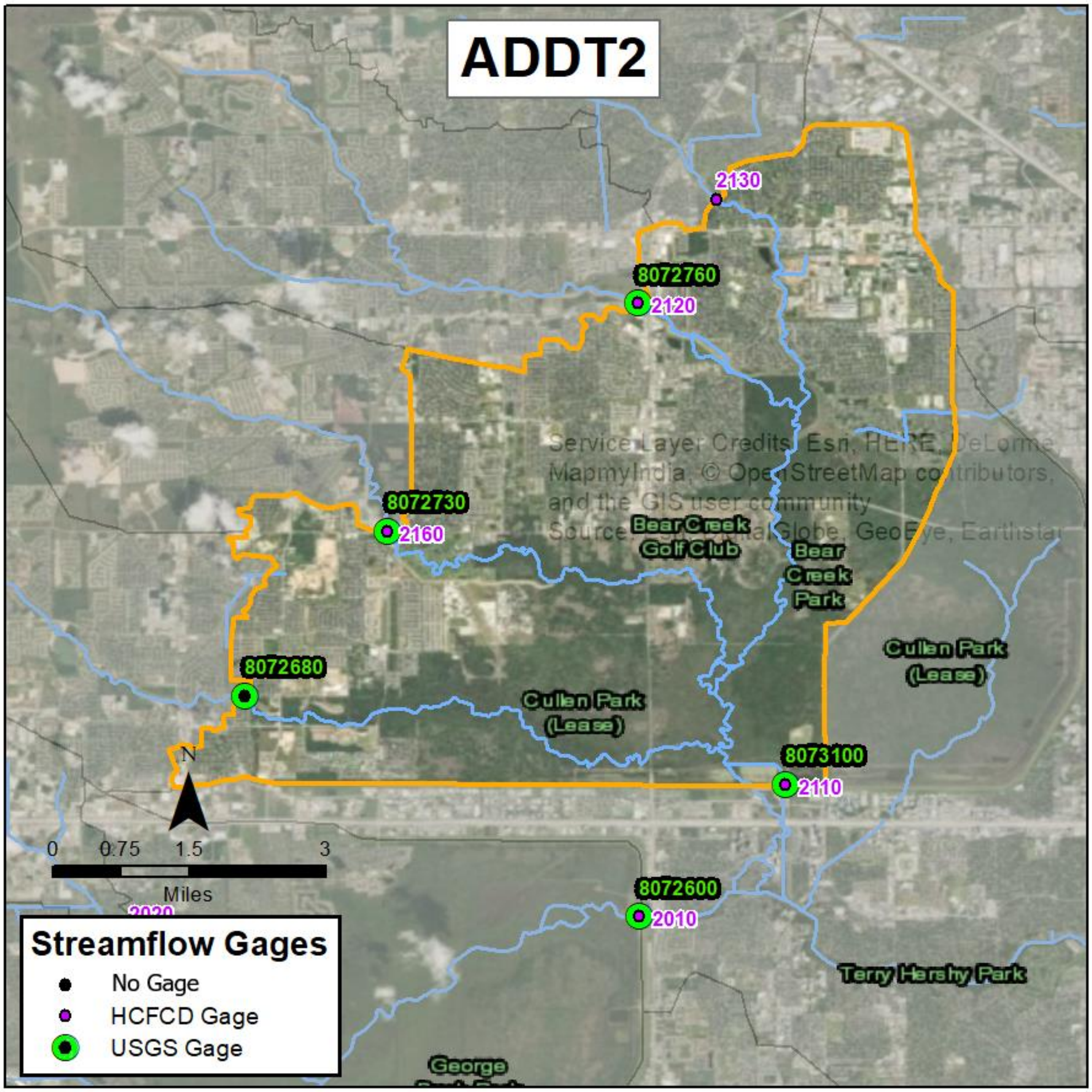
BBAT2 - Bear Ck nr Barker, TX



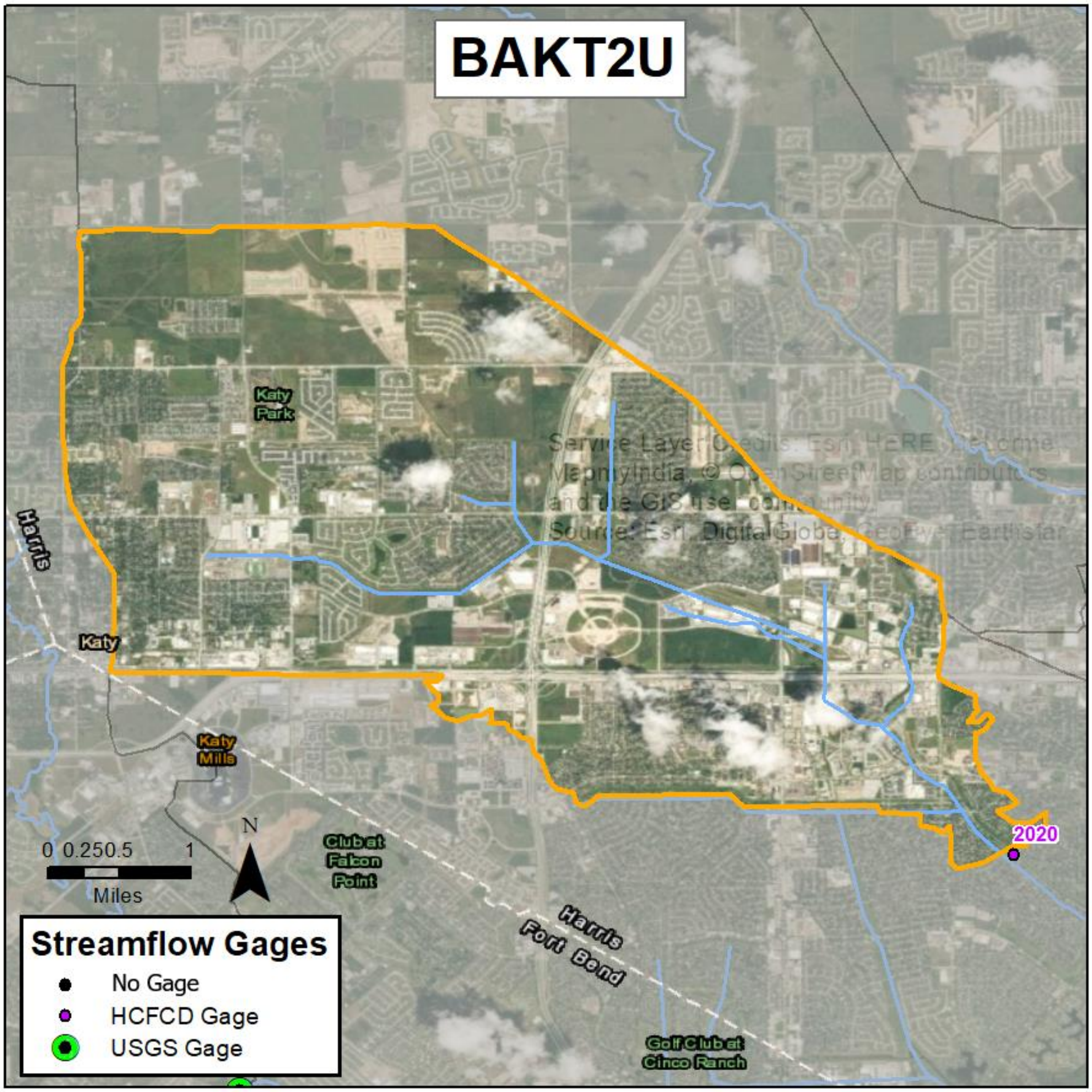
SMAT2 - S Mayde Ck at Heathergold Dr nr Addicks, TX



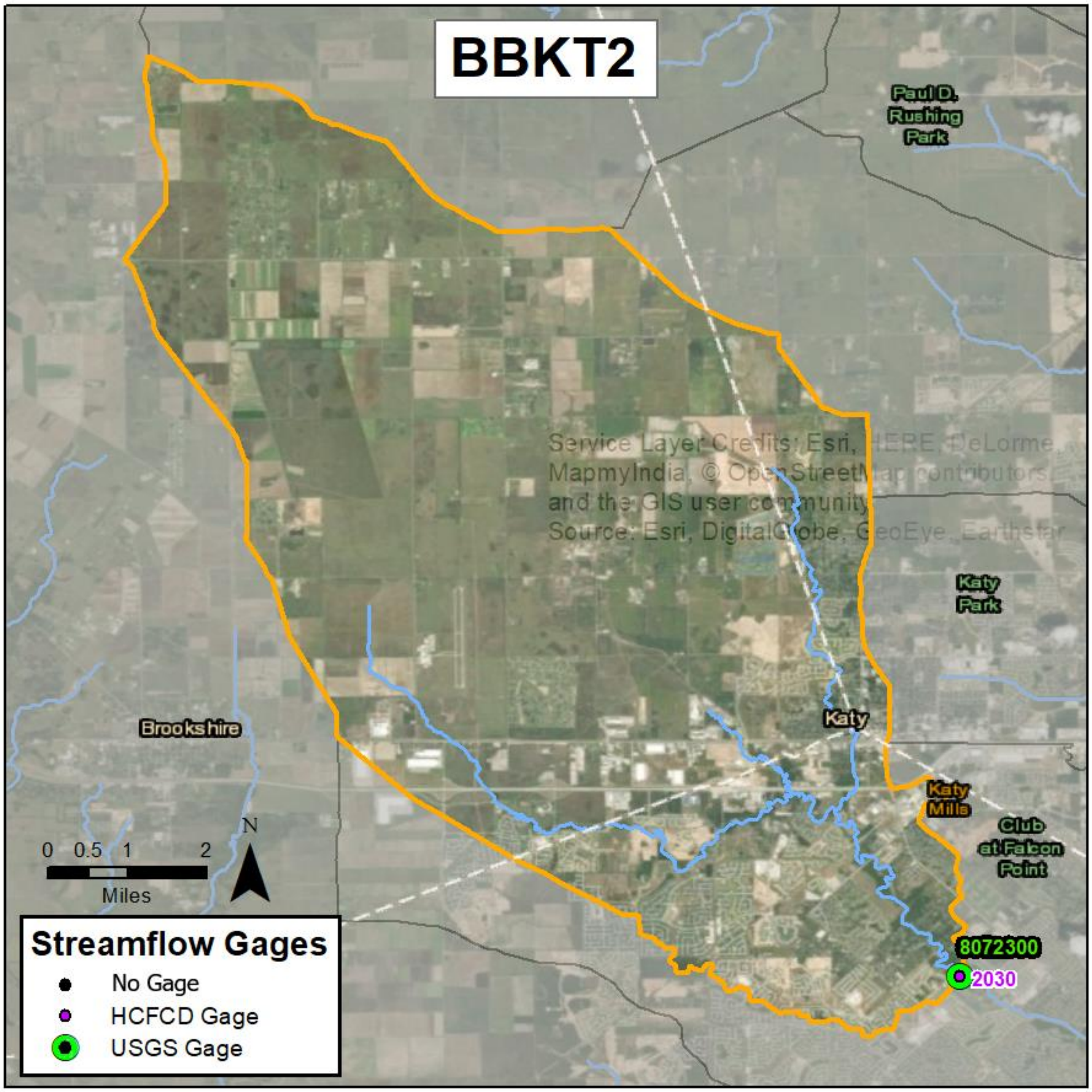
ADDT2 - Langham Ck at Addicks Res Outflow nr Addicks, TX



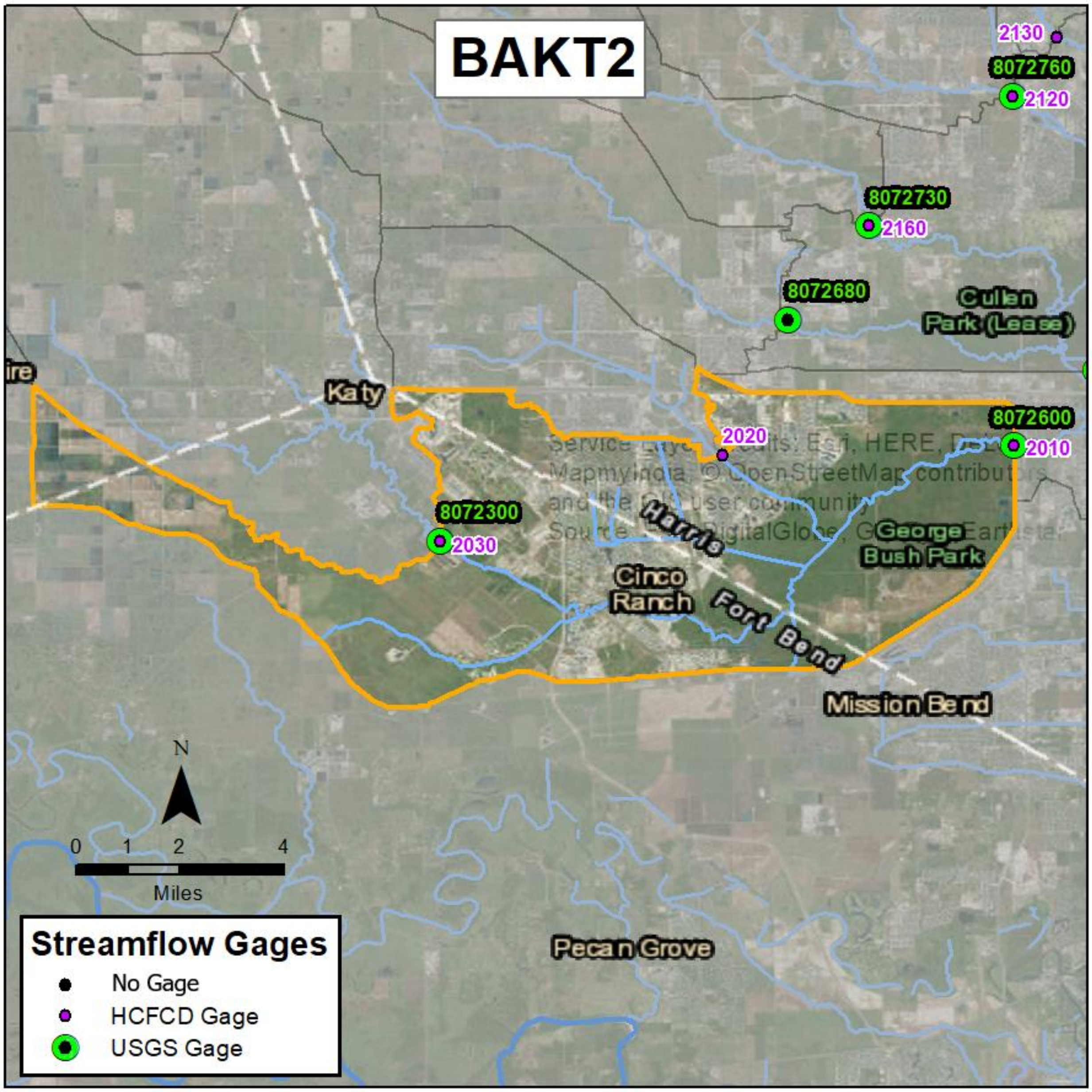
BAKT2U - Mason Creek at Prince Cr Dr abv Barker



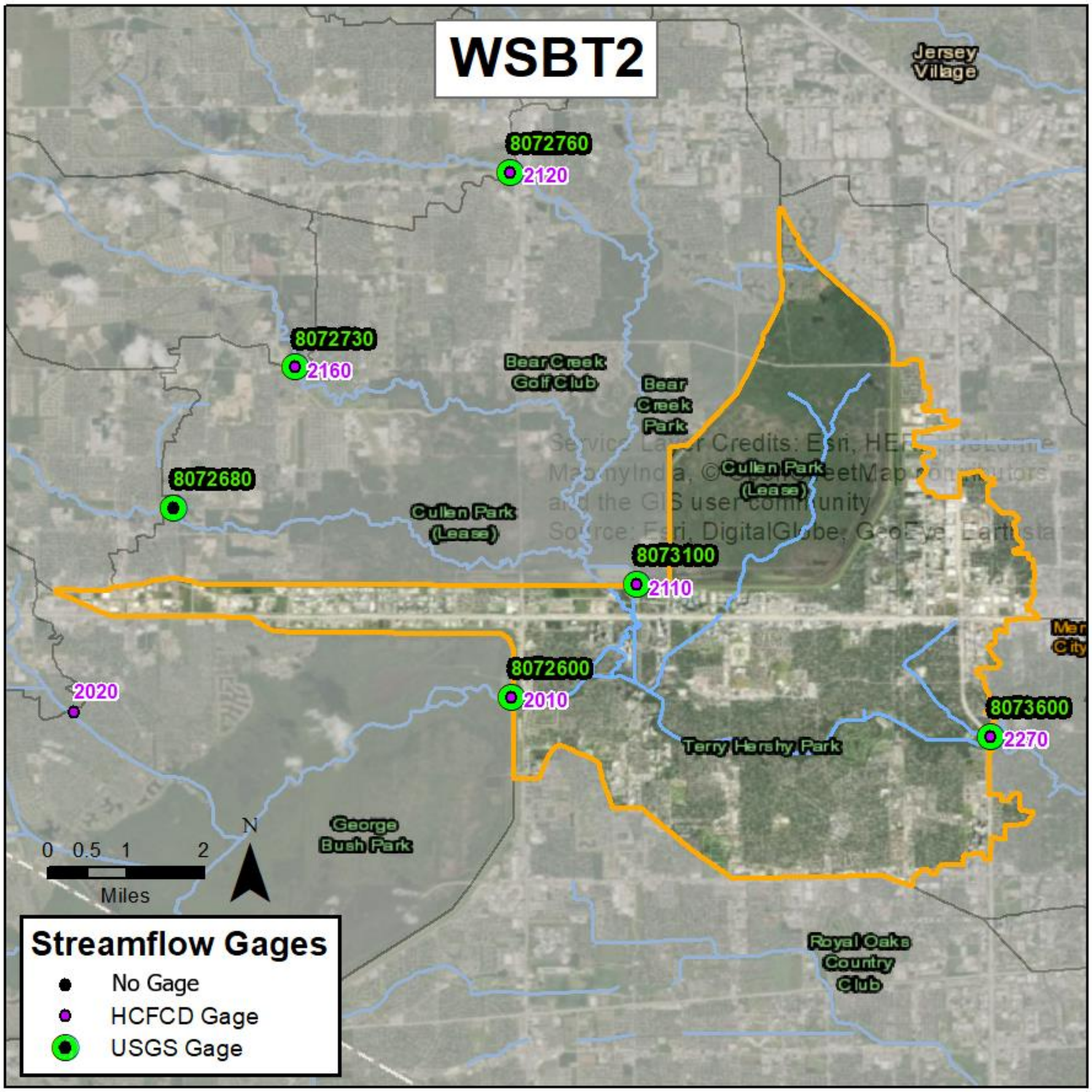
BBKT2 - Buffalo Bayou nr Katy, TX



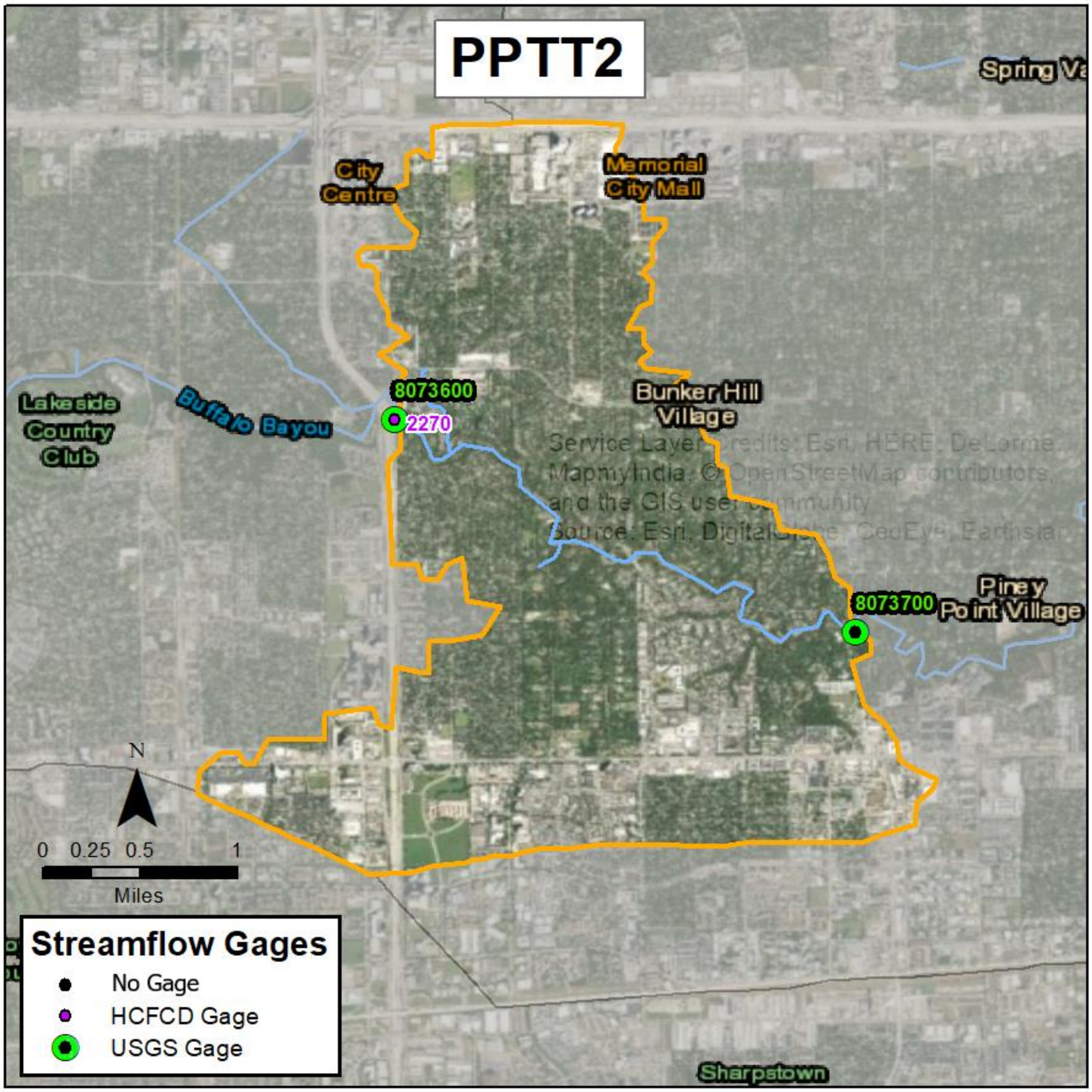
BAKT2 - Buffalo Bayou at State Hwy 6 nr Addicks, TX



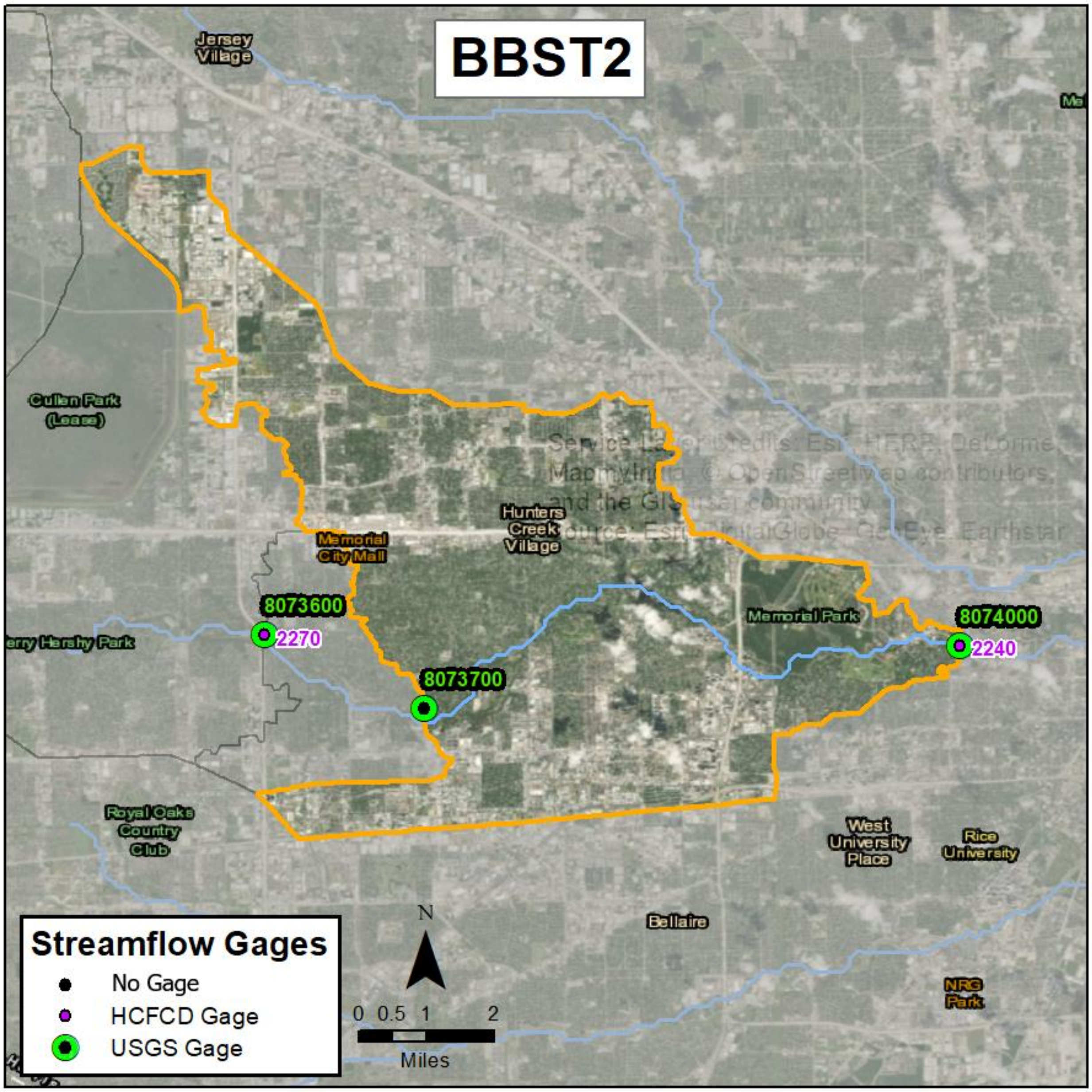
WSBT2 - Buffalo Bayou at W Belt Dr, Houston, TX



PPTT2 - Buffalo Bayou at Piney Point, TX



BBST2 - Buffalo Bayou at Houston, TX



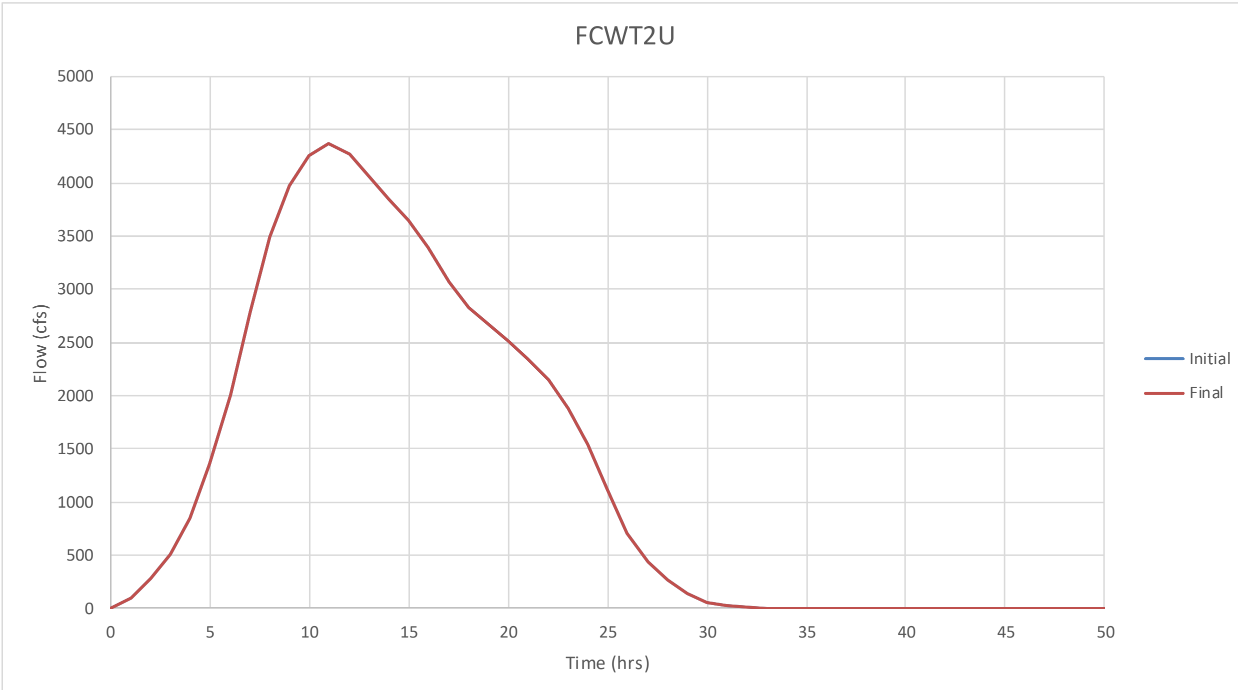
Appendix C:
Final Unit Hydrographs

Appendix C presents the results of the Unit Hydrograph development for each sub-basin. Initial Unit Hydrograph models were developed using both manual and GIS-based procedures. Final Unit Hydrographs incorporate adjustments made during the model calibration analysis.

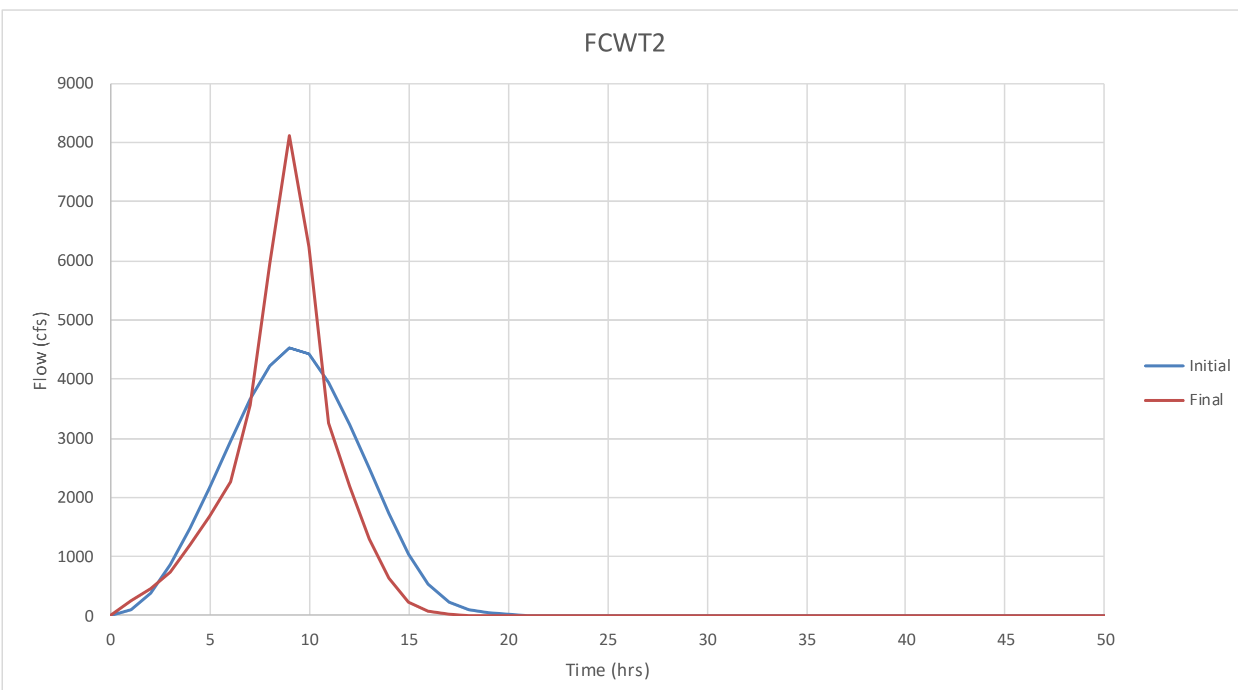
San Jacinto Basin

DDBT2 - Lake Ck nr Dobbin, TX

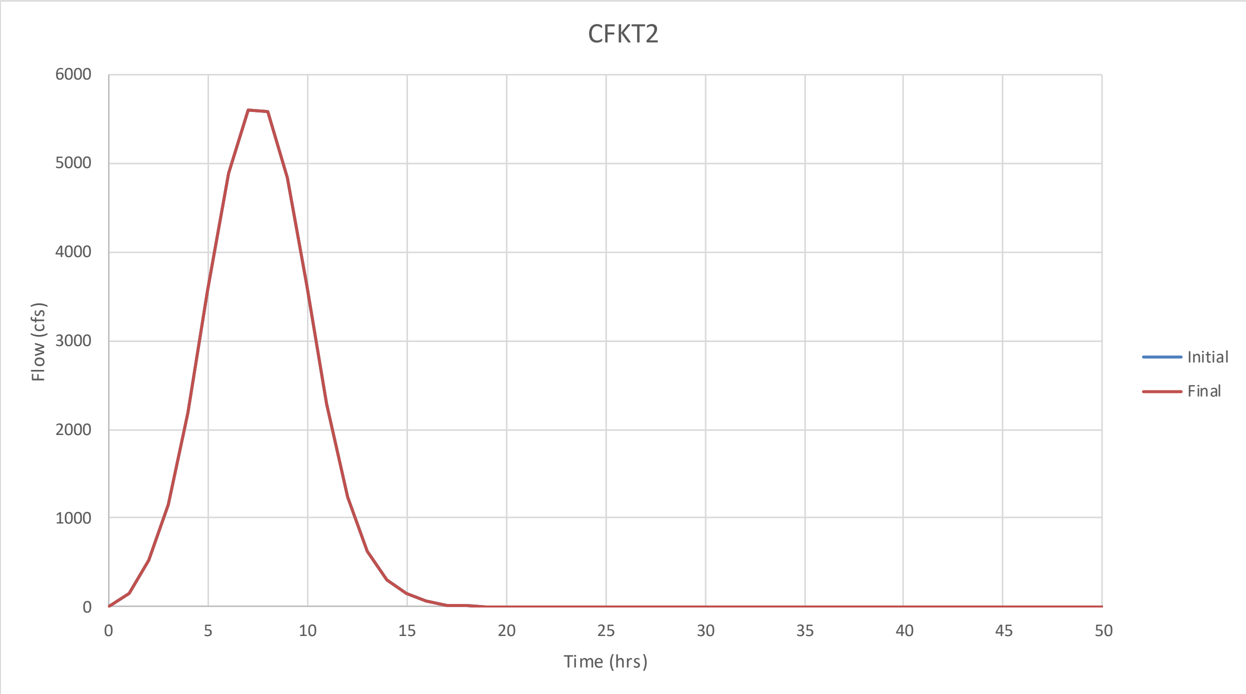
FCWT2U - Lake Ck nr Karen, TX



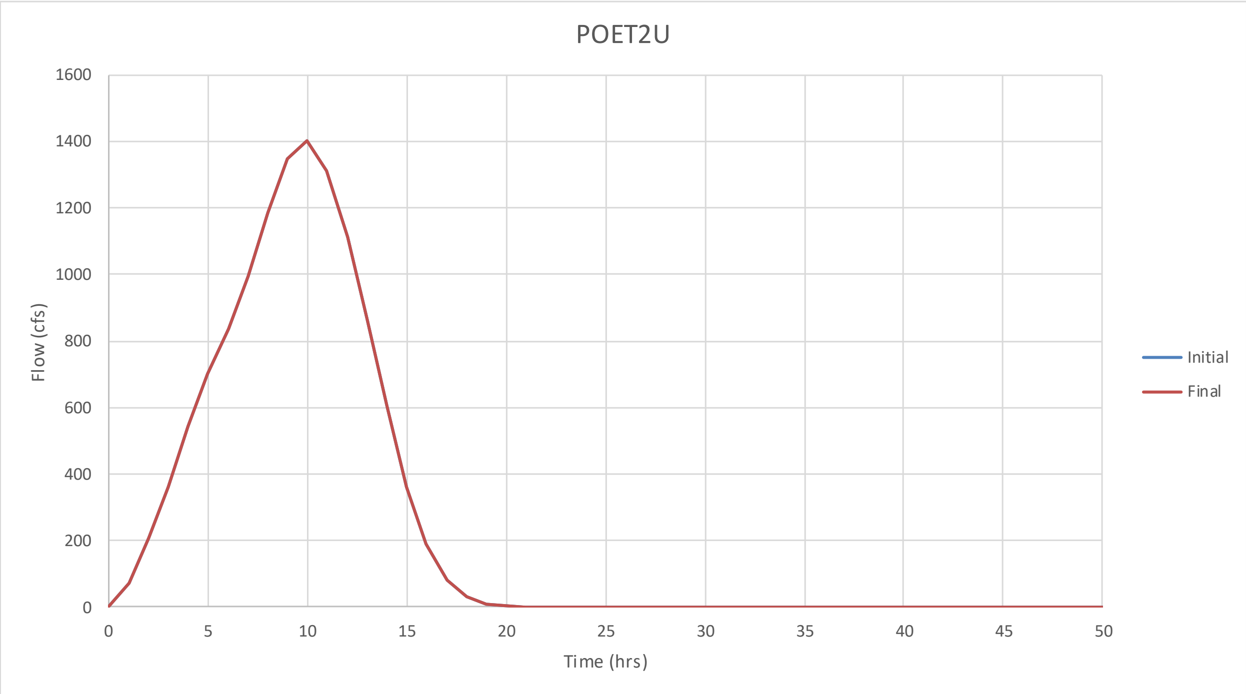
FCWT2 - Lake Ck at Sendera Ranch Rd nr Conroe, TX



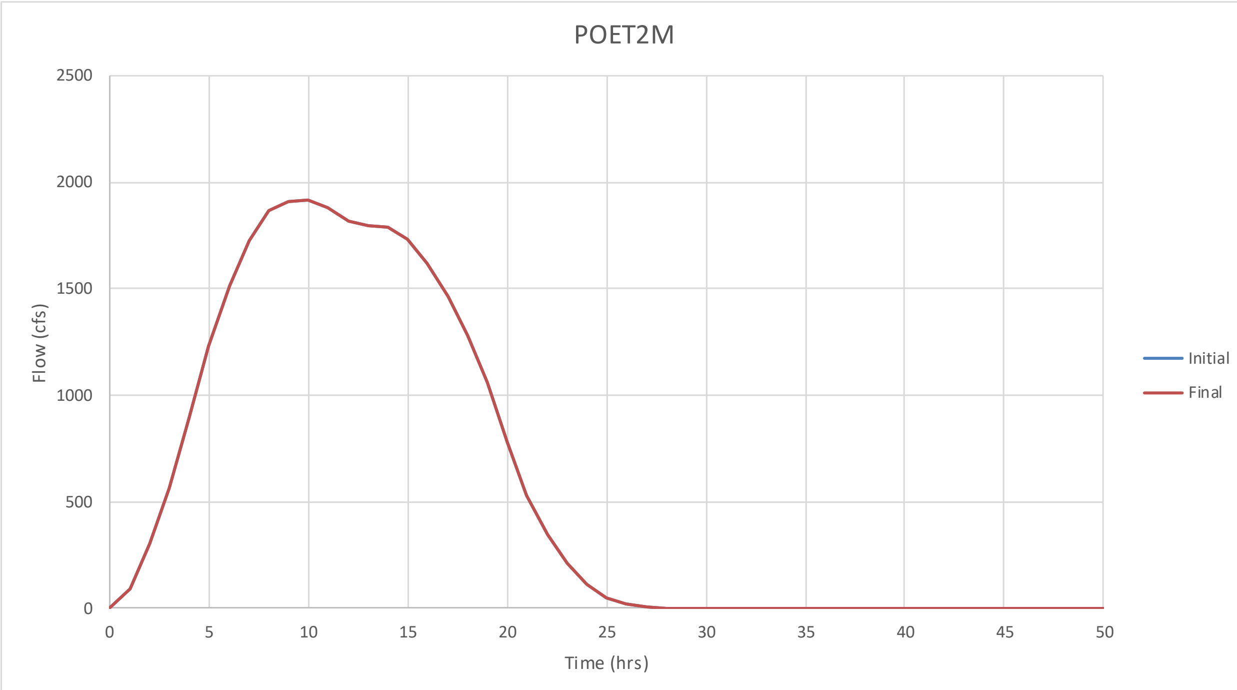
CFKT2 - W Fk San Jacinto Rv nr Conroe, TX



POET2U - Stewarts Creek at Crighton Rd

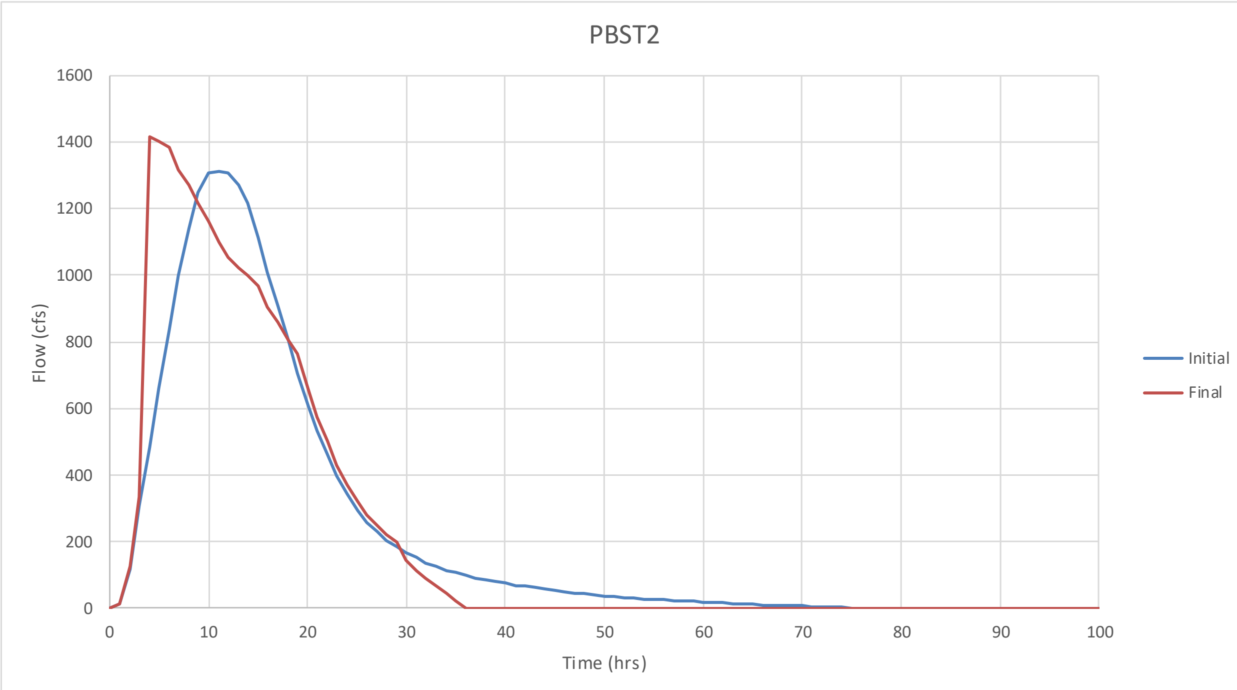


POET2M - Crystal Creek at FM1314

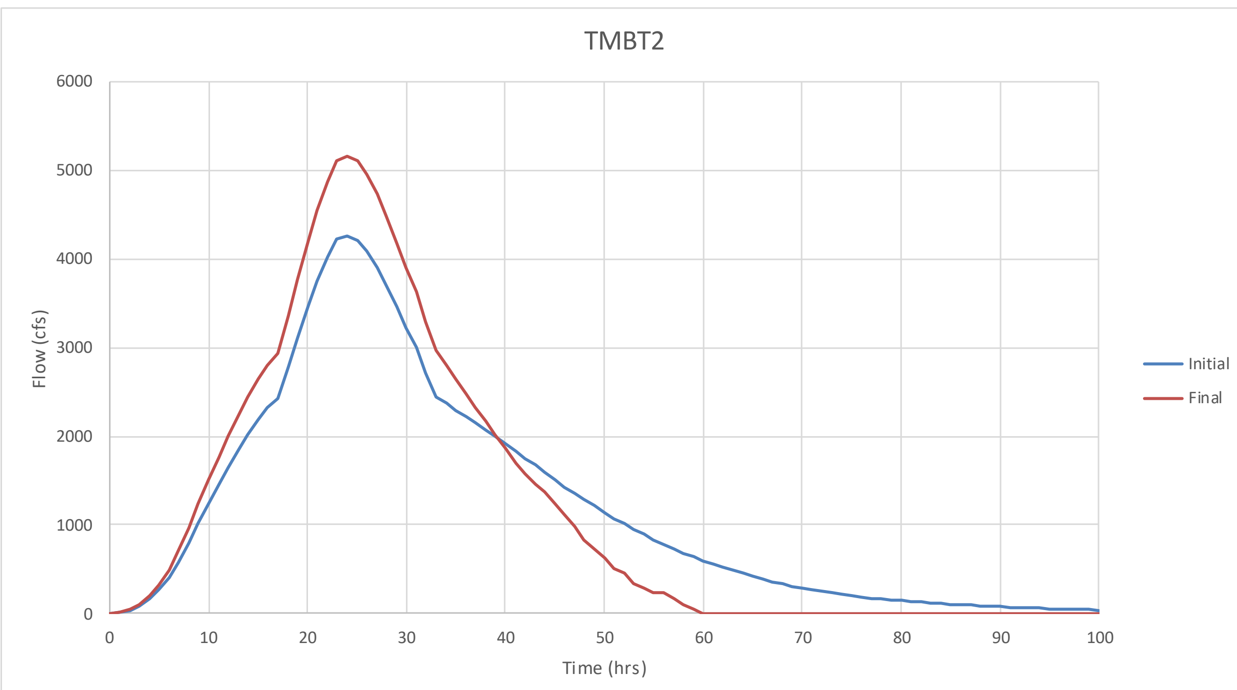


POET2 - W Fk San Jacinto Rv Abv Lk Houston nr Porter, TX

PBST2 - Panther Br nr Spring, TX

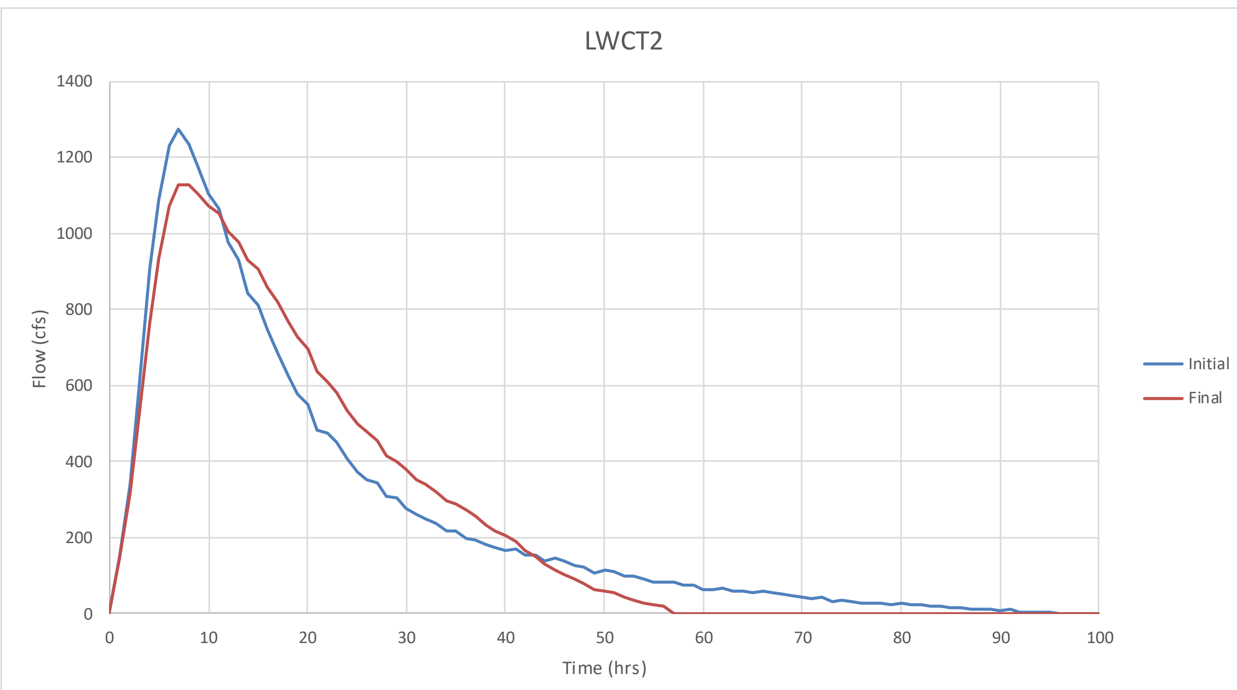


TMBT2 - Spring Ck nr Tomball, TX



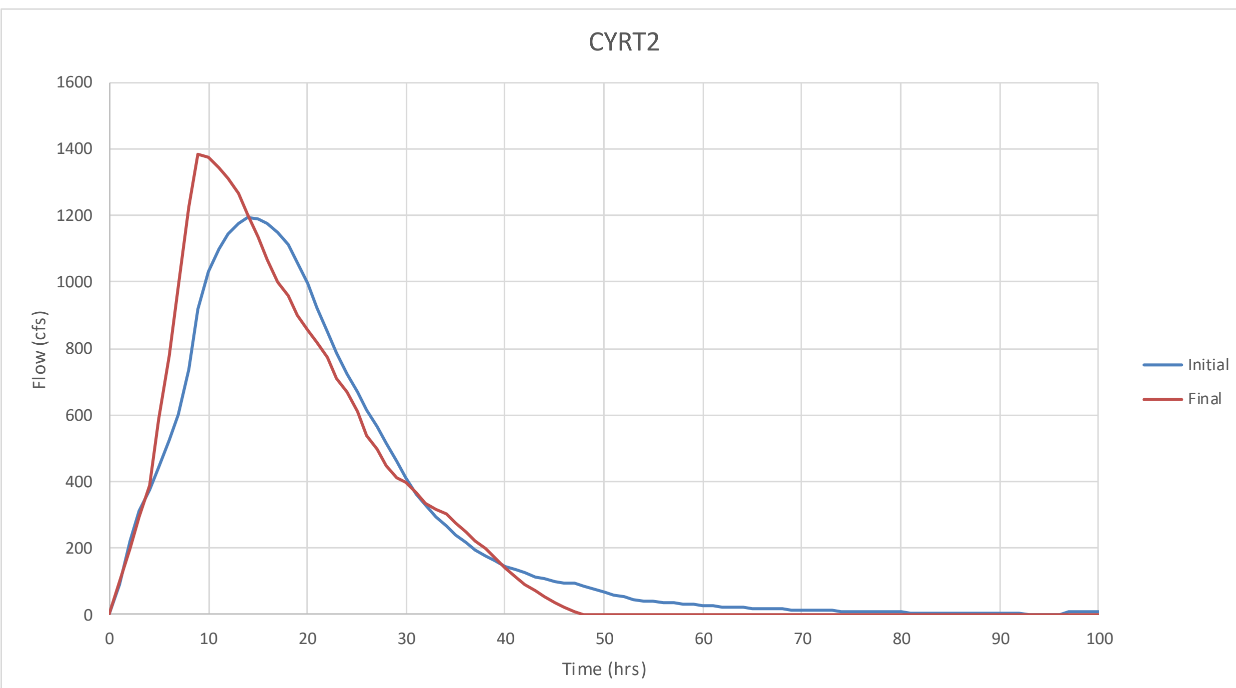
SCKT2 - Spring Ck at Kuykendahl, The Woodlands, TX

LWCT2 - Willow Ck nr Tomball, TX

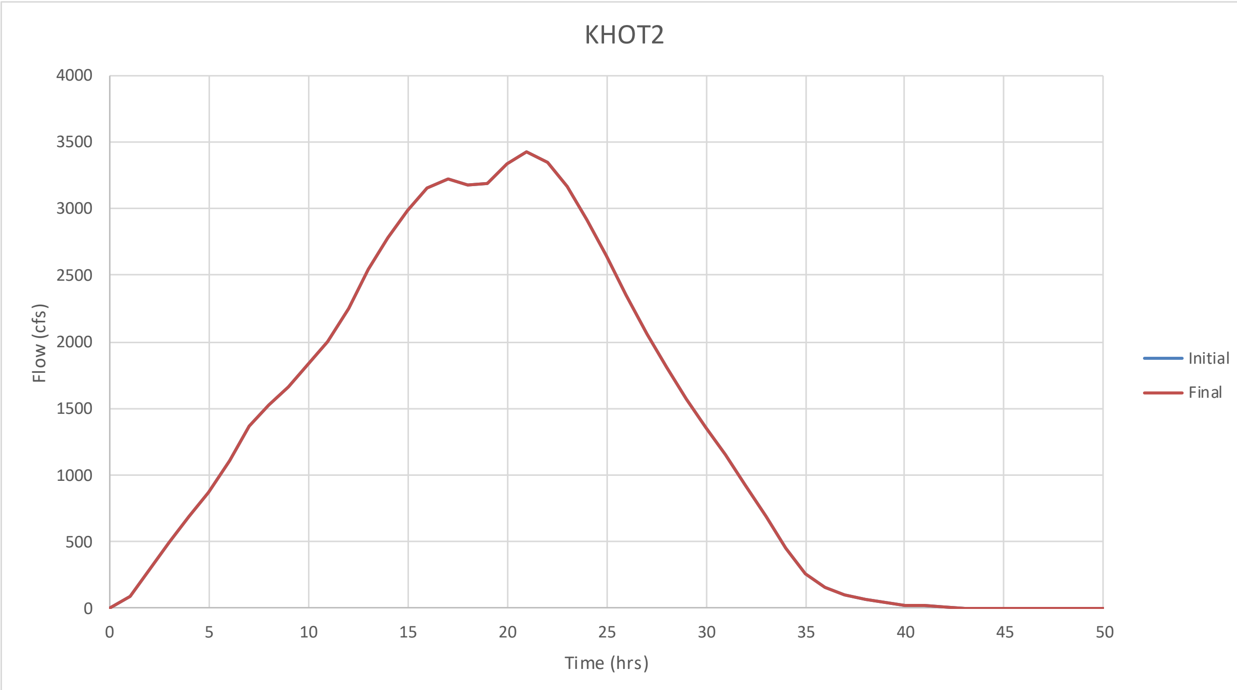


SPNT2 - Spring Ck nr Spring, TX

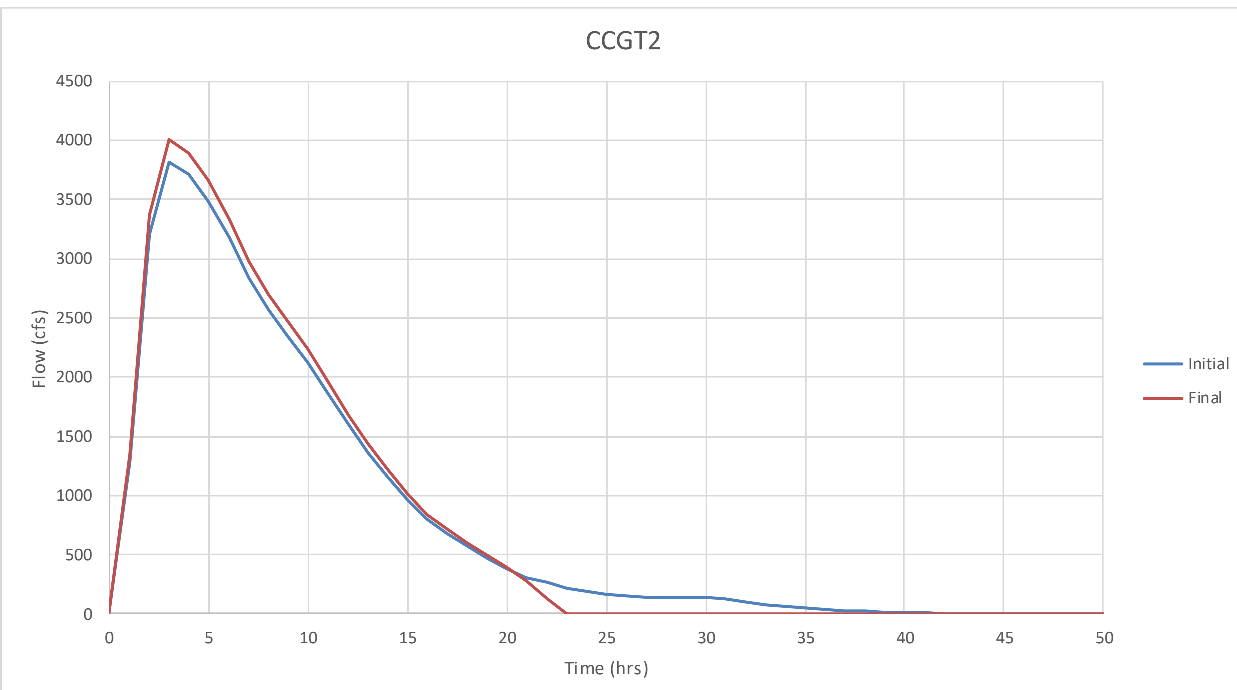
CYRT2 - Little Cypress Ck nr Cypress, TX



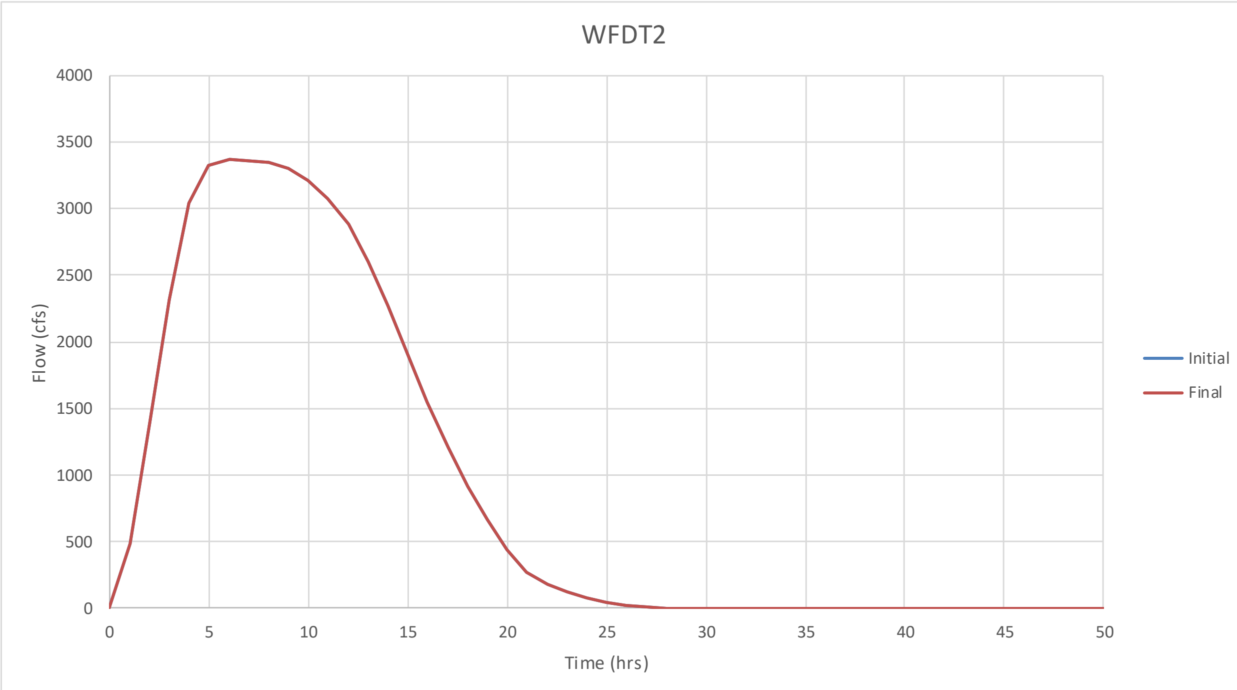
KHOT2 - Cypress Ck at Katy-Hockley Rd nr Hockley, TX



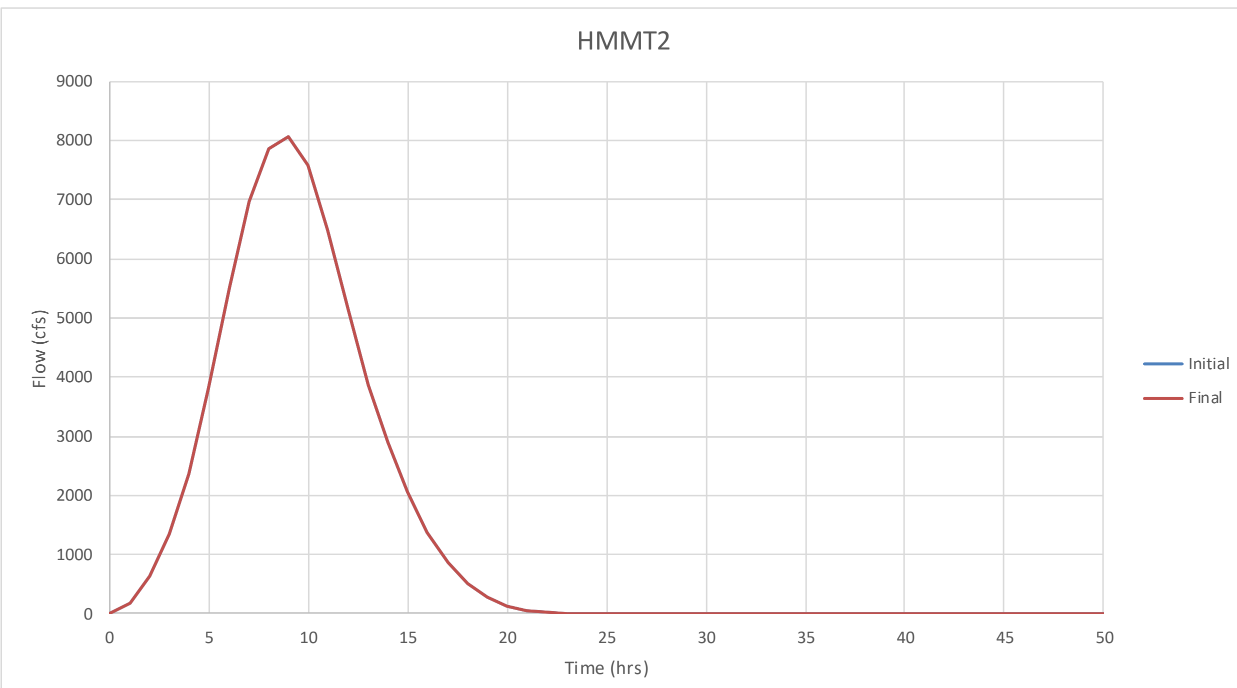
CCGT2 - Cypress Ck at Grant Rd nr Cypress, TX



WFDT2 - Cypress Ck nr Westfield, TX

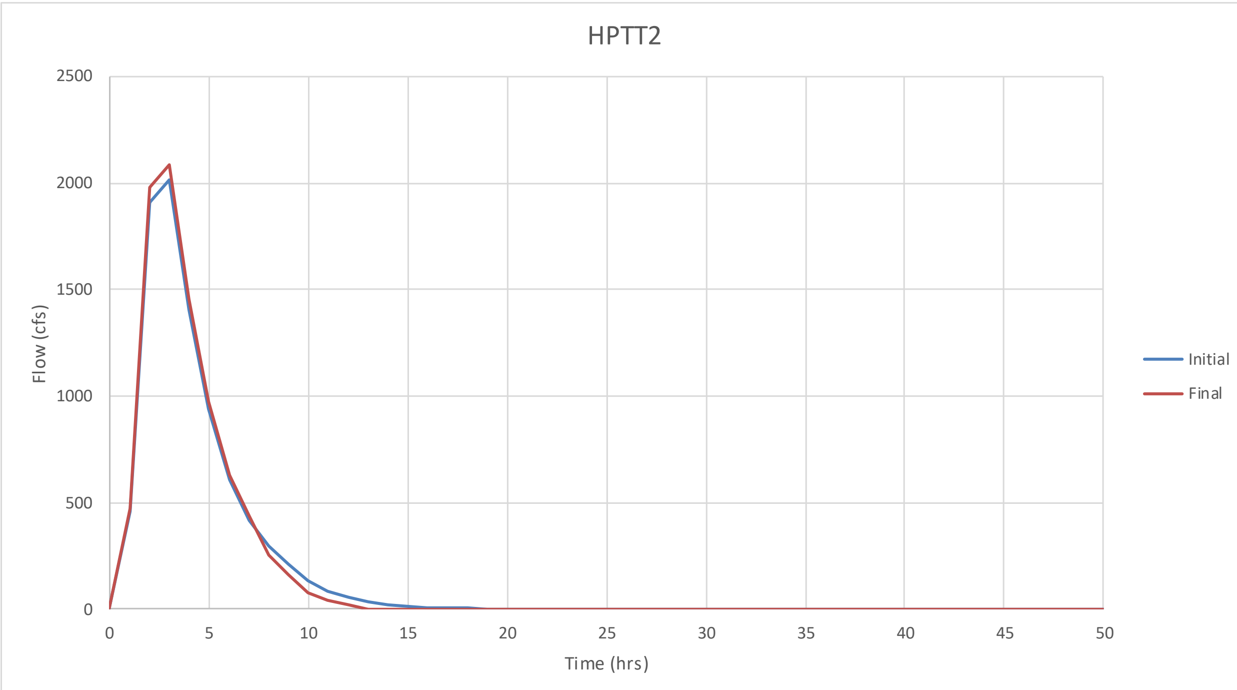


HMMT2 - W Fk San Jacinto Rv nr Humble, TX

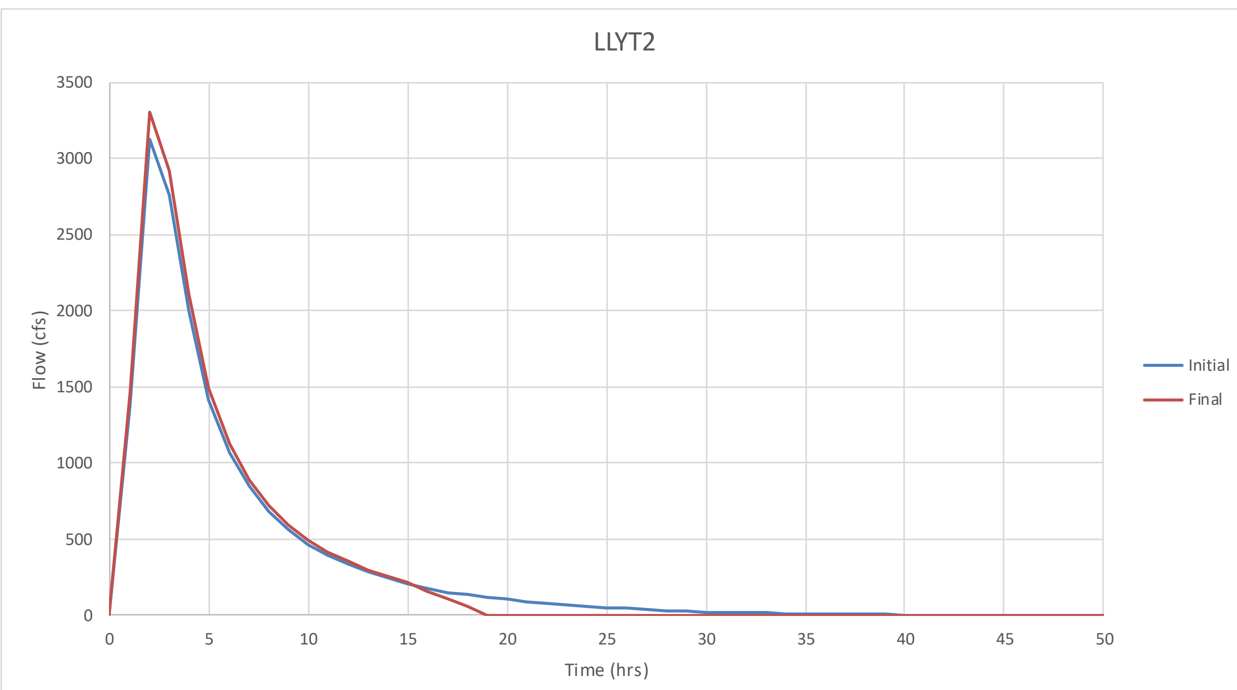


Buffalo Bayou Basin

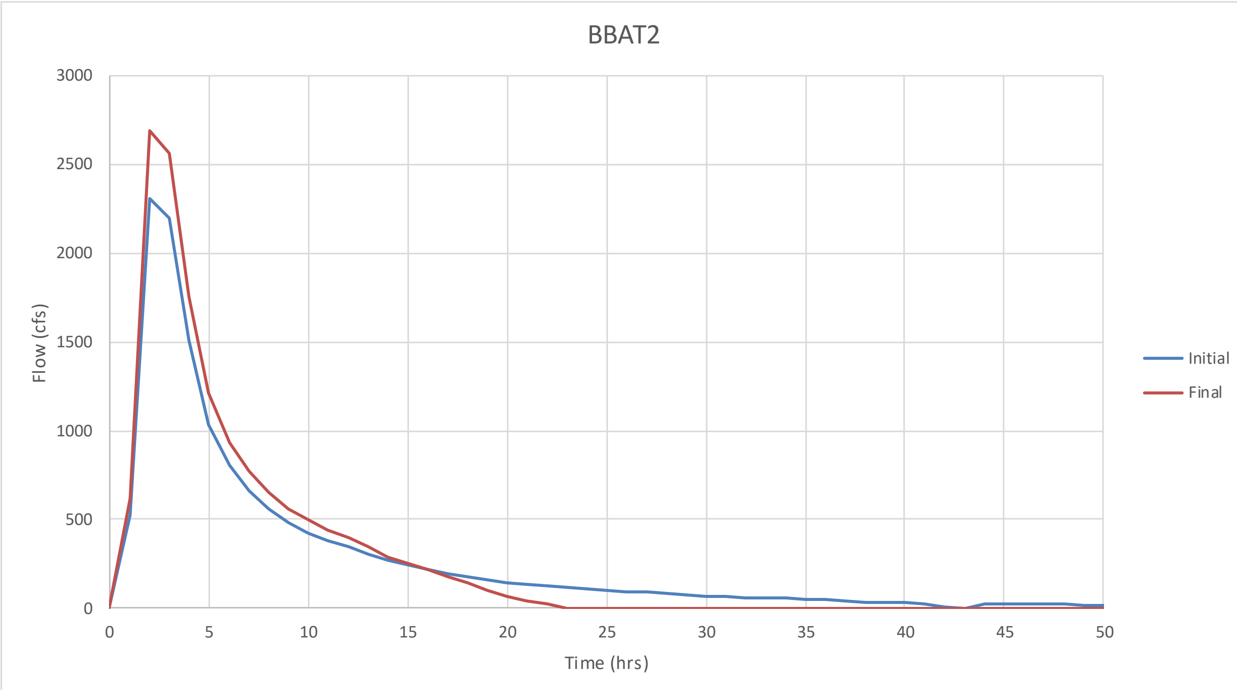
HPTT2 - Horsepen Creek at Trailside Drive



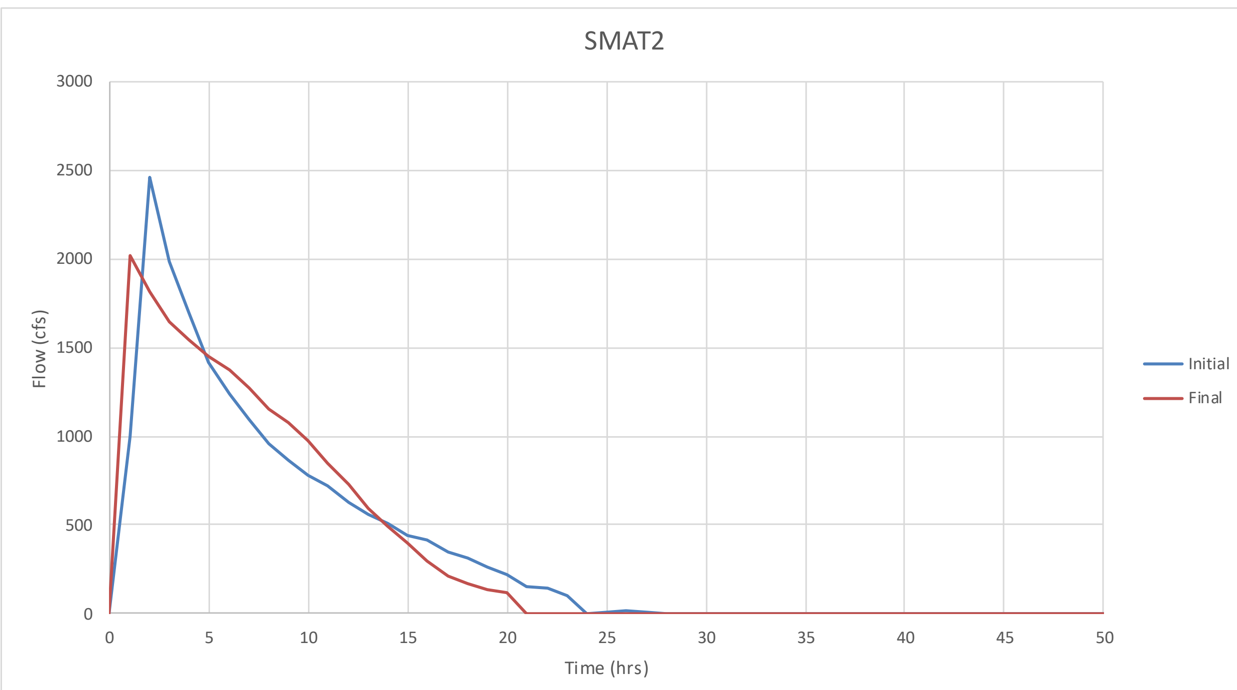
LLYT2 - Langham Ck at W Little York Rd nr Addicks, TX



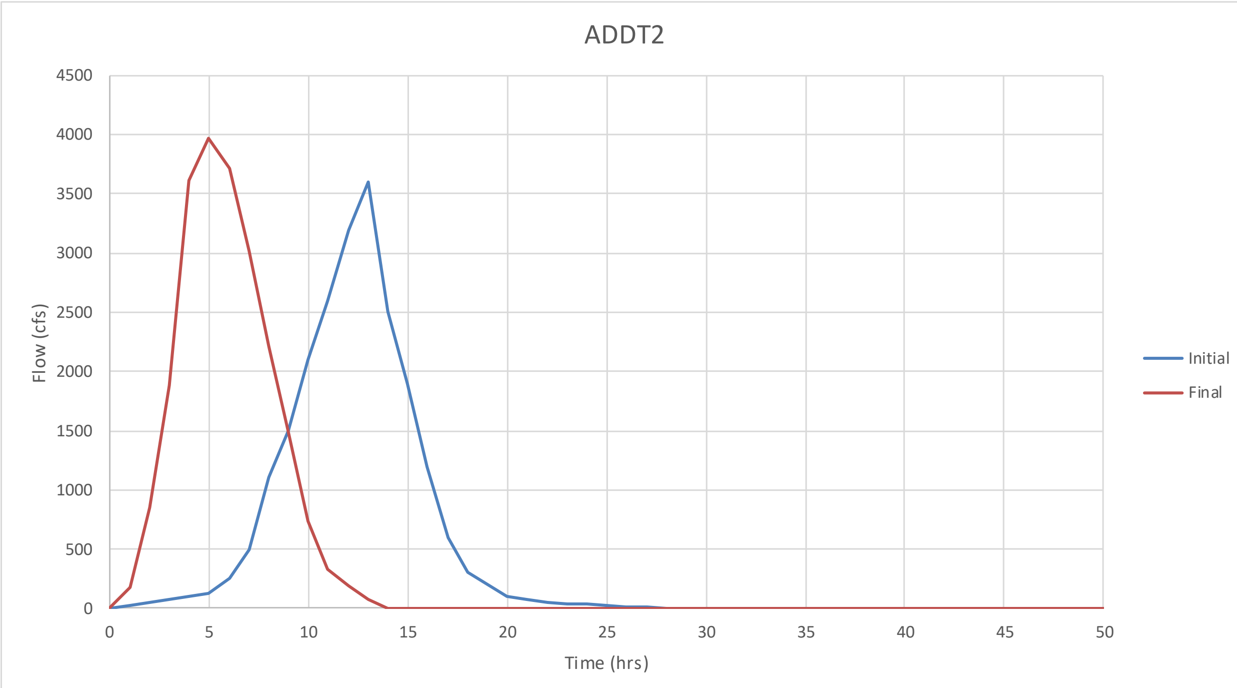
BBAT2 - Bear Ck nr Barker, TX



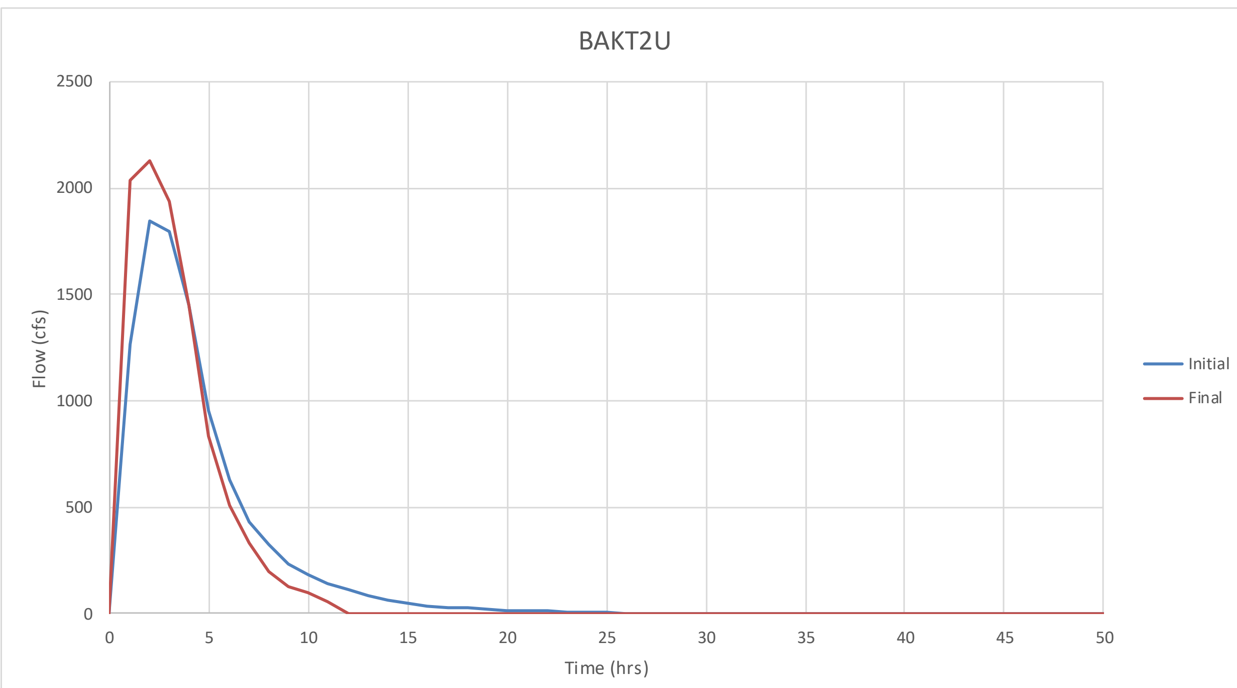
SMAT2 - S Mayde Ck at Heathergold Dr nr Addicks, TX



ADDT2 - Langham Ck at Addicks Res Outflow nr Addicks, TX

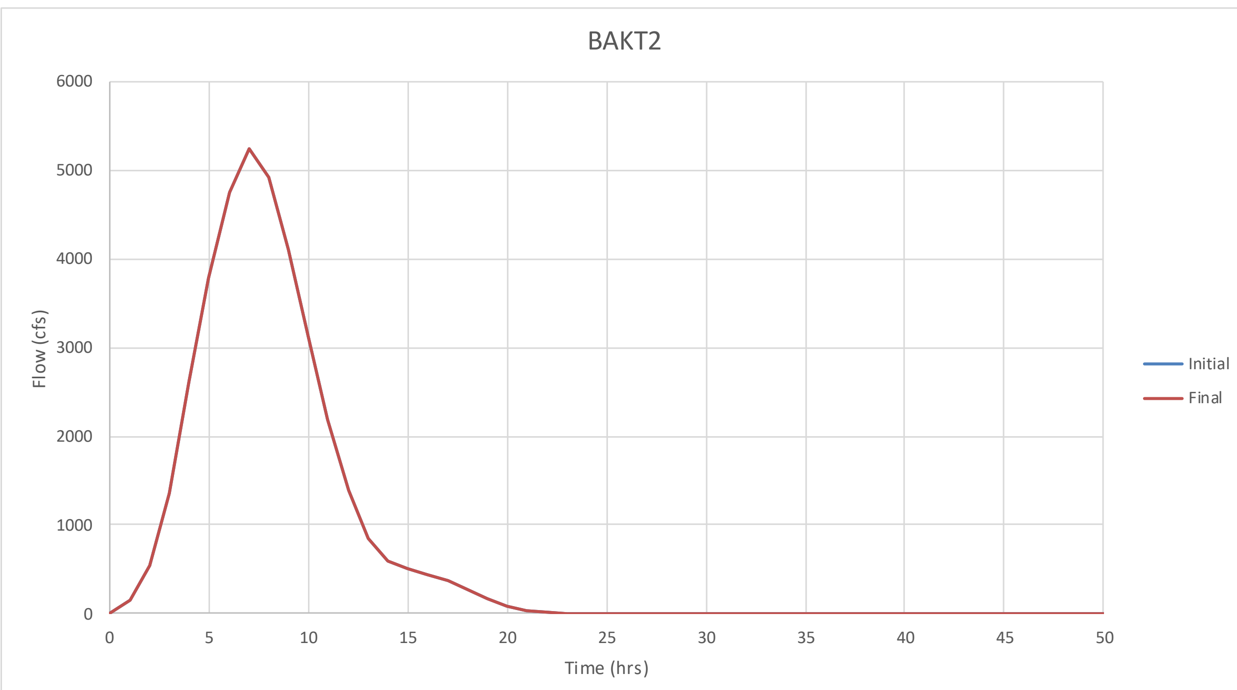


BAKT2U - Mason Creek at Prince Cr Dr abv Barker

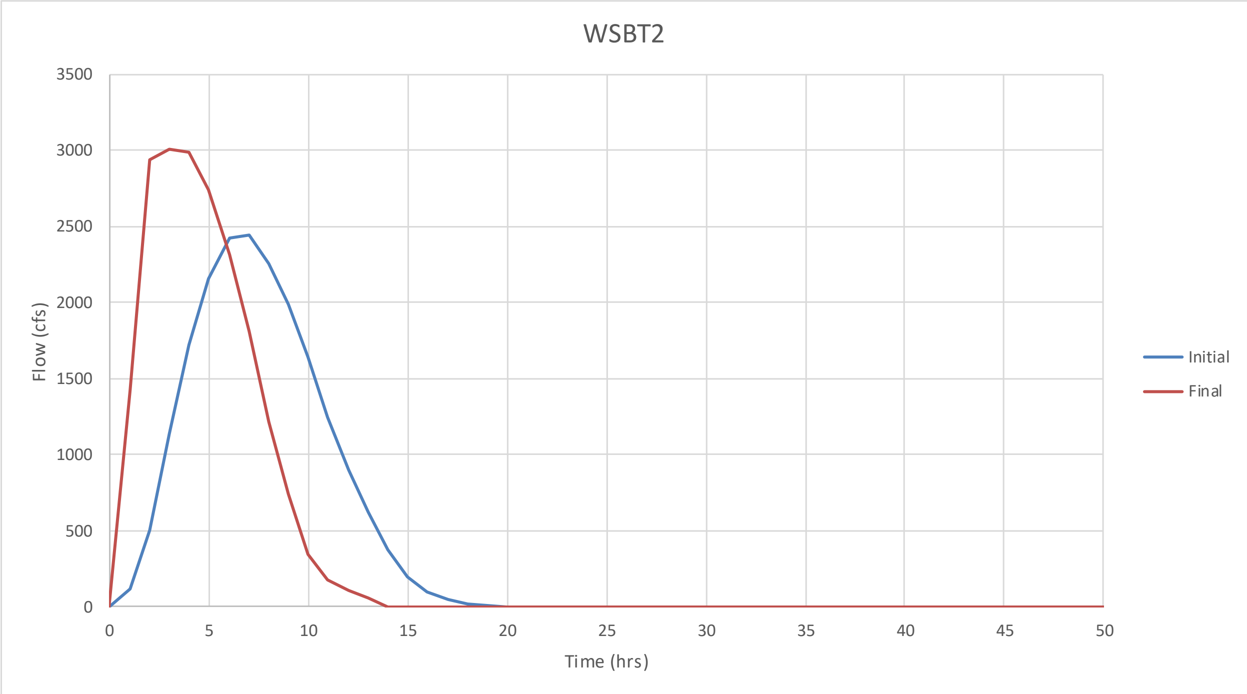


BBKT2 - Buffalo Bayou nr Katy, TX

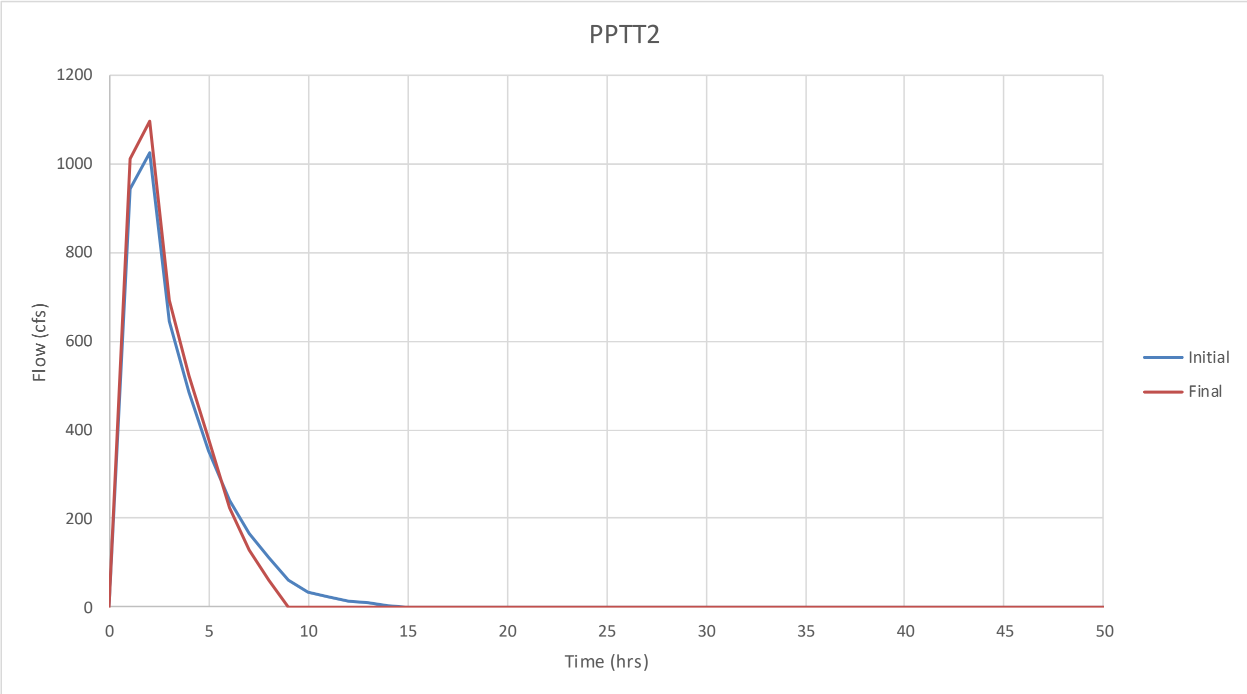
BAKT2 - Buffalo Bayou at State Hwy 6 nr Addicks, TX



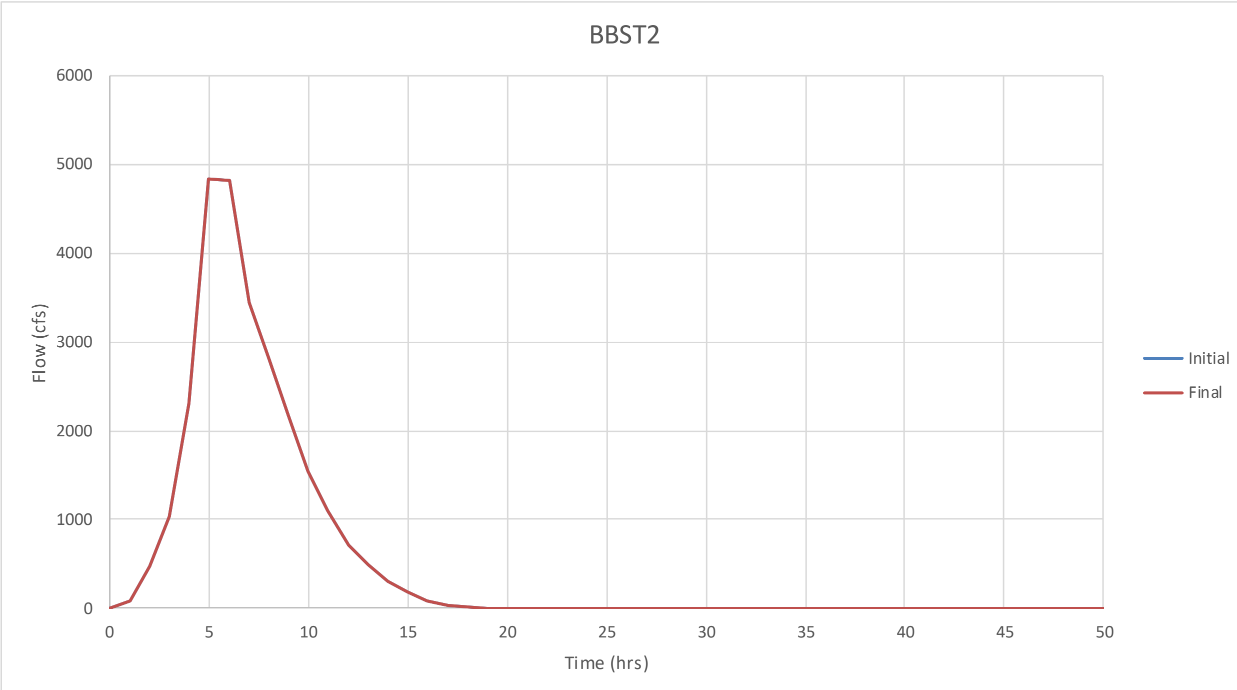
WSBT2 - Buffalo Bayou at W Belt Dr, Houston, TX



PPTT2 - Buffalo Bayou at Piney Point, TX



BBST2 - Buffalo Bayou at Houston, TX



Appendix D:
ICP Hydrographs of Recent Flood Events

San Jacinto Basin

DDBT2 - Lake Ck nr Dobbin, TX

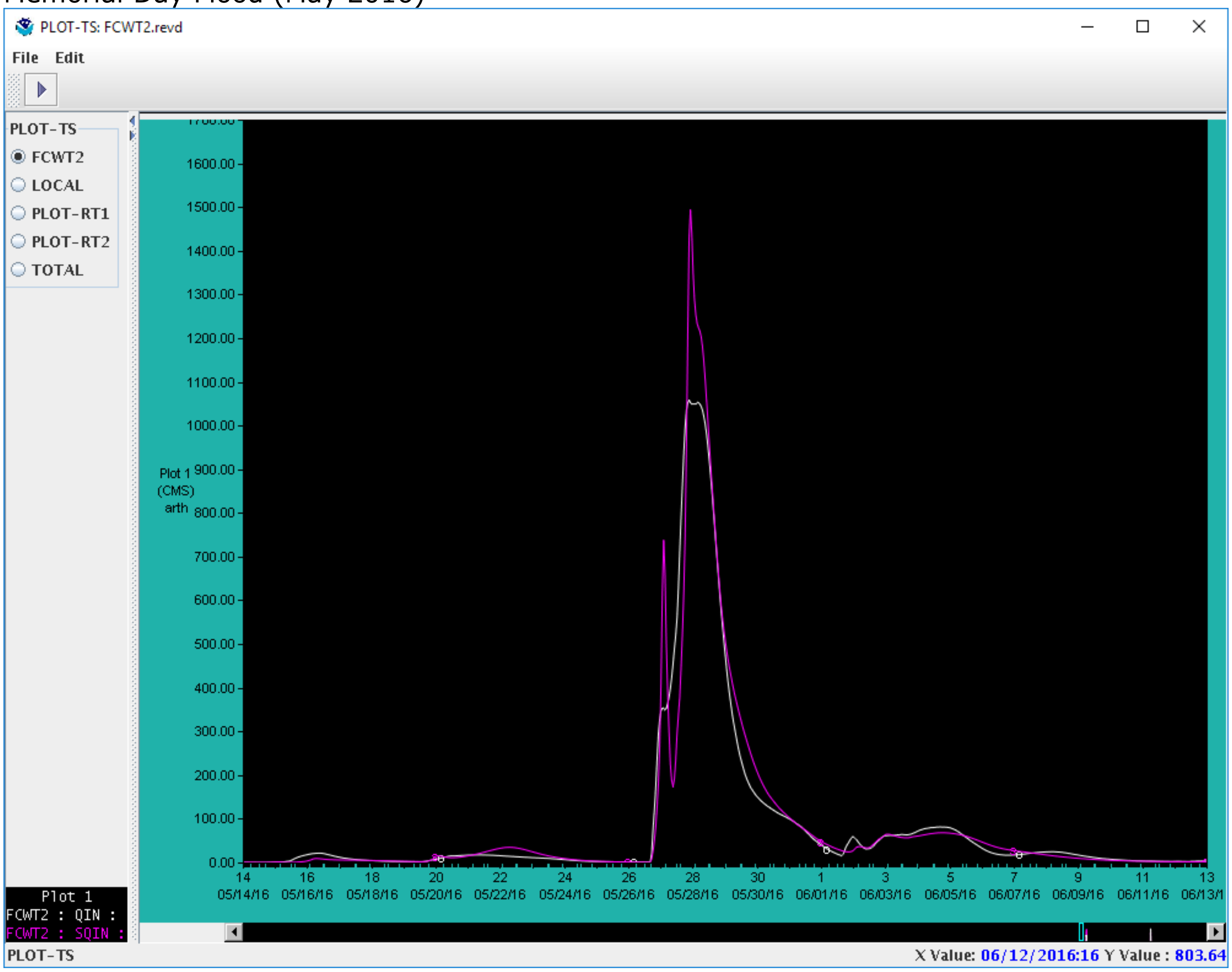
No observed data available

FCWT2U - Lake Ck nr Karen, TX

No observed data available

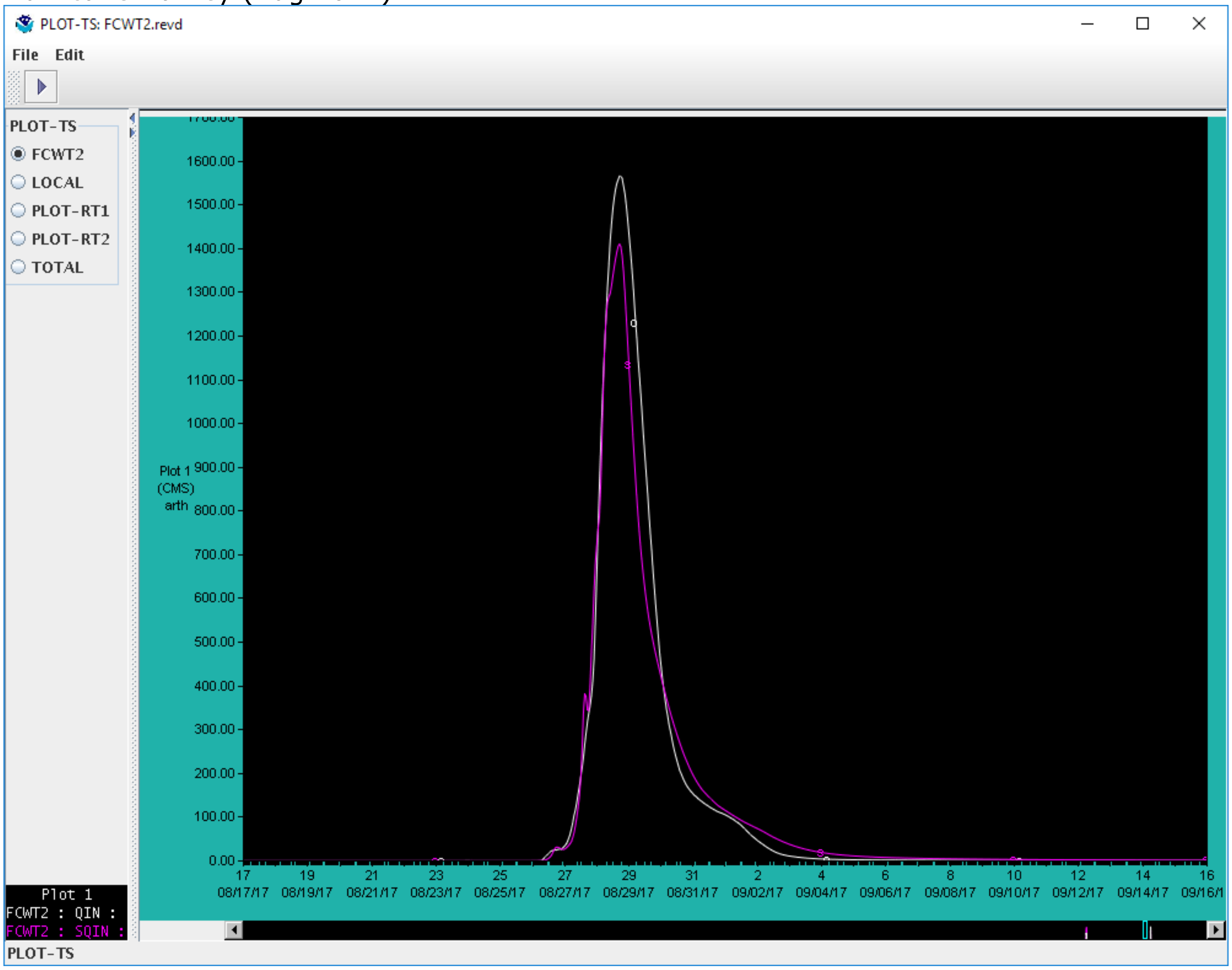
FCWT2 - Lake Ck at Sendera Ranch Rd nr Conroe, TX

Memorial Day Flood (May 2016)



(Purple Line = Simulated, White Line = Observed)

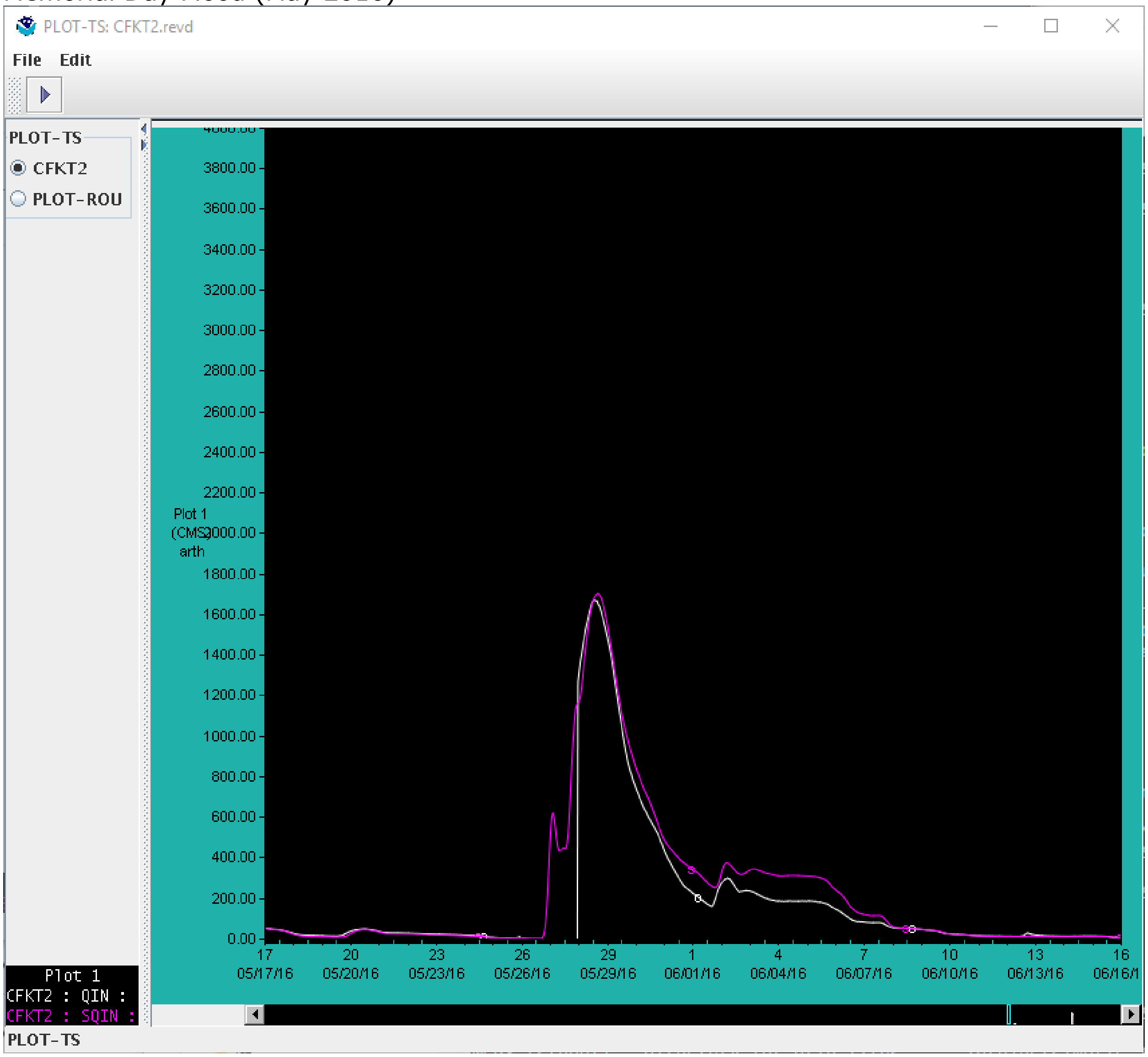
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

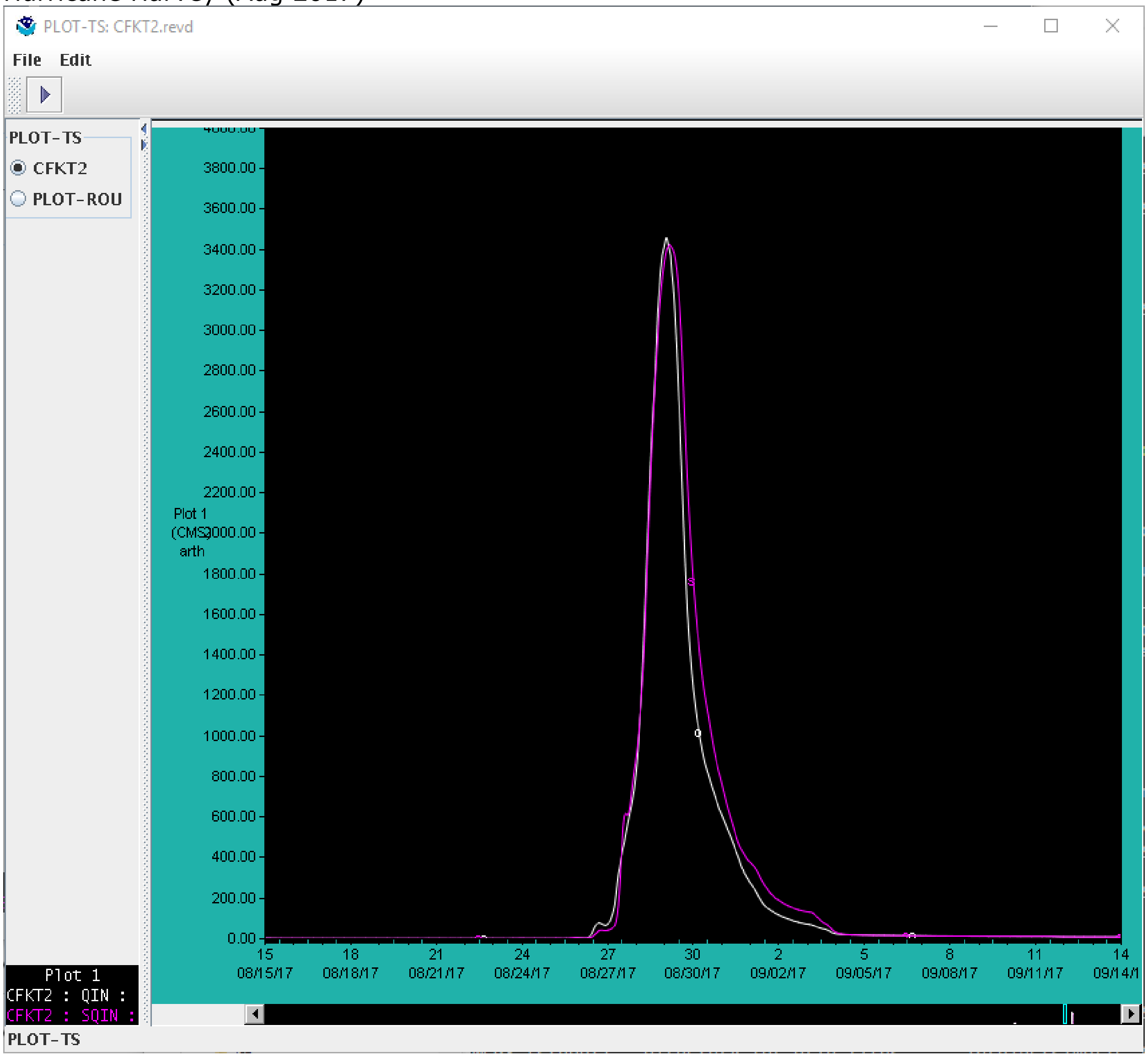
CFKT2 - W Fk San Jacinto Rv nr Conroe, TX

Memorial Day Flood (May 2016)



(Purple Line = Simulated, White Line = Observed)

Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

POET2U - Stewarts Creek at Crighton Rd

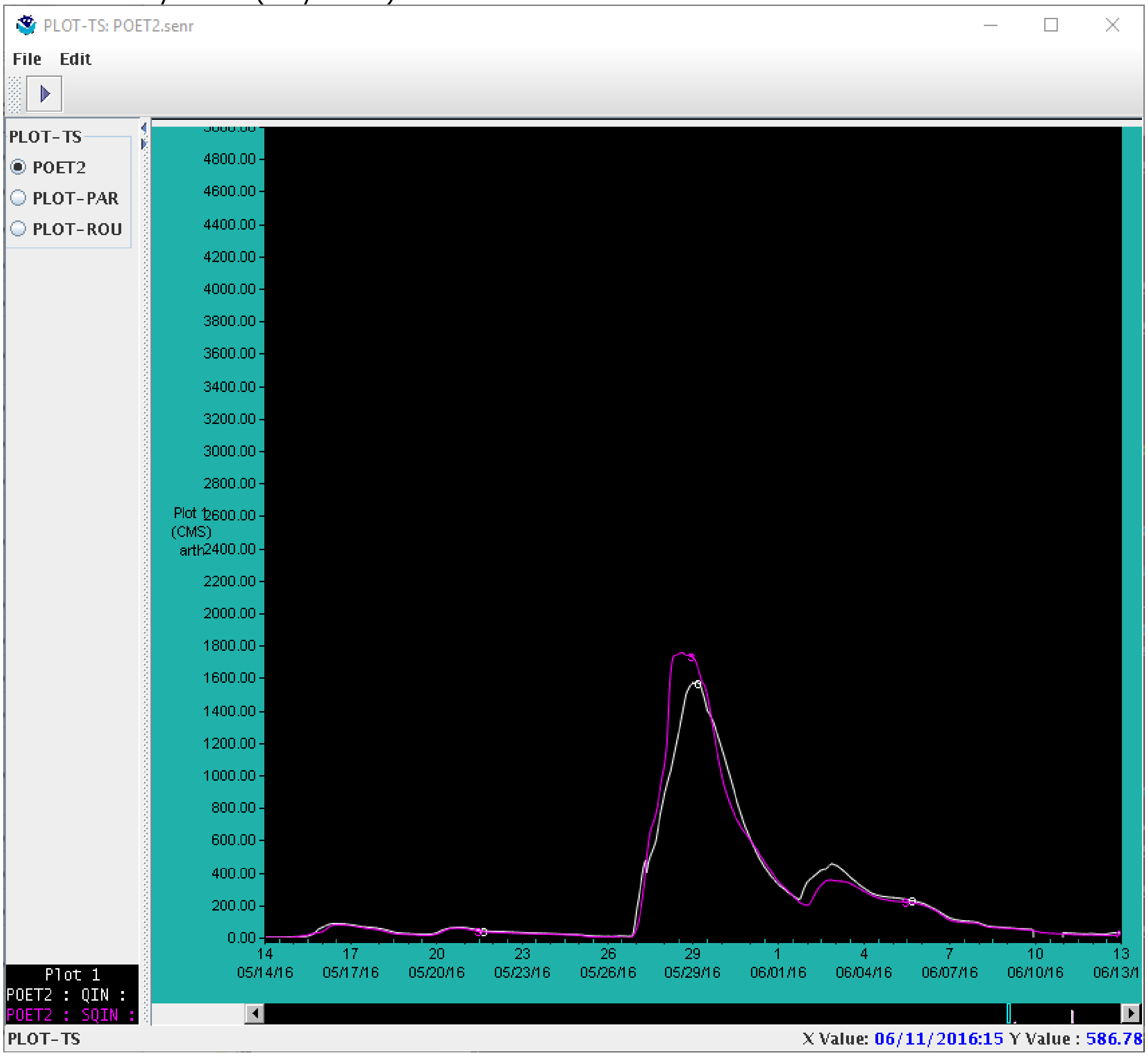
No observed data available

POET2M - Crystal Creek at FM1314

No observed data available

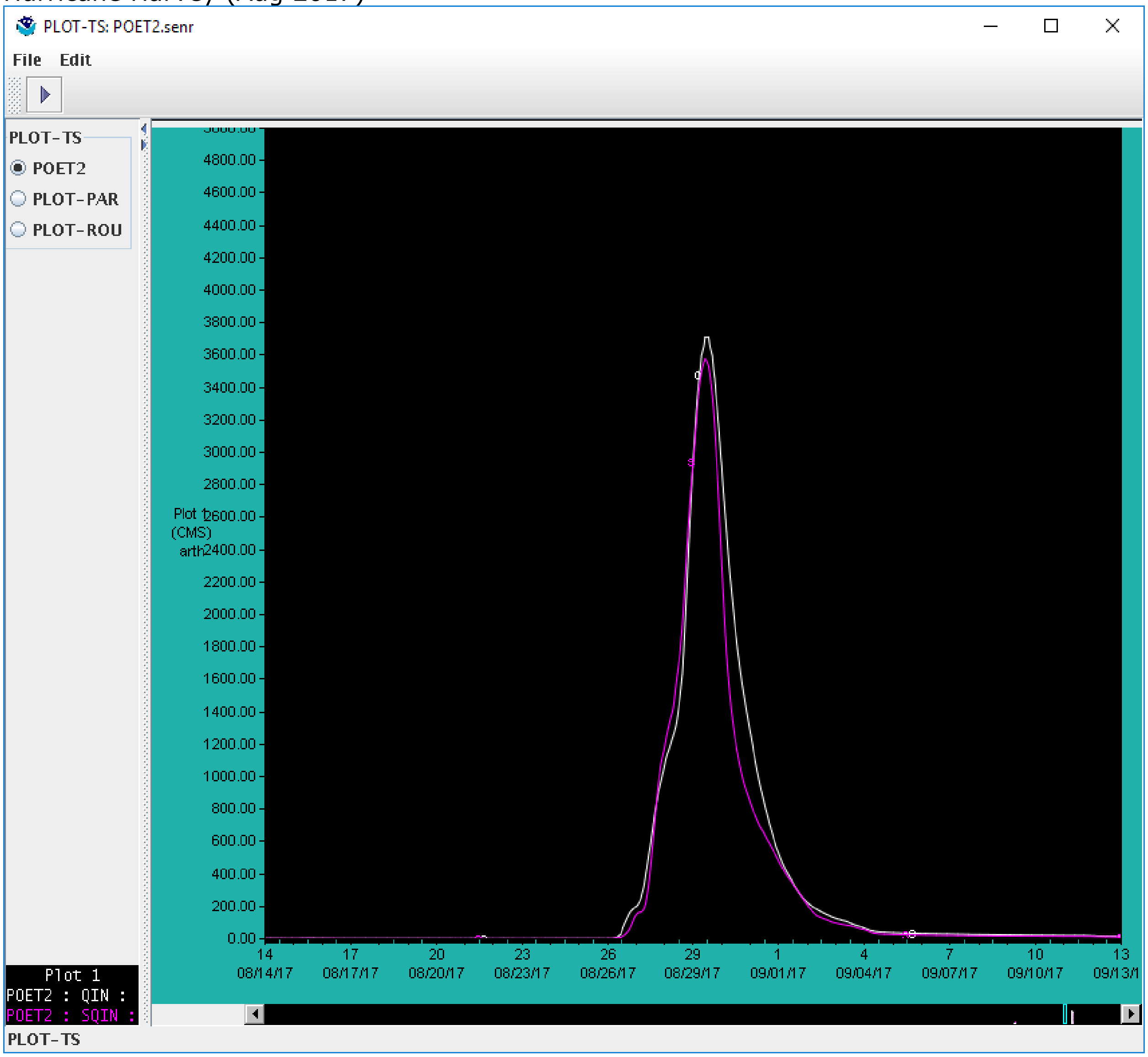
POET2 - W Fk San Jacinto Rv Abv Lk Houston nr Porter, TX

Memorial Day Flood (May 2016)



(Purple Line = Simulated, White Line = Observed)

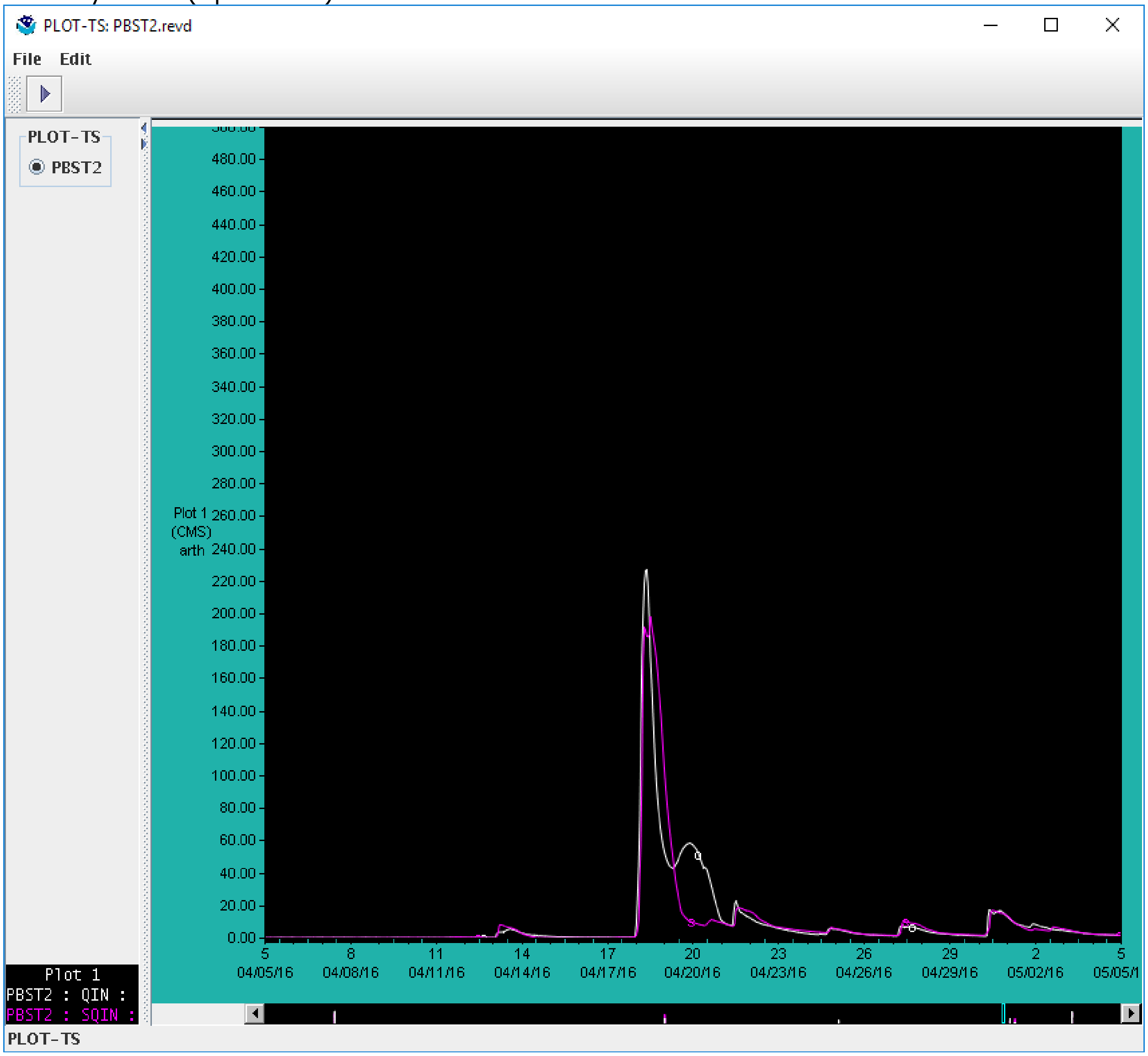
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

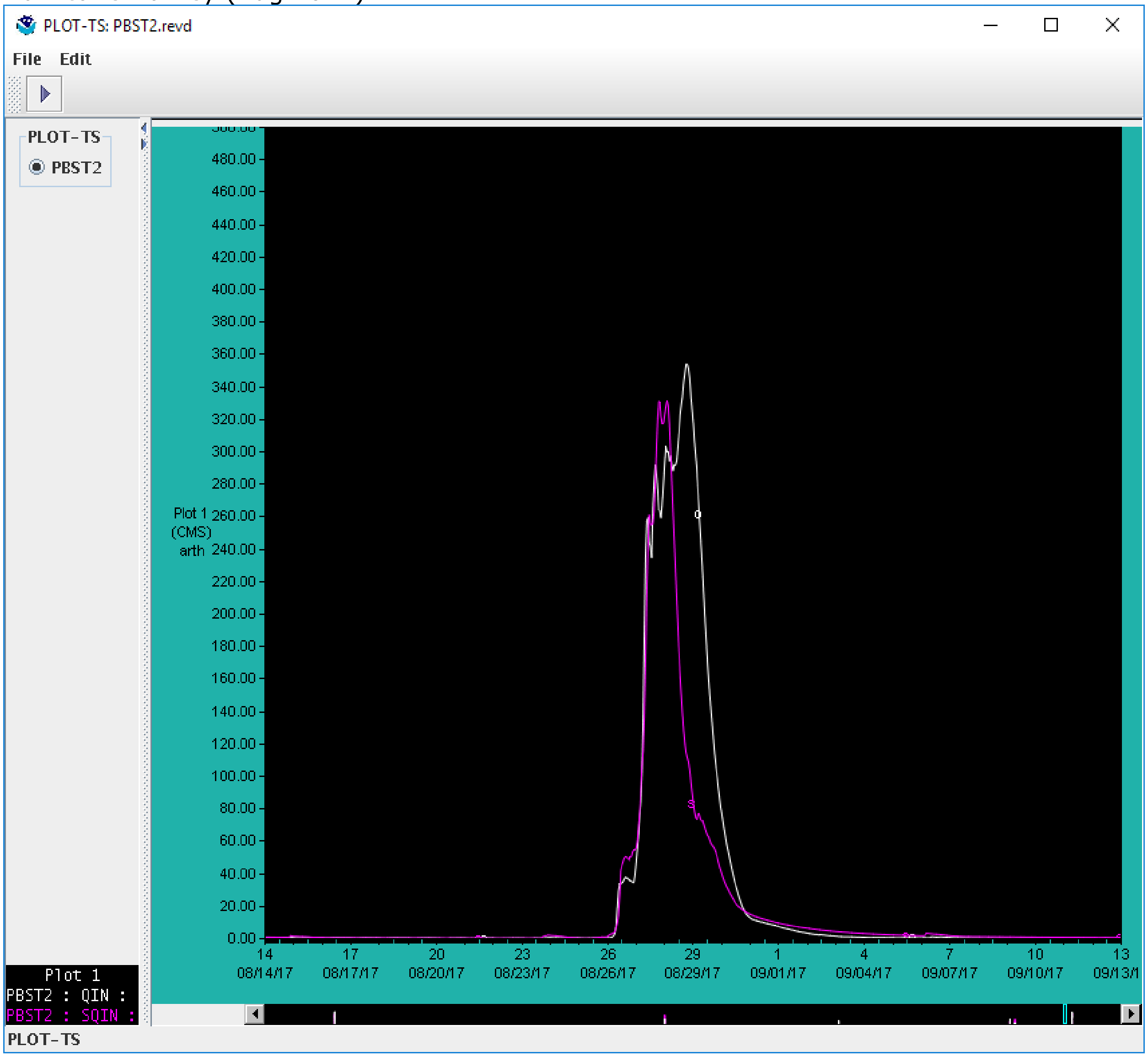
PBST2 - Panther Br nr Spring, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

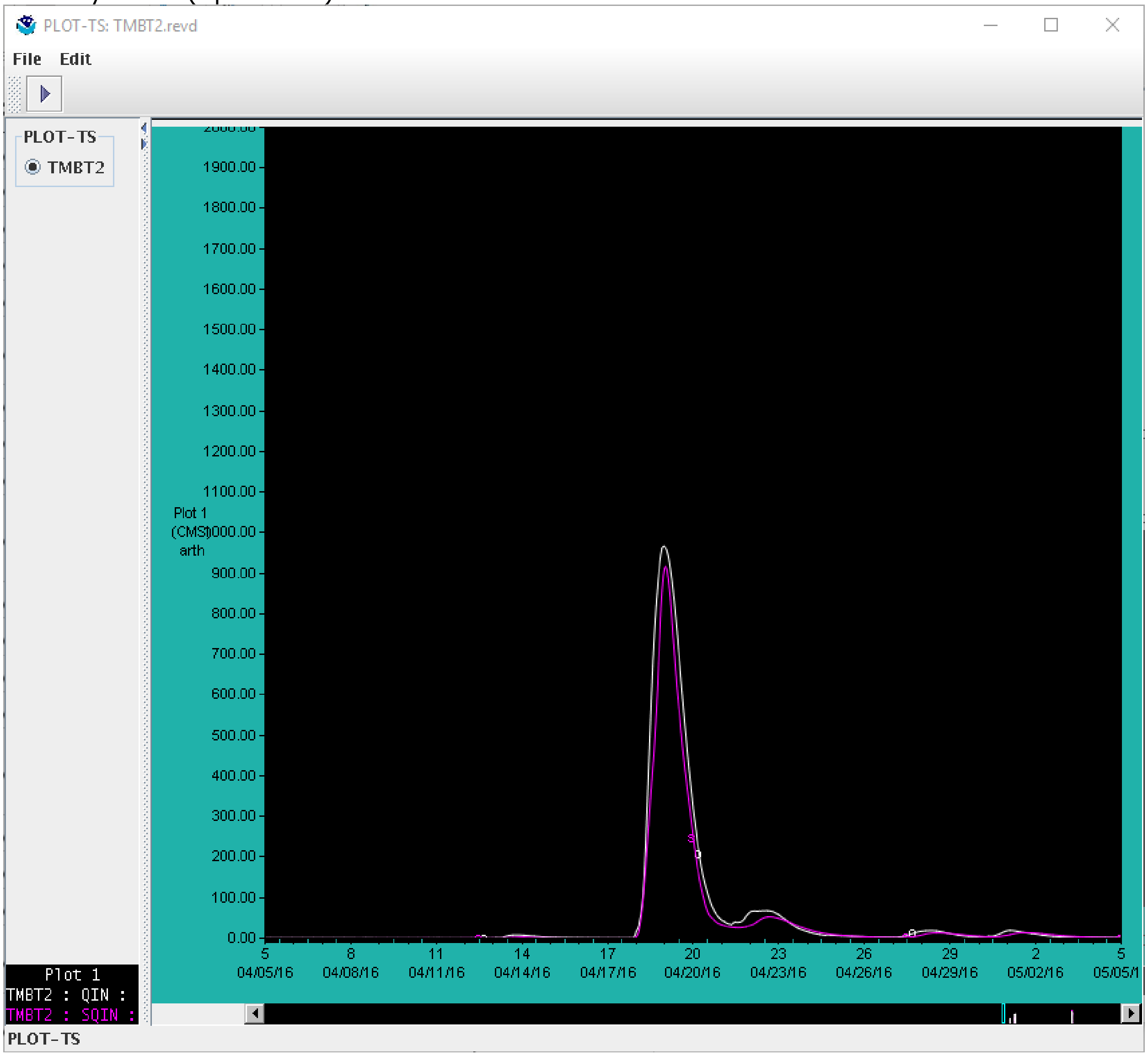
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

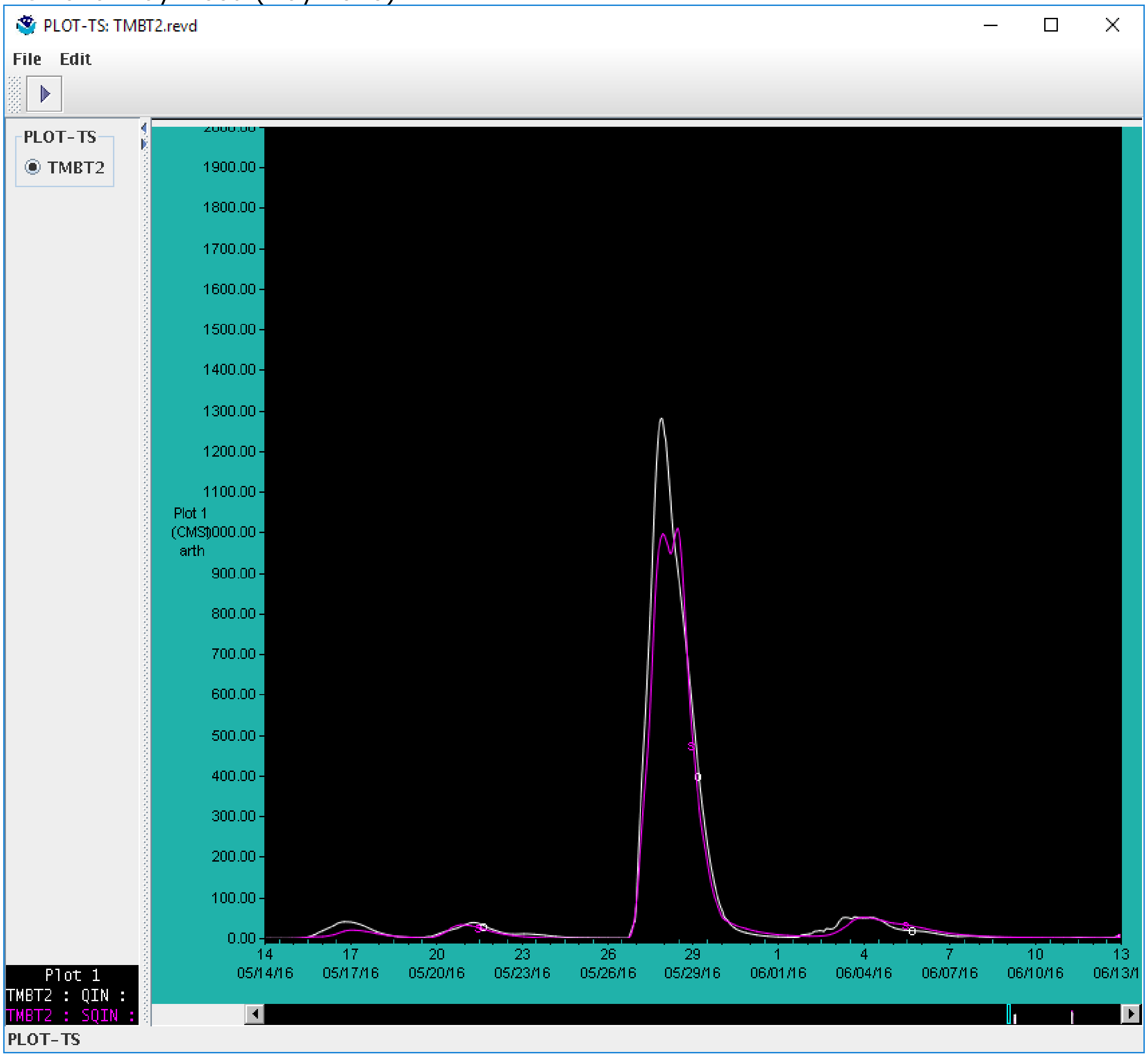
TMBT2 - Spring Ck nr Tomball, TX

Tax Day Flood (April 2016)



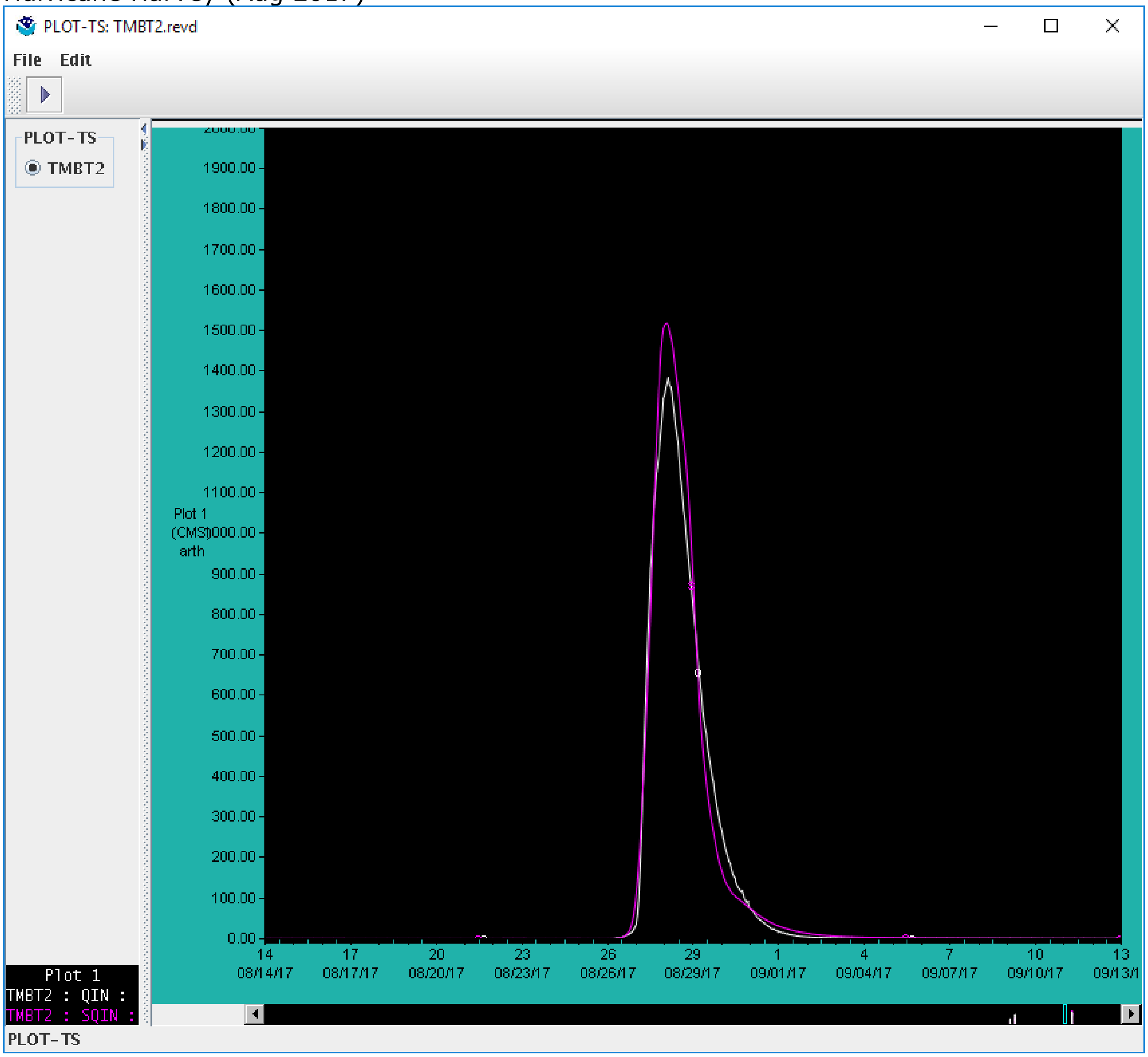
(Purple Line = Simulated, White Line = Observed)

Memorial Day Flood (May 2016)



(Purple Line = Simulated, White Line = Observed)

Hurricane Harvey (Aug 2017)



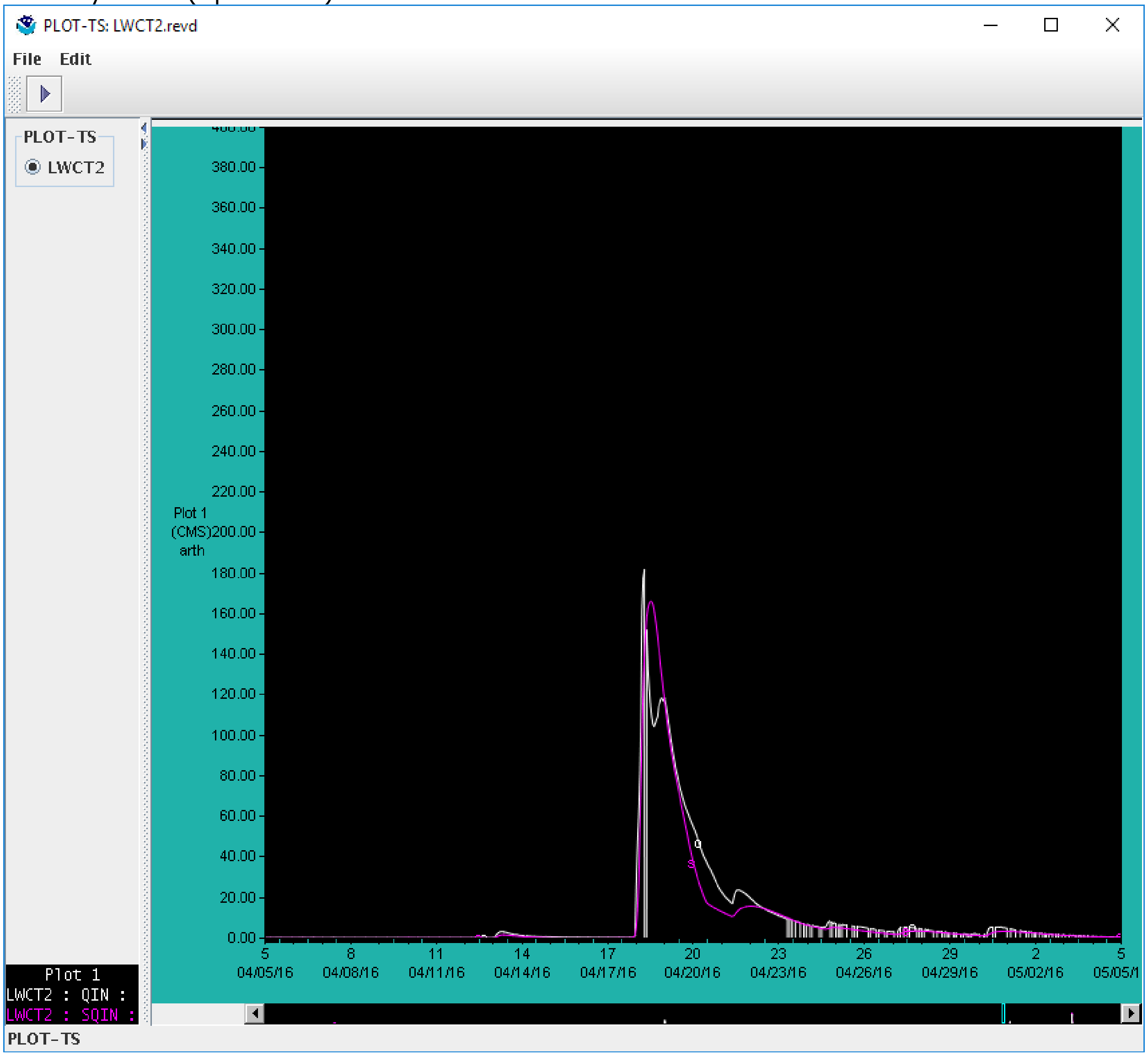
(Purple Line = Simulated, White Line = Observed)

SCKT2 - Spring Ck at Kuykendahl, The Woodlands, TX

No observed data available

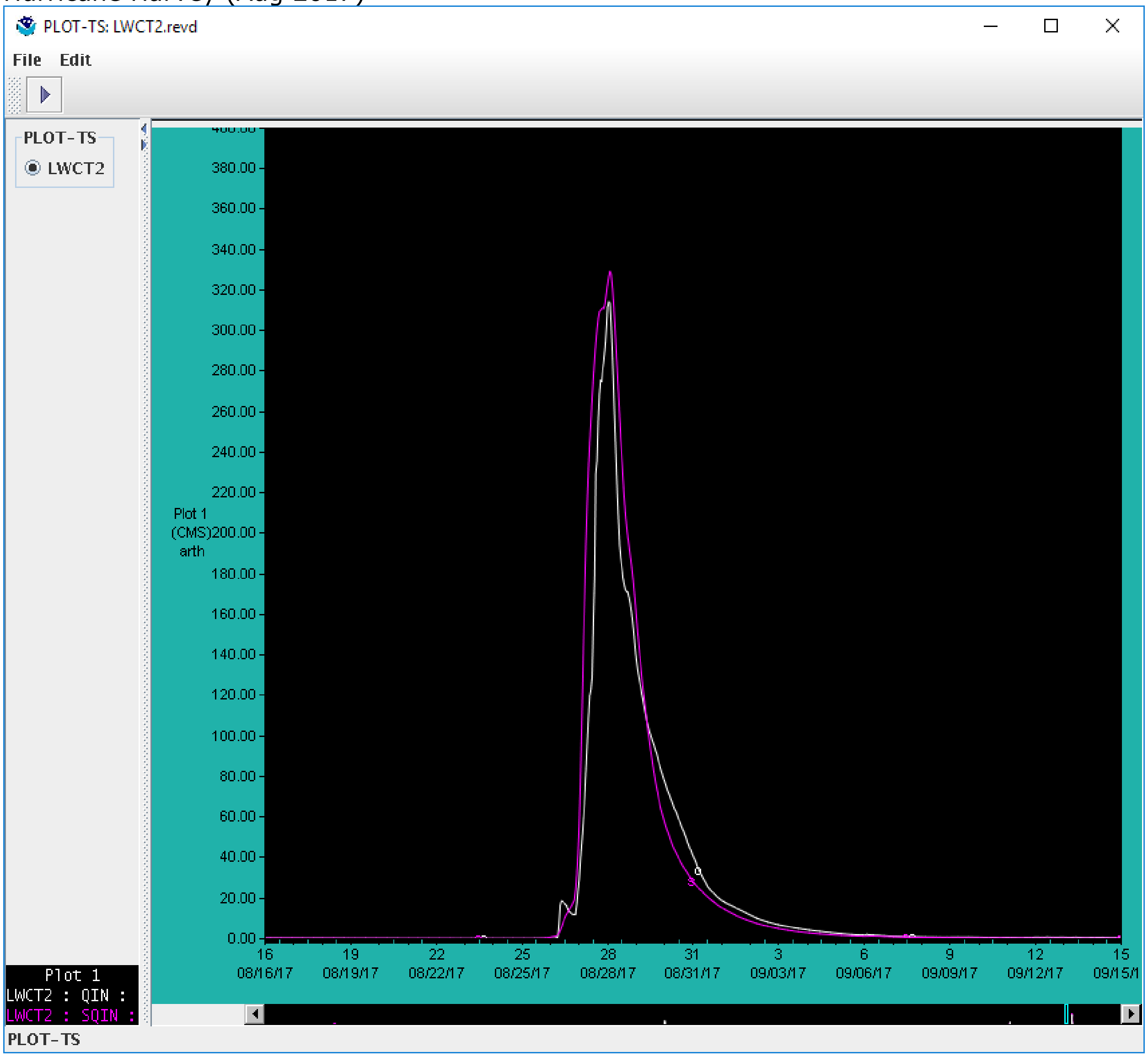
LWCT2 - Willow Ck nr Tomball, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

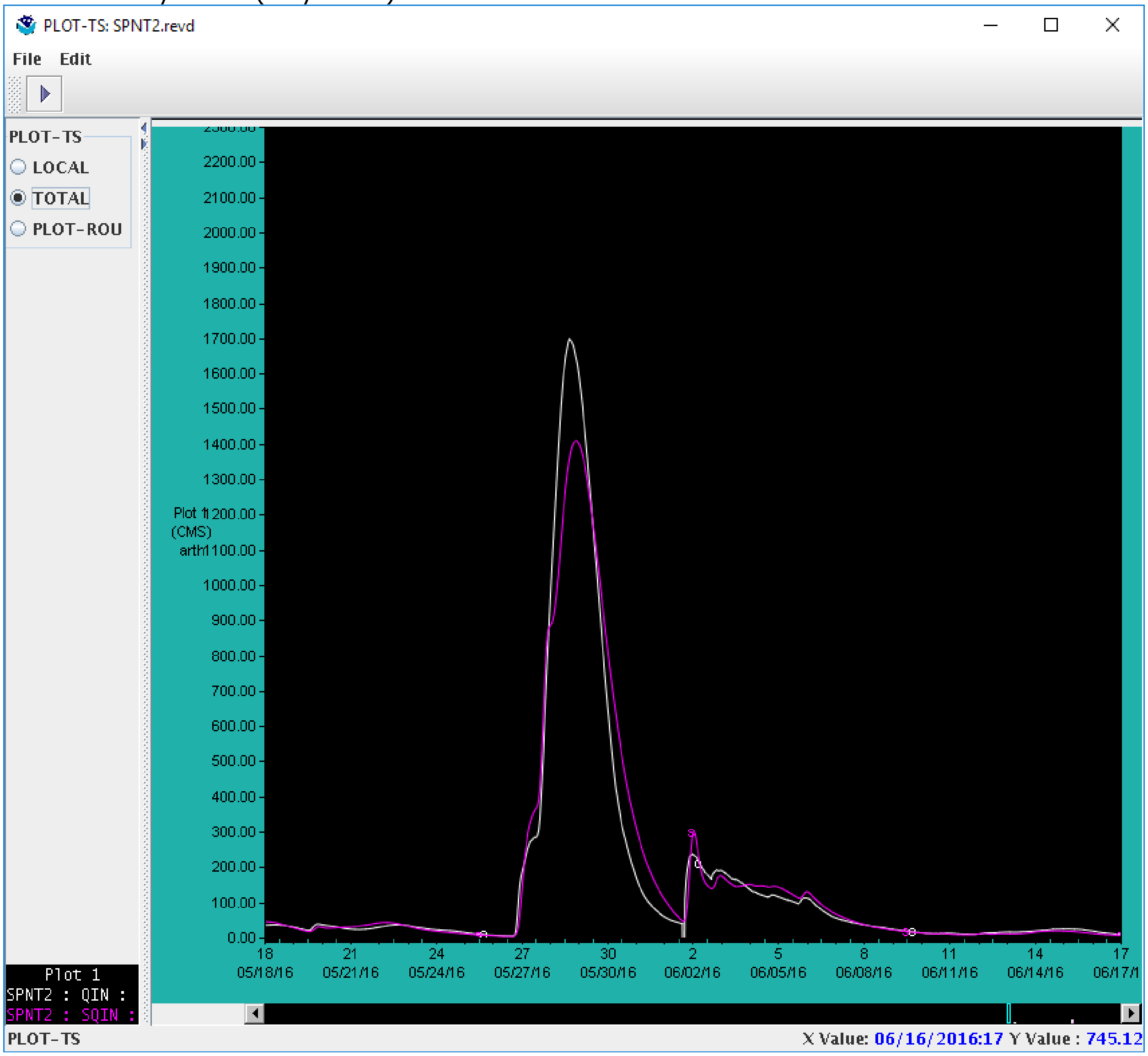
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

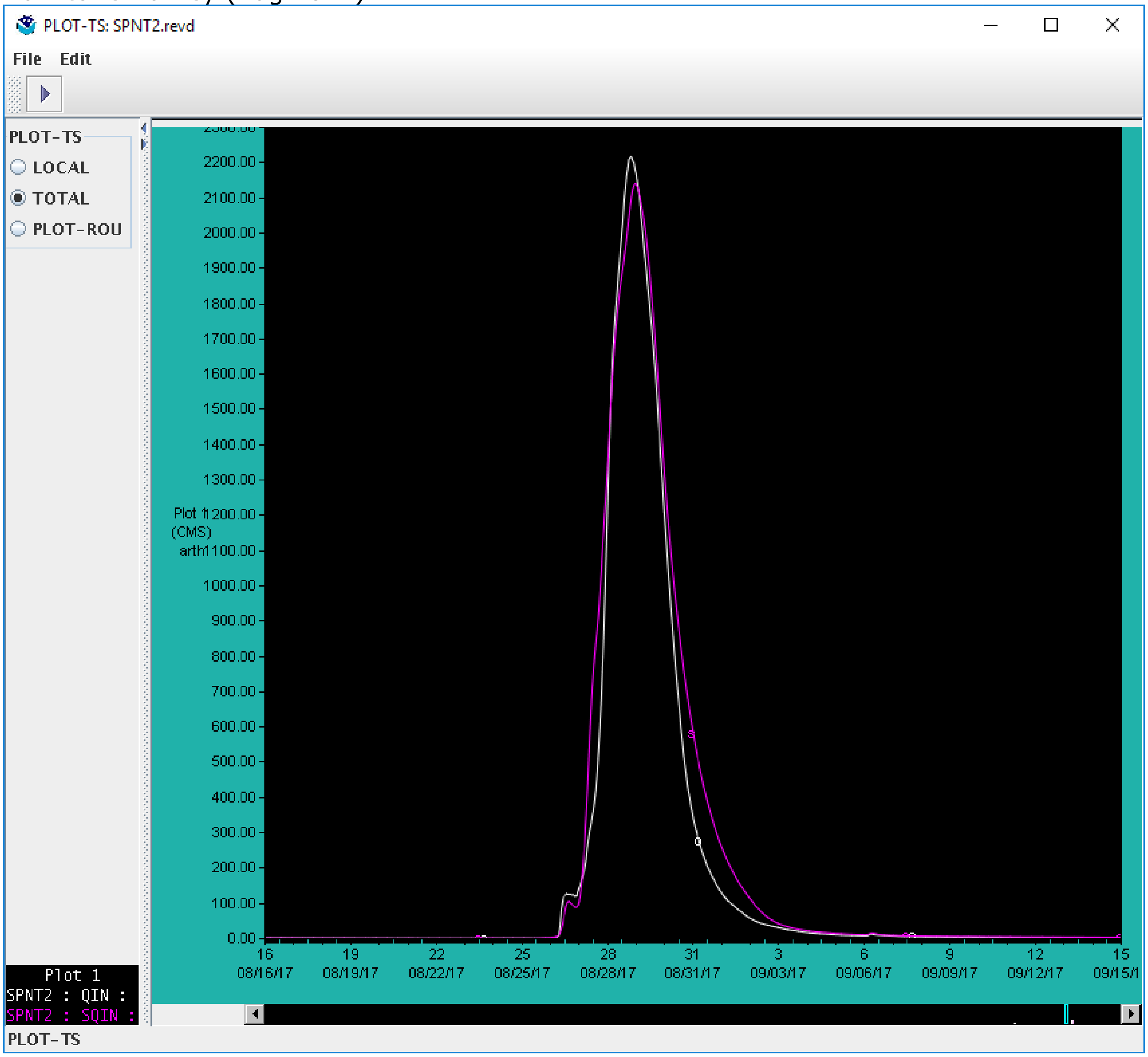
SPNT2 - Spring Ck nr Spring, TX

Memorial Day Flood (May 2016)



(Purple Line = Simulated, White Line = Observed)

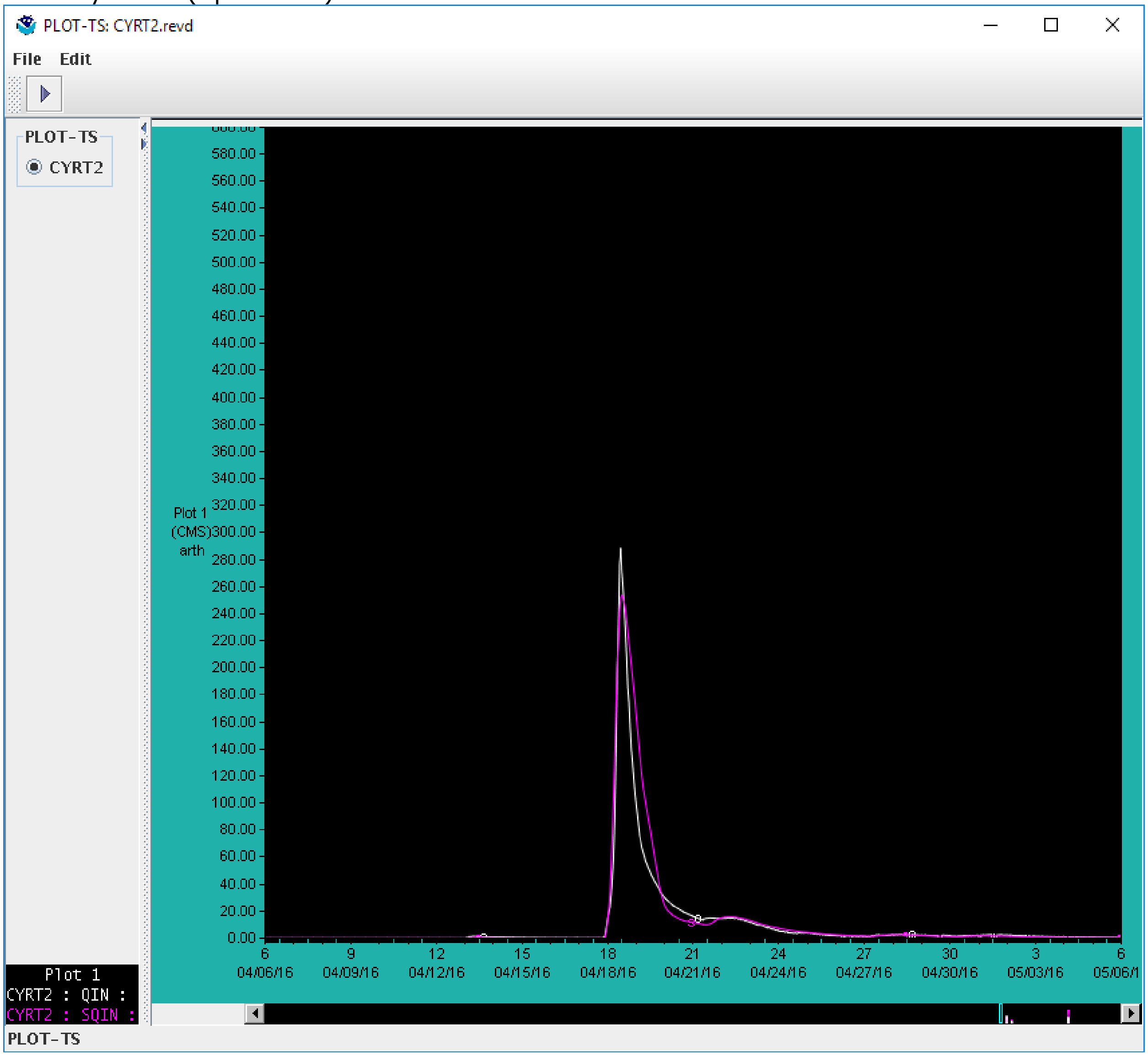
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

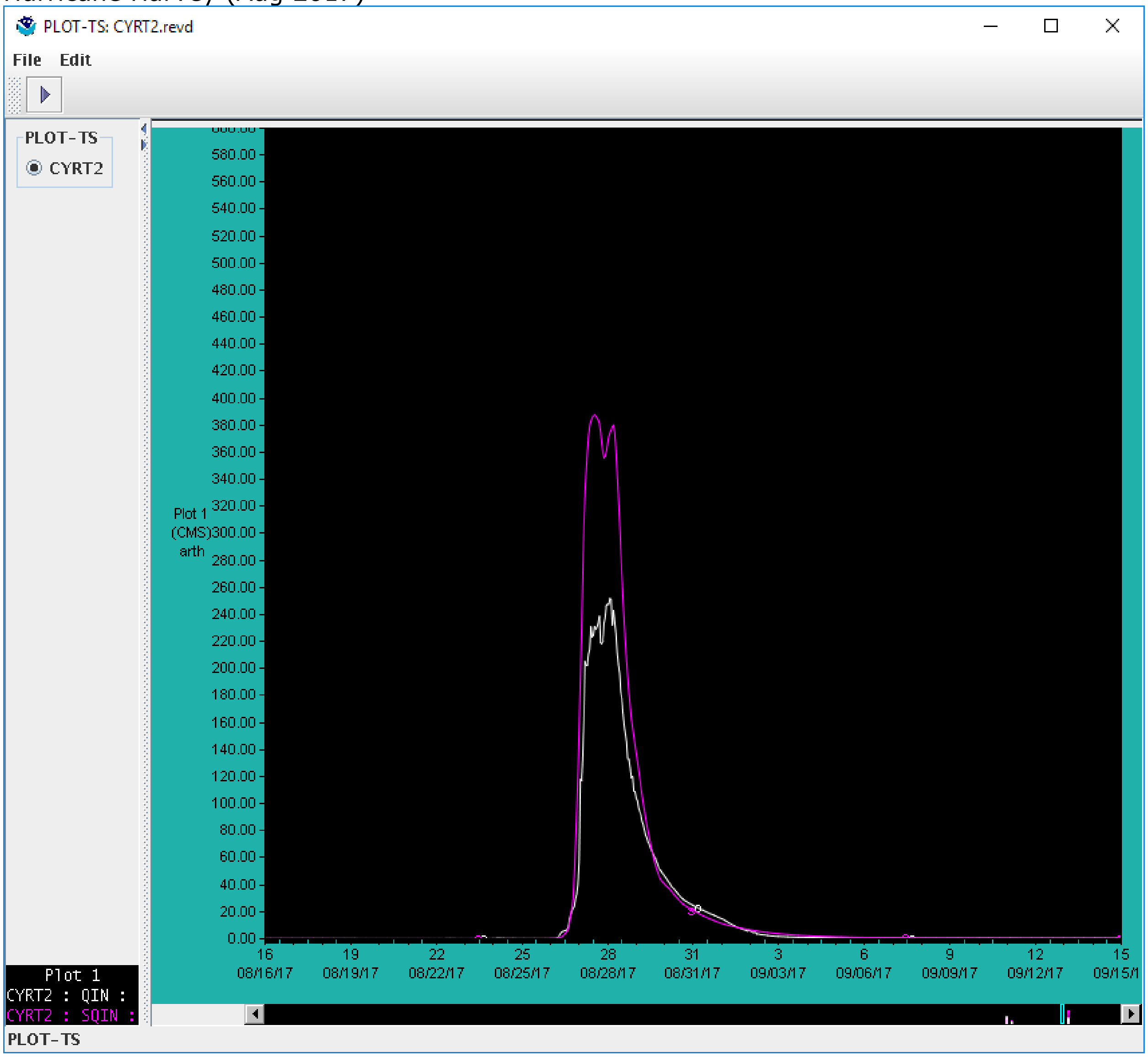
CYRT2 - Little Cypress Ck nr Cypress, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

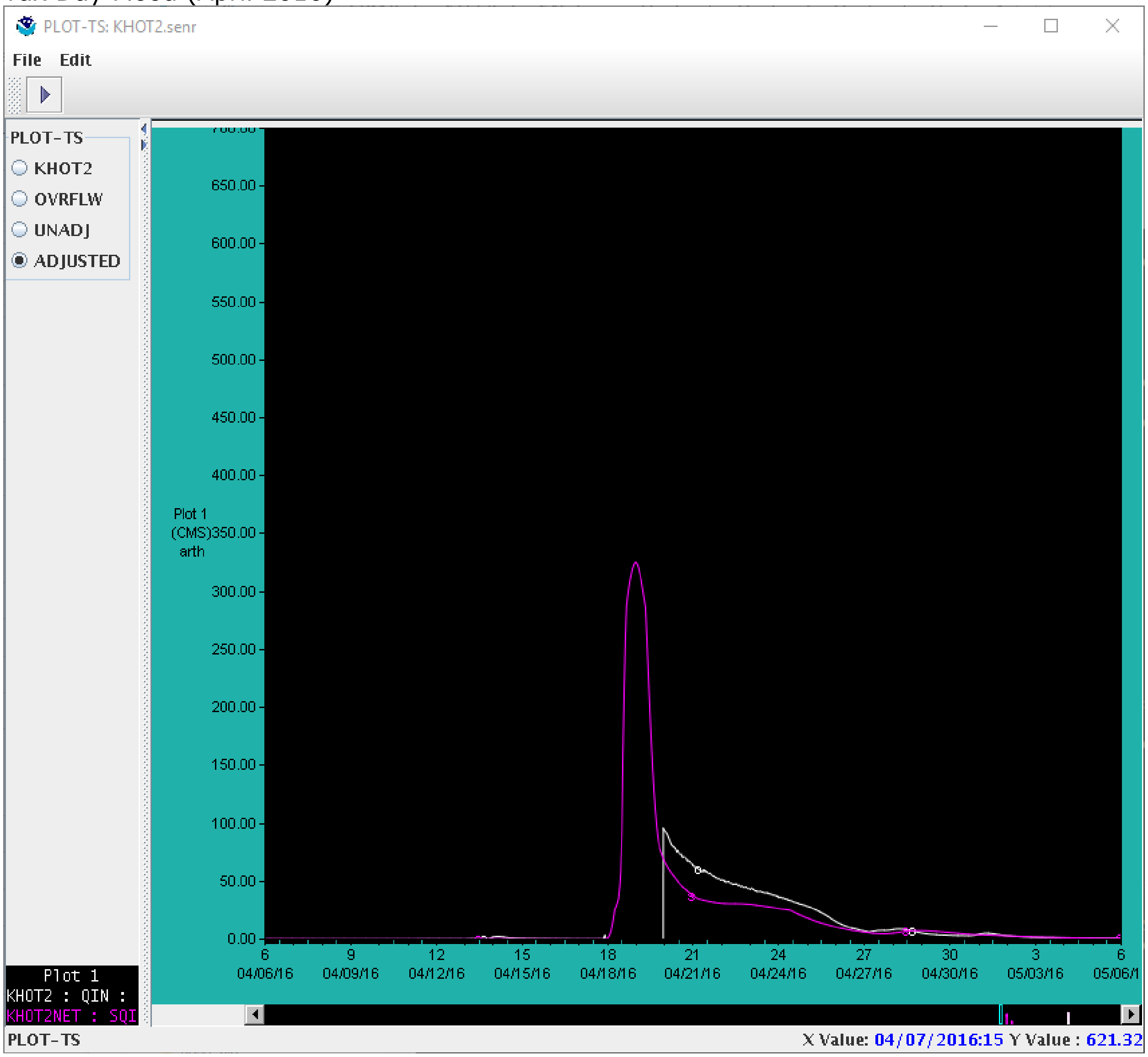
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

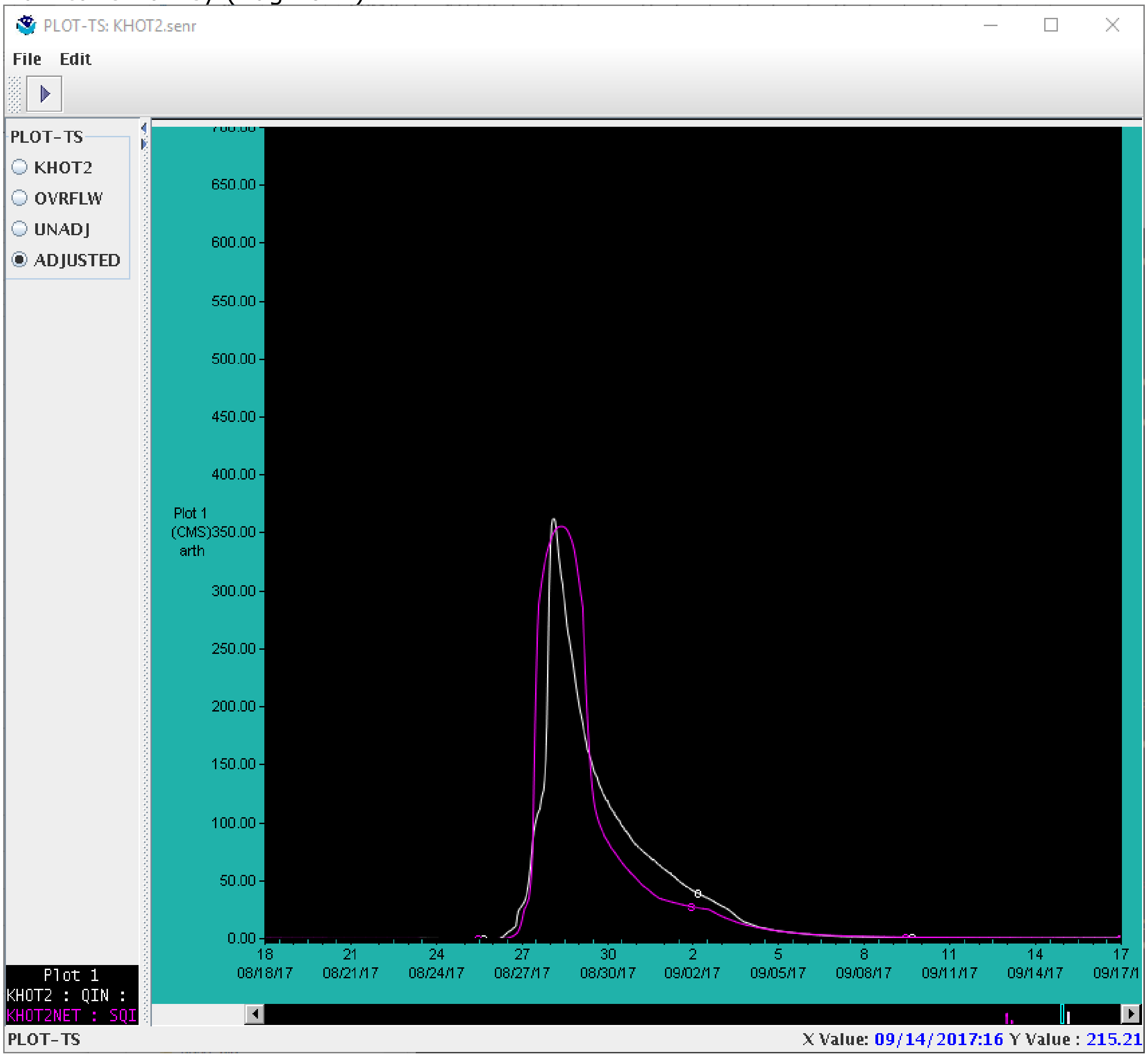
KHOT2 - Cypress Ck at Katy-Hockley Rd nr Hockley, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

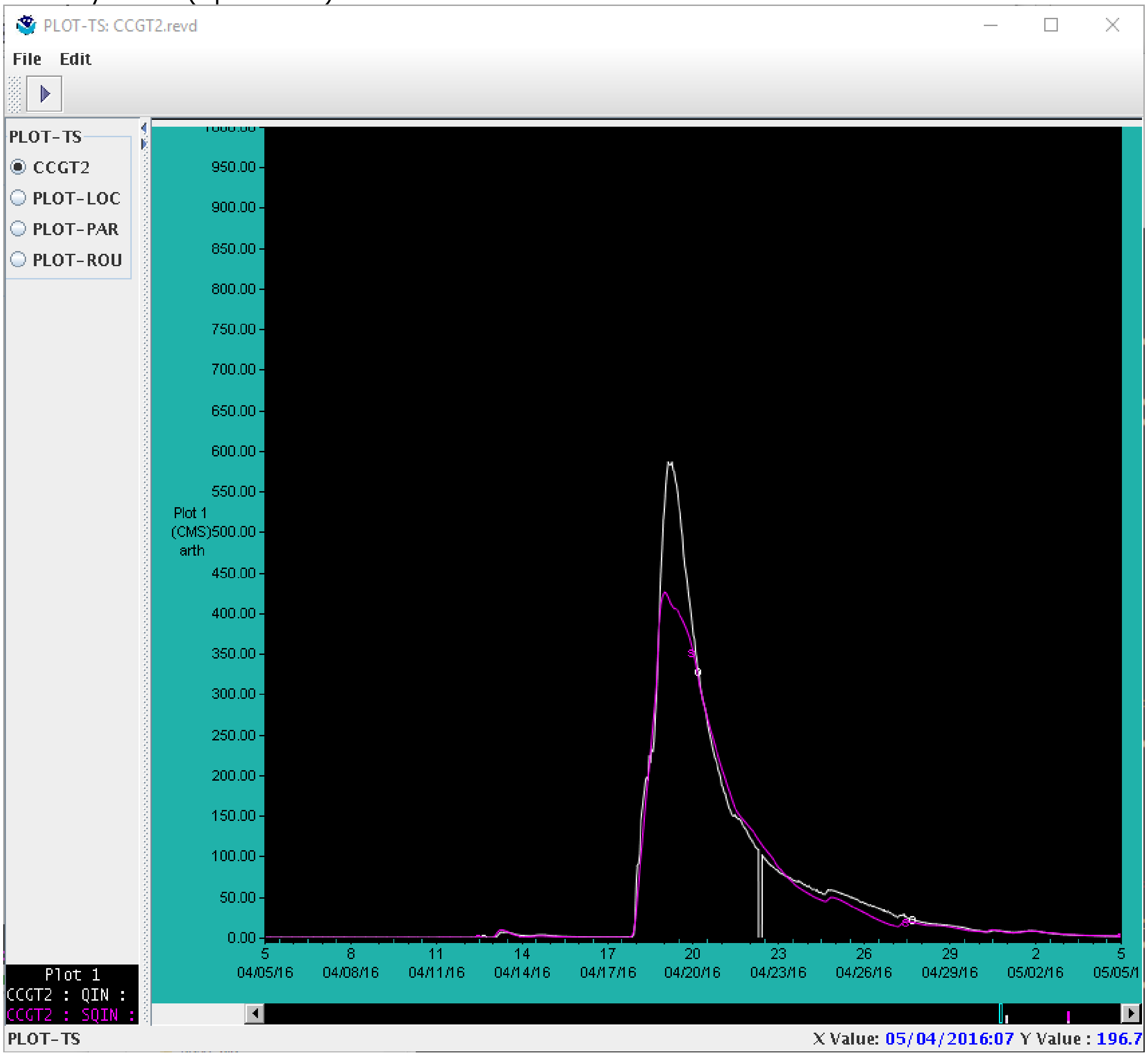
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

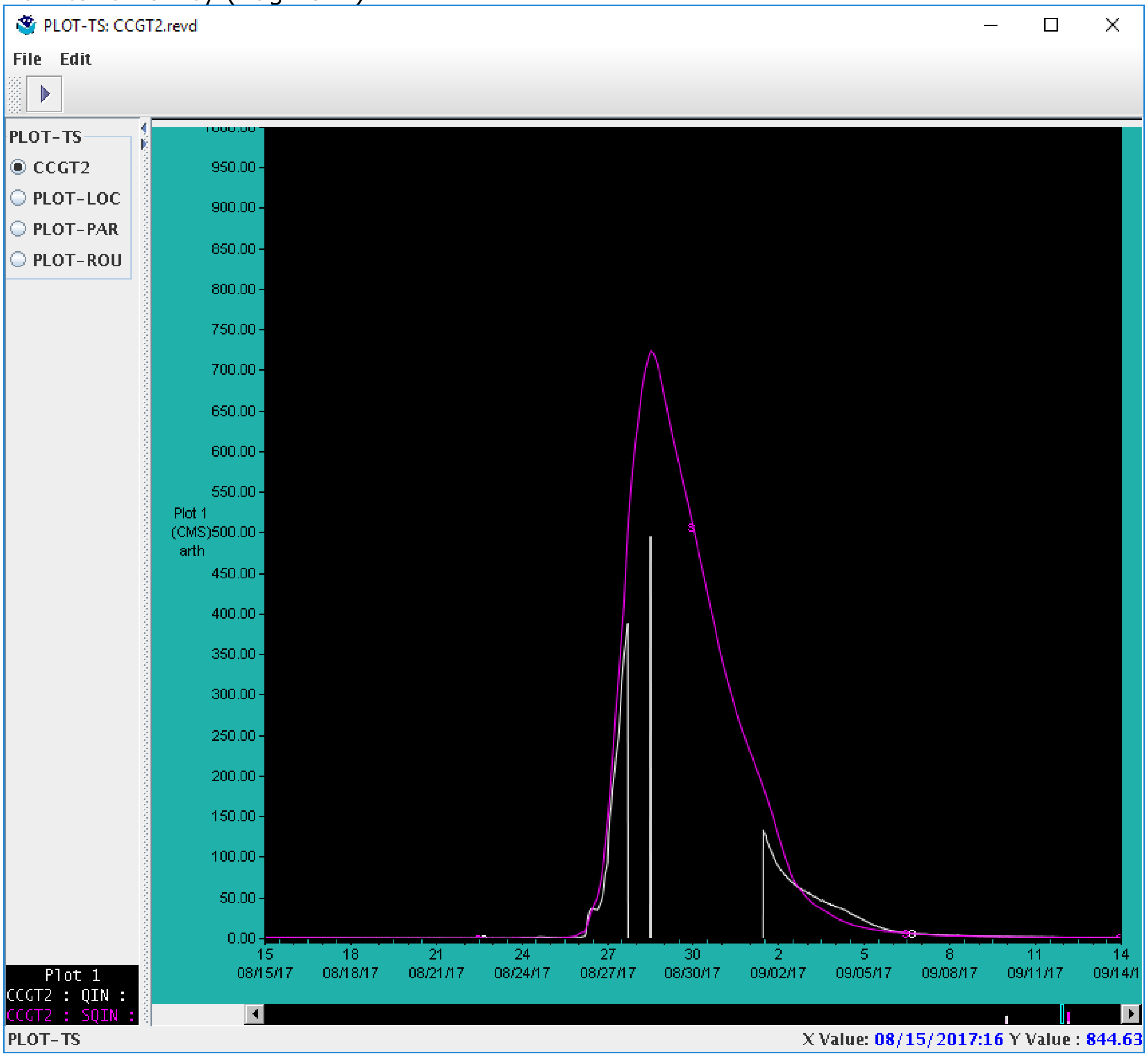
CCGT2 - Cypress Ck at Grant Rd nr Cypress, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

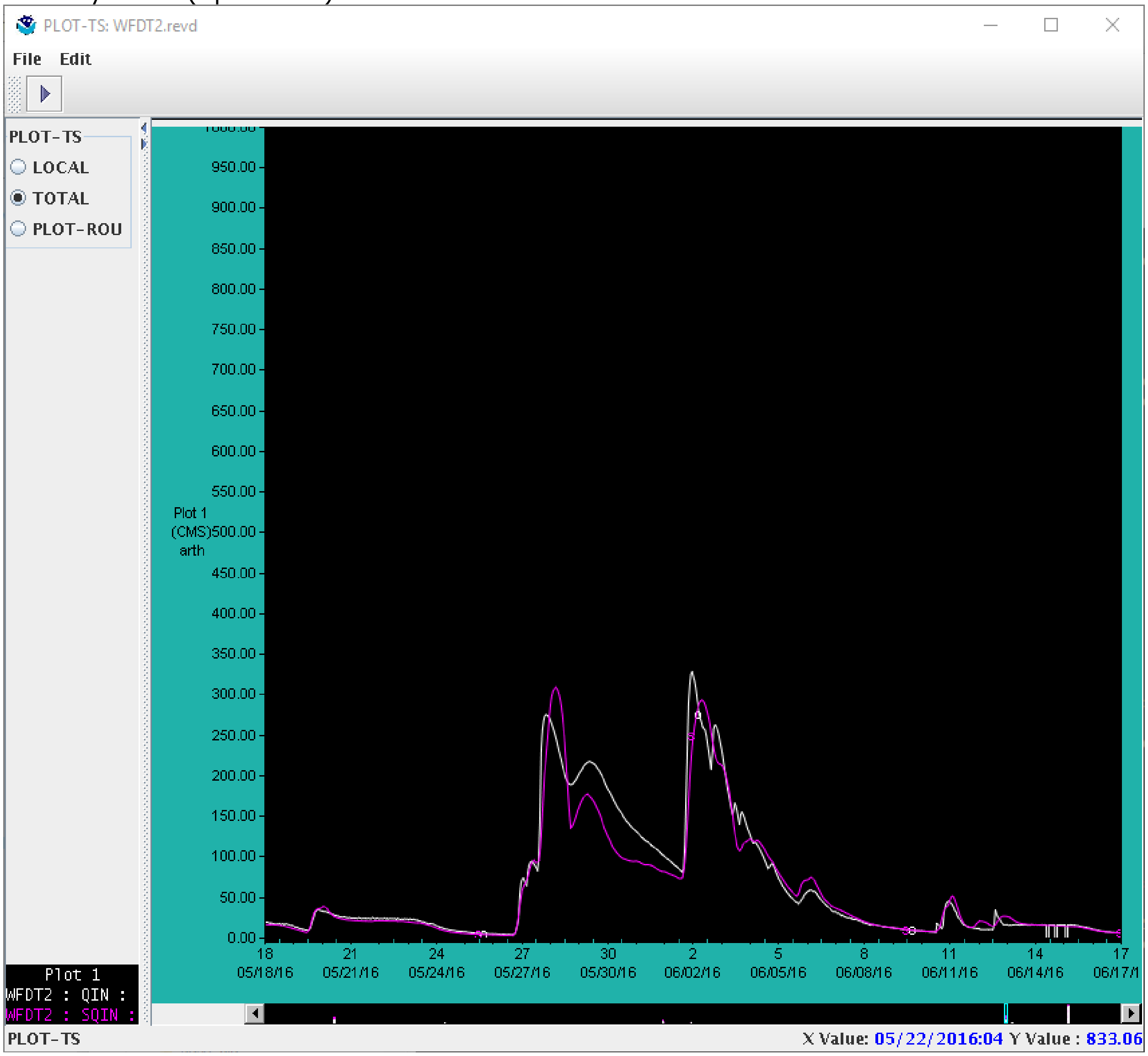
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

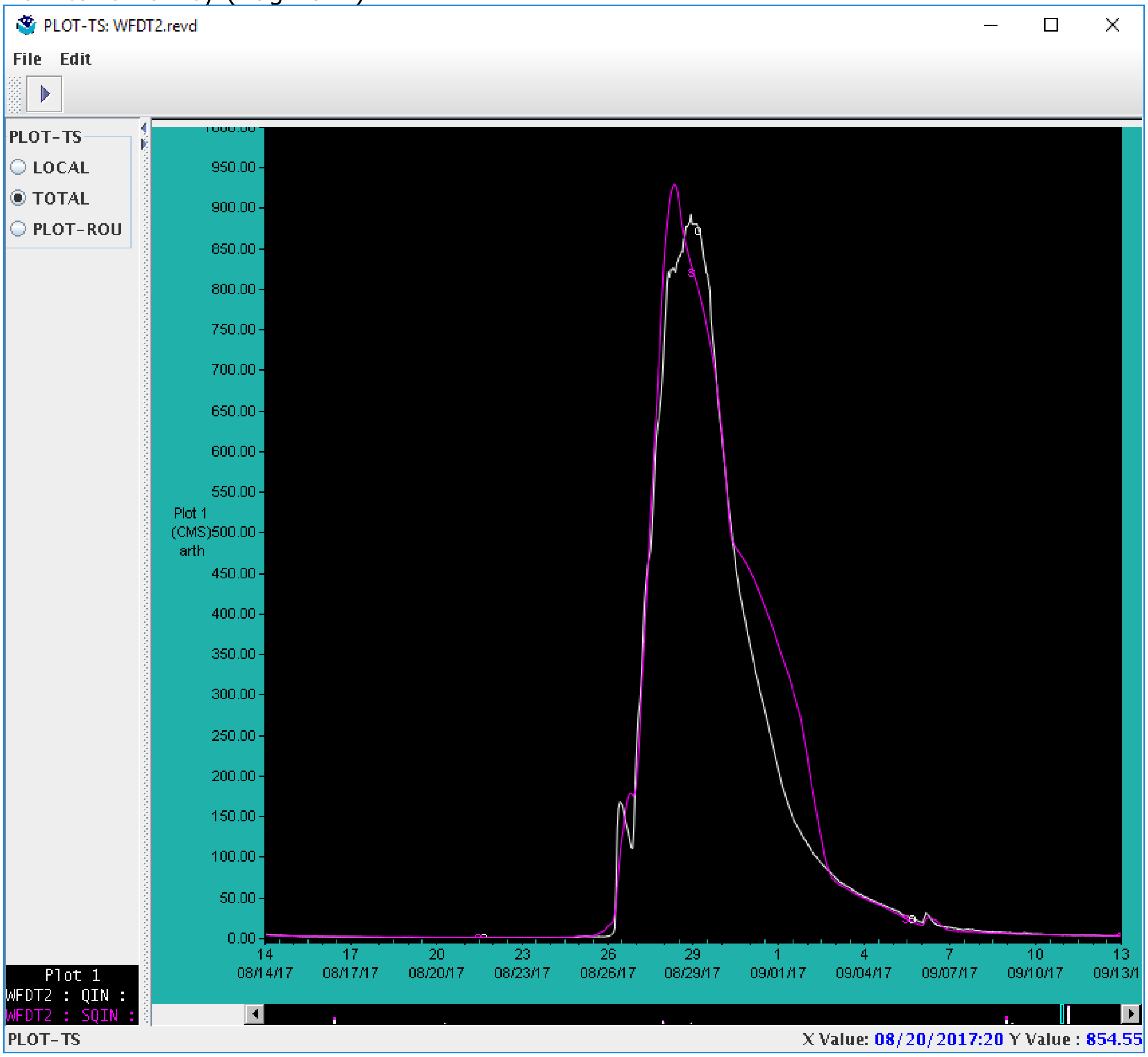
WFDT2 - Cypress Ck nr Westfield, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

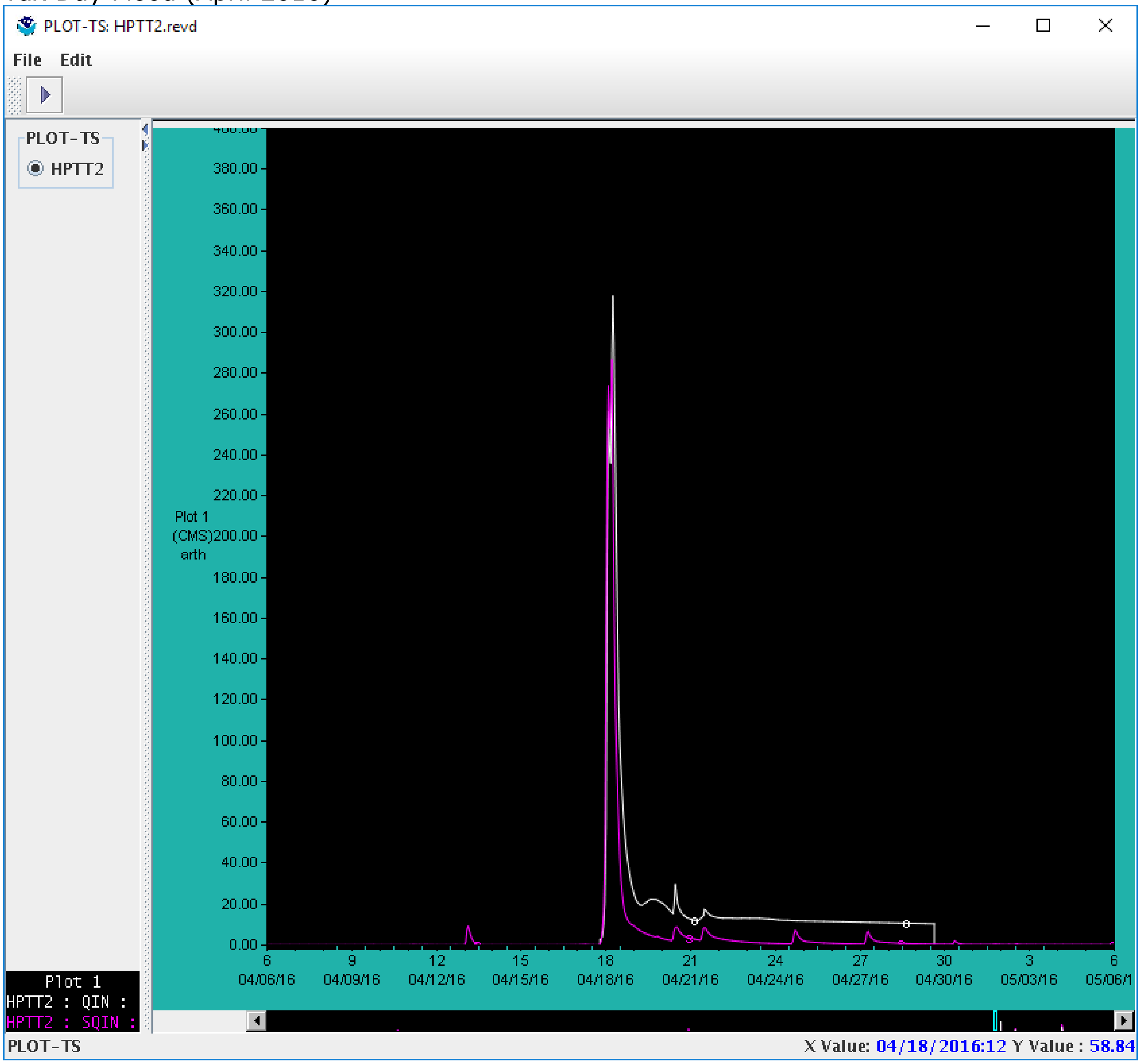
HMMT2 - W Fk San Jacinto Rv nr Humble, TX

No observed data available

Buffalo Bayou Basin

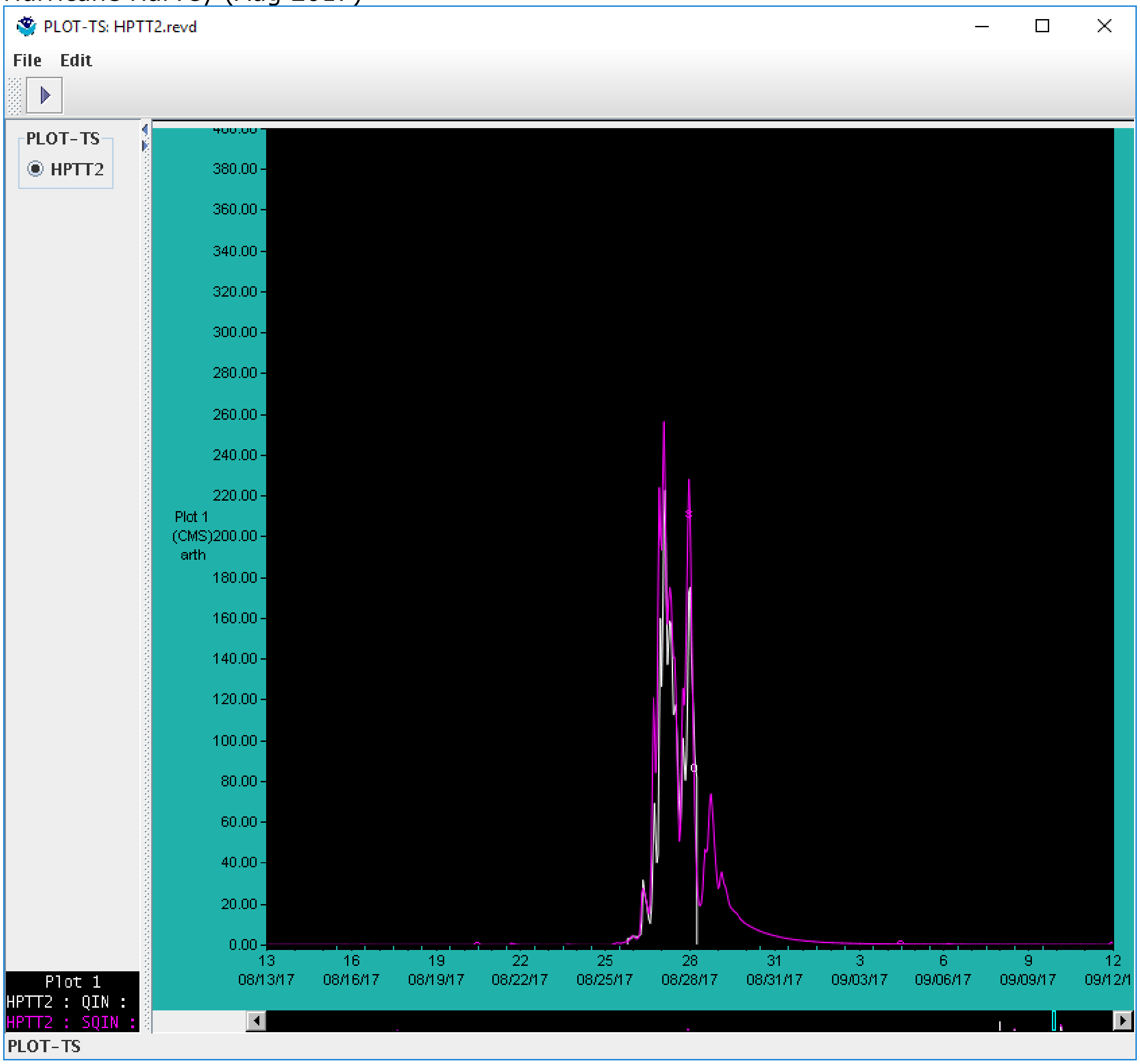
HPTT2 - Horsepen Creek at Trailside Drive

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

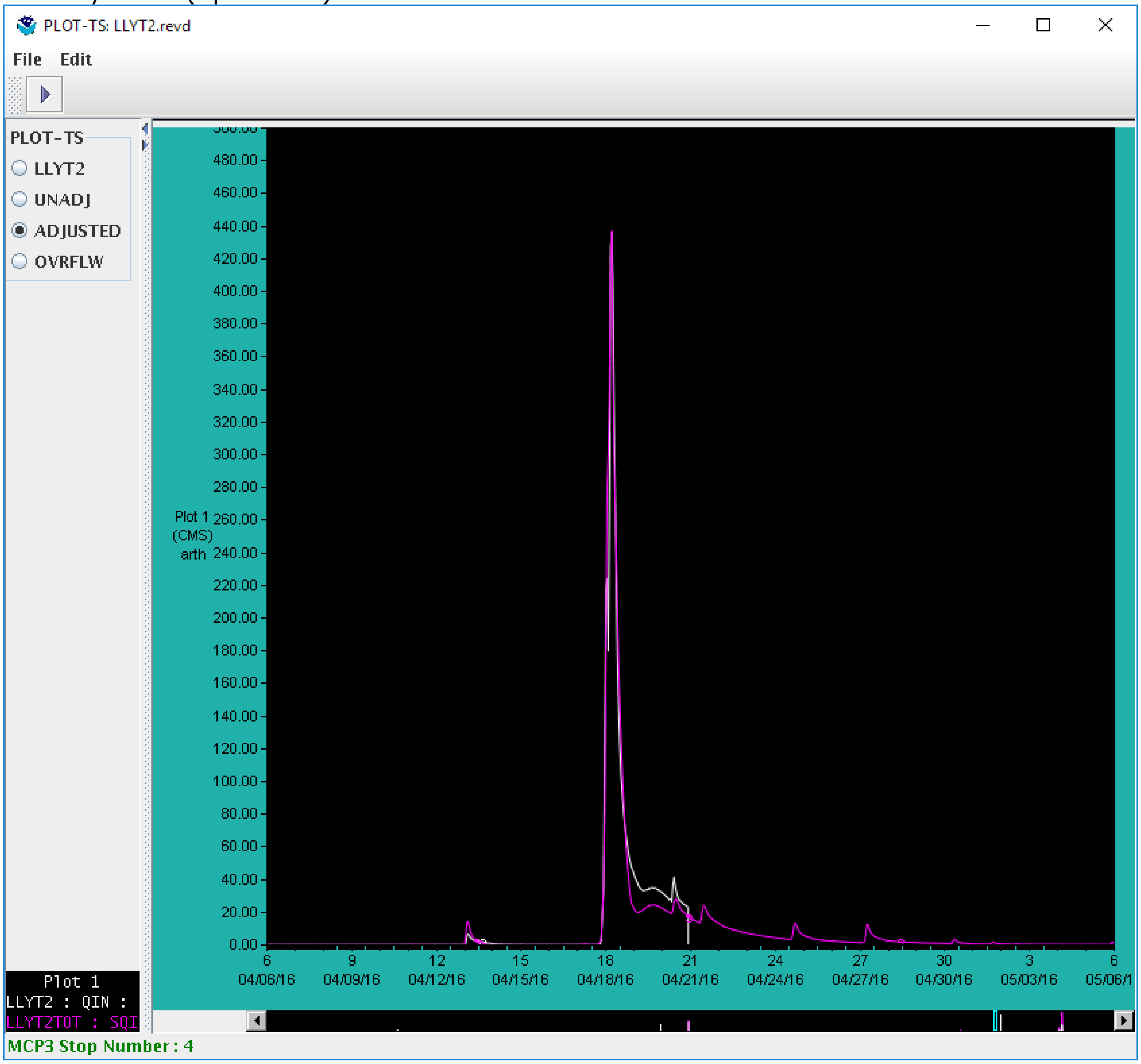
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

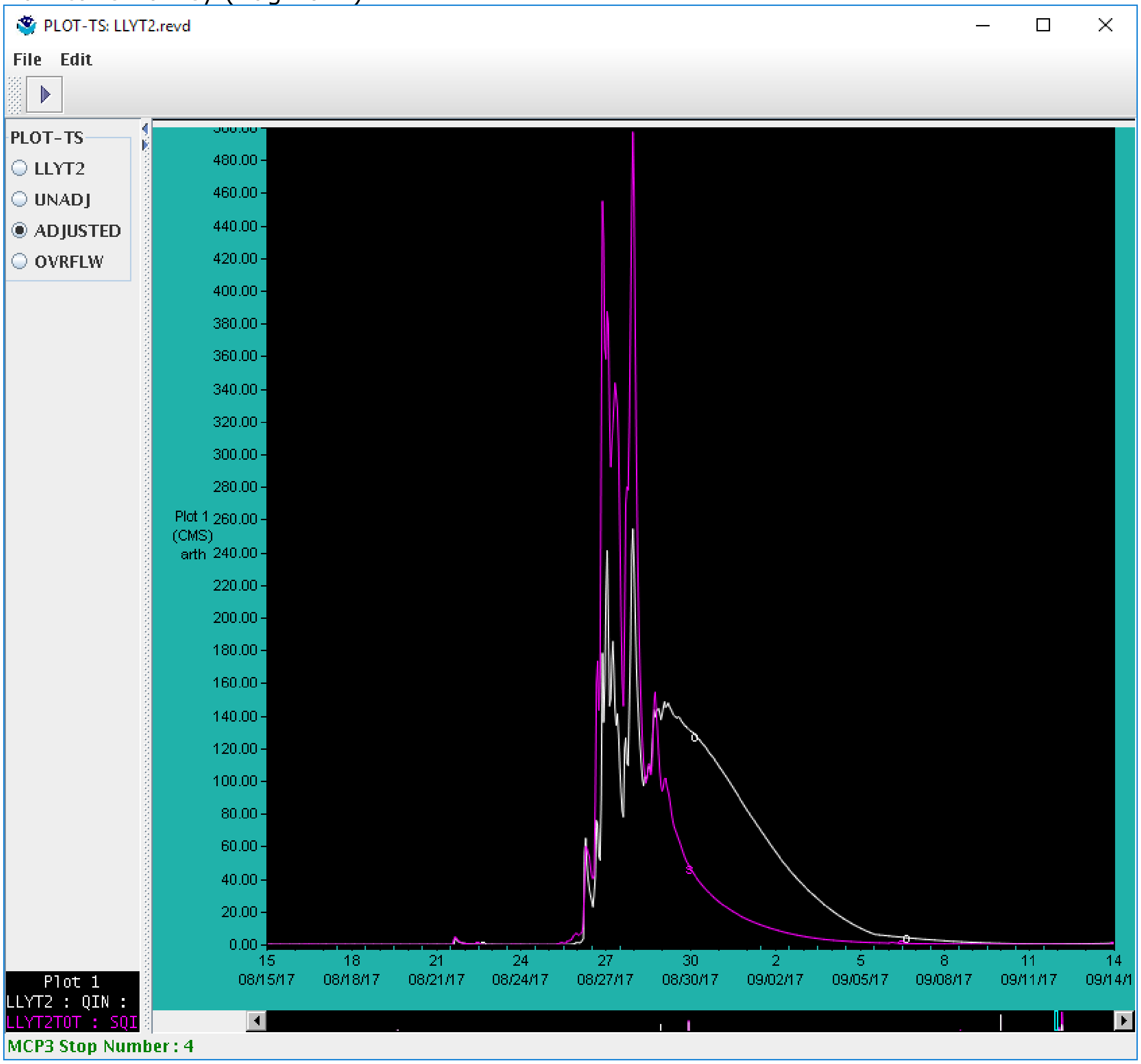
LLYT2 - Langham Ck at W Little York Rd nr Addicks, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

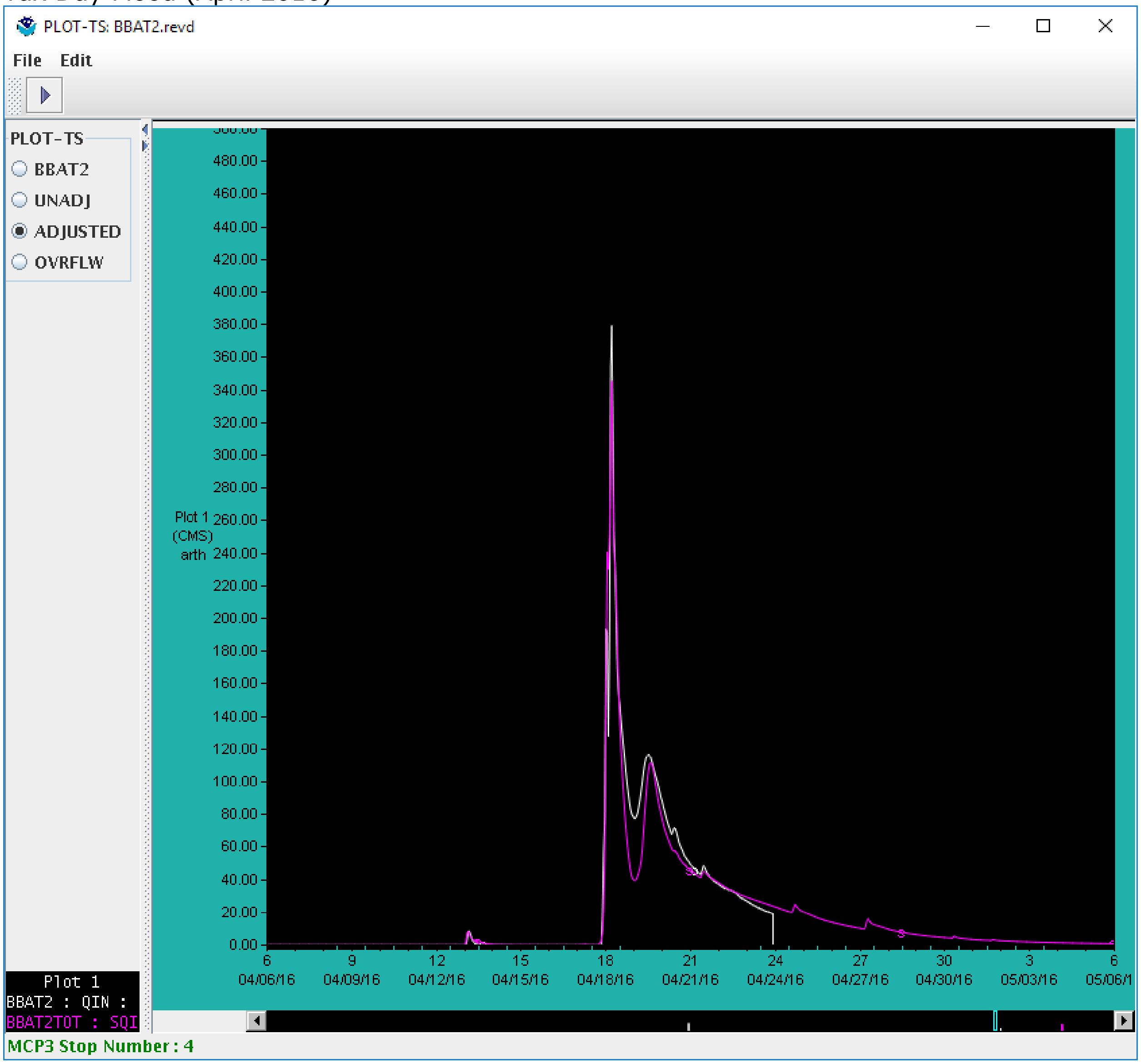
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

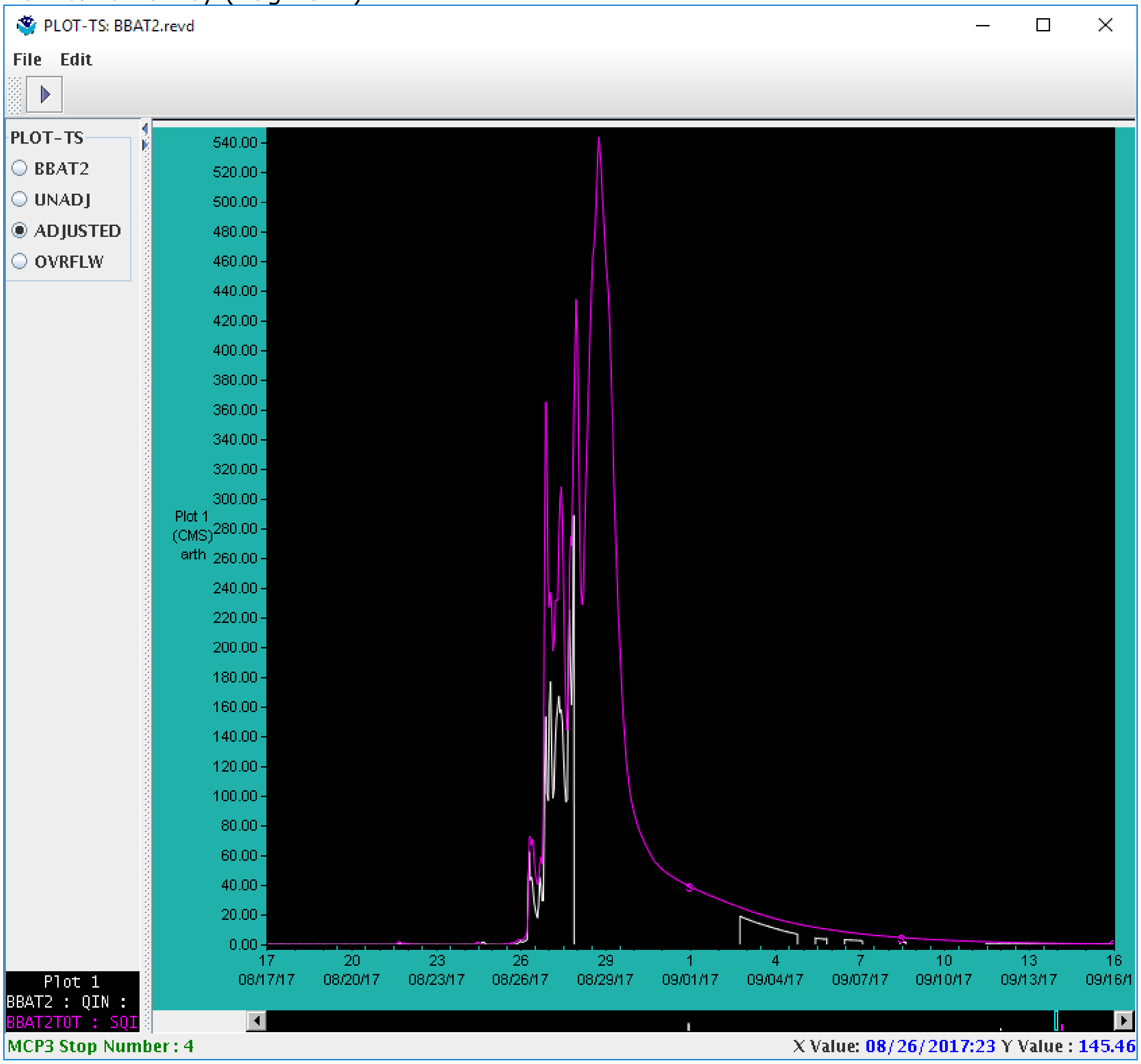
BBAT2 - Bear Ck nr Barker, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

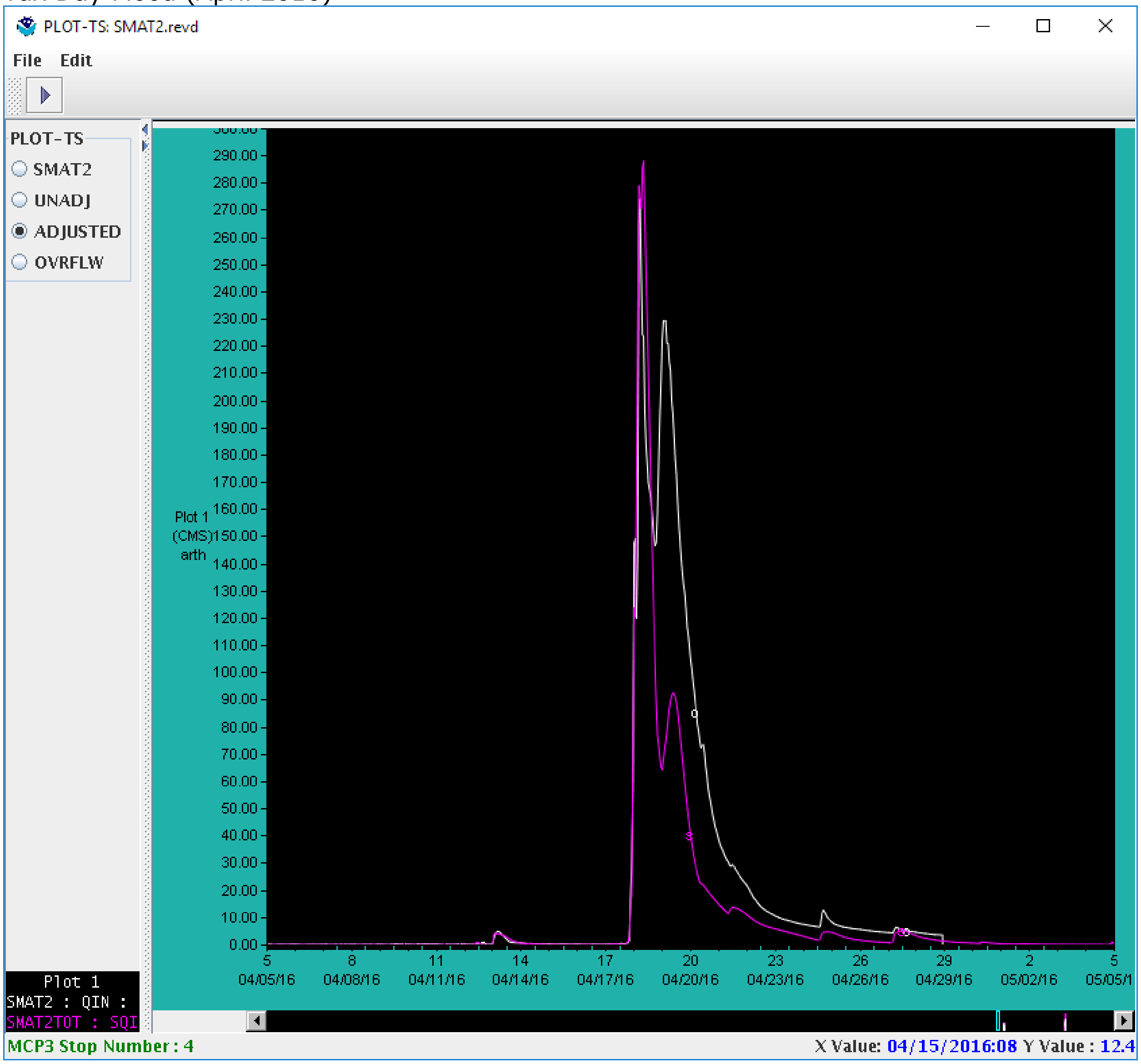
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

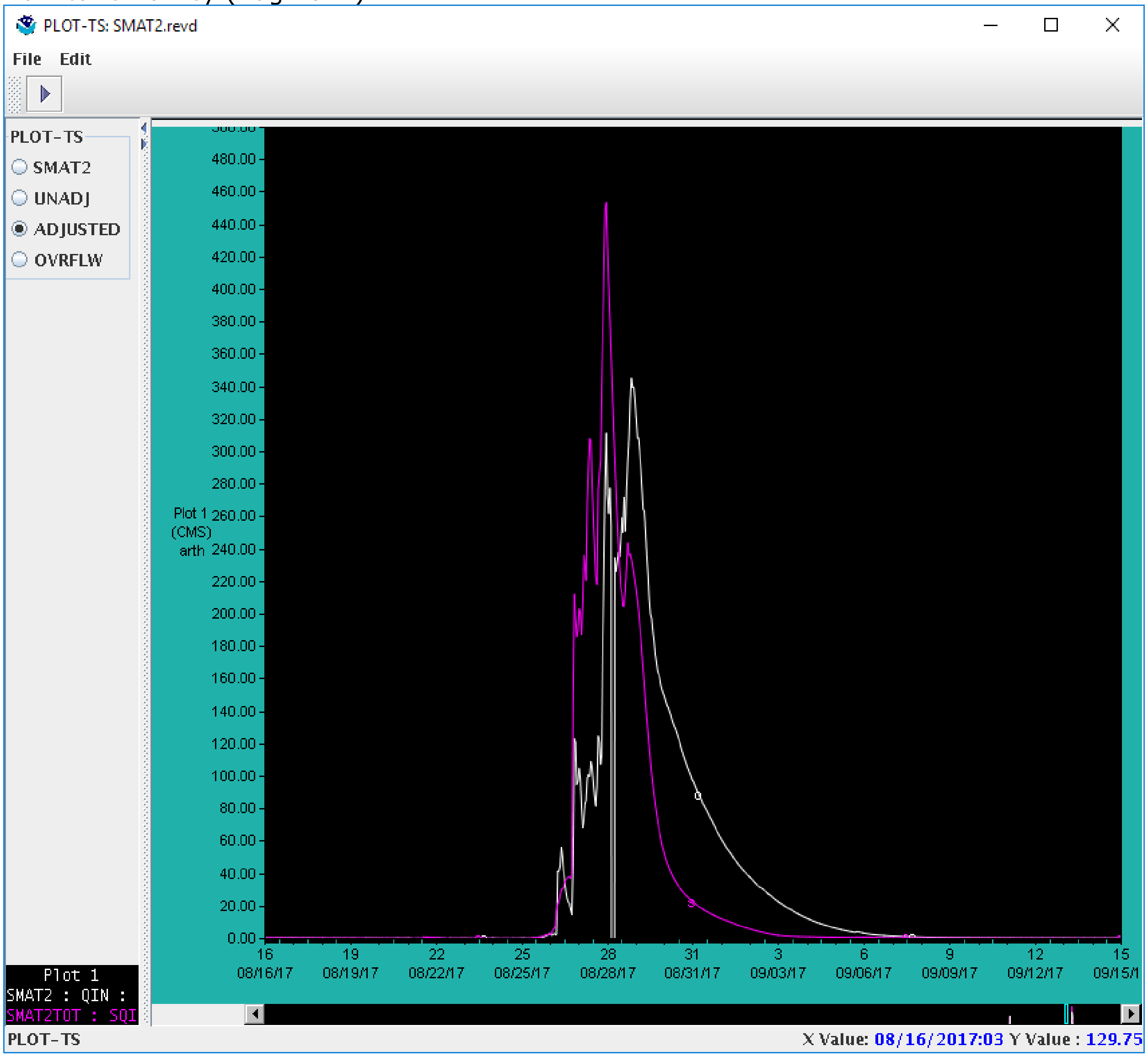
SMAT2 - S Mayde Ck at Heathergold Dr nr Addicks, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

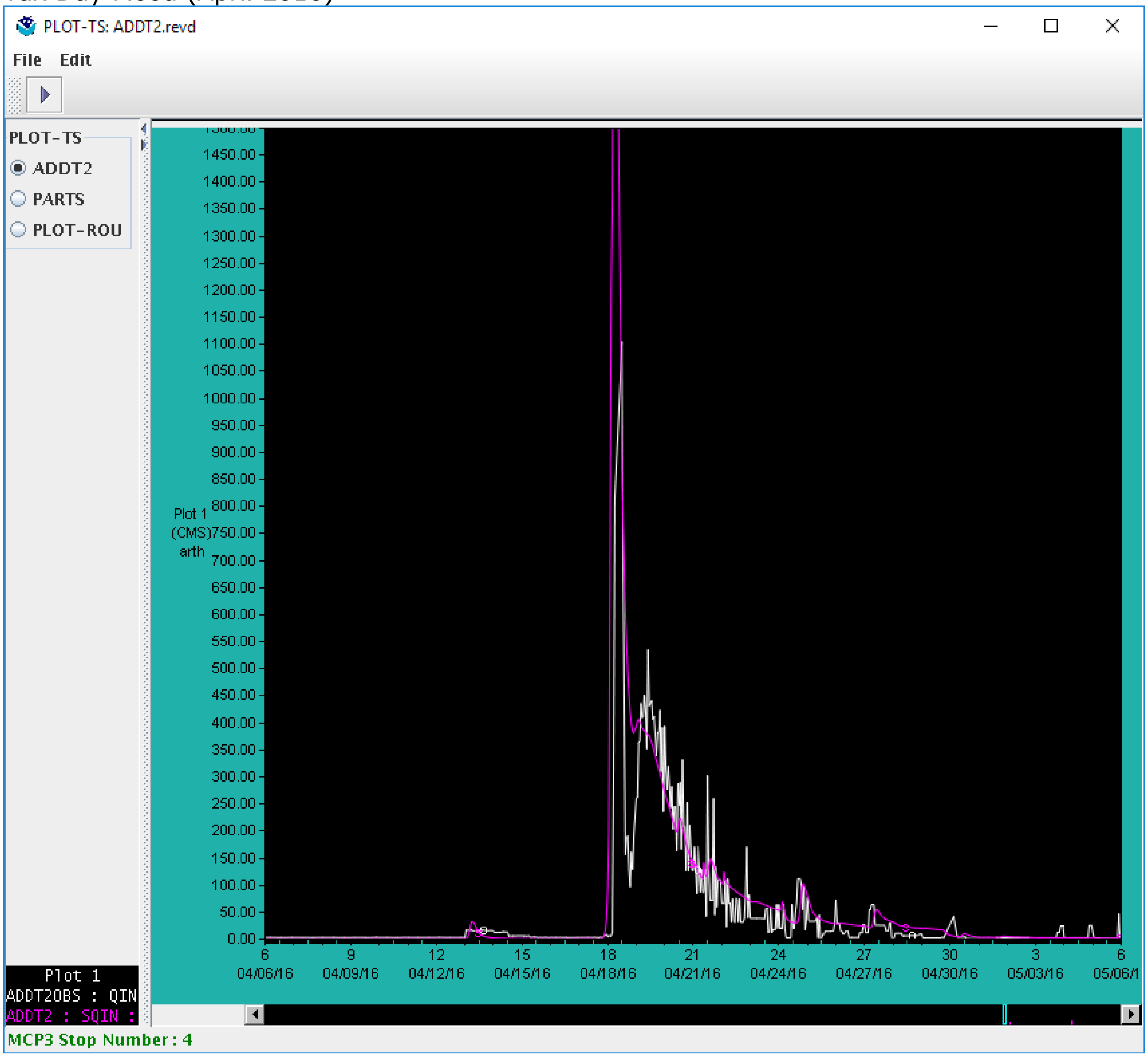
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

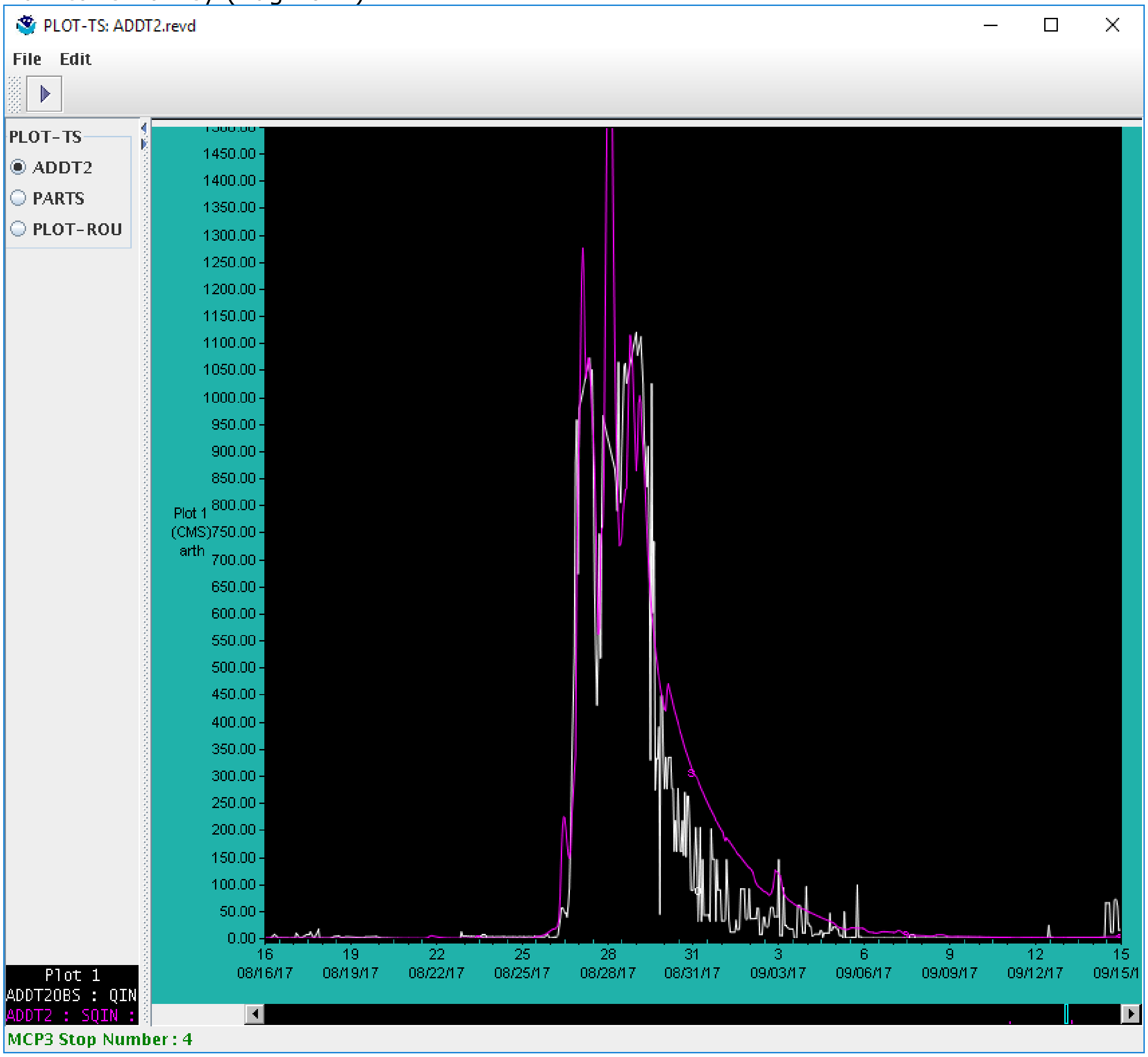
ADDT2 - Langham Ck at Addicks Res Outflow nr Addicks, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

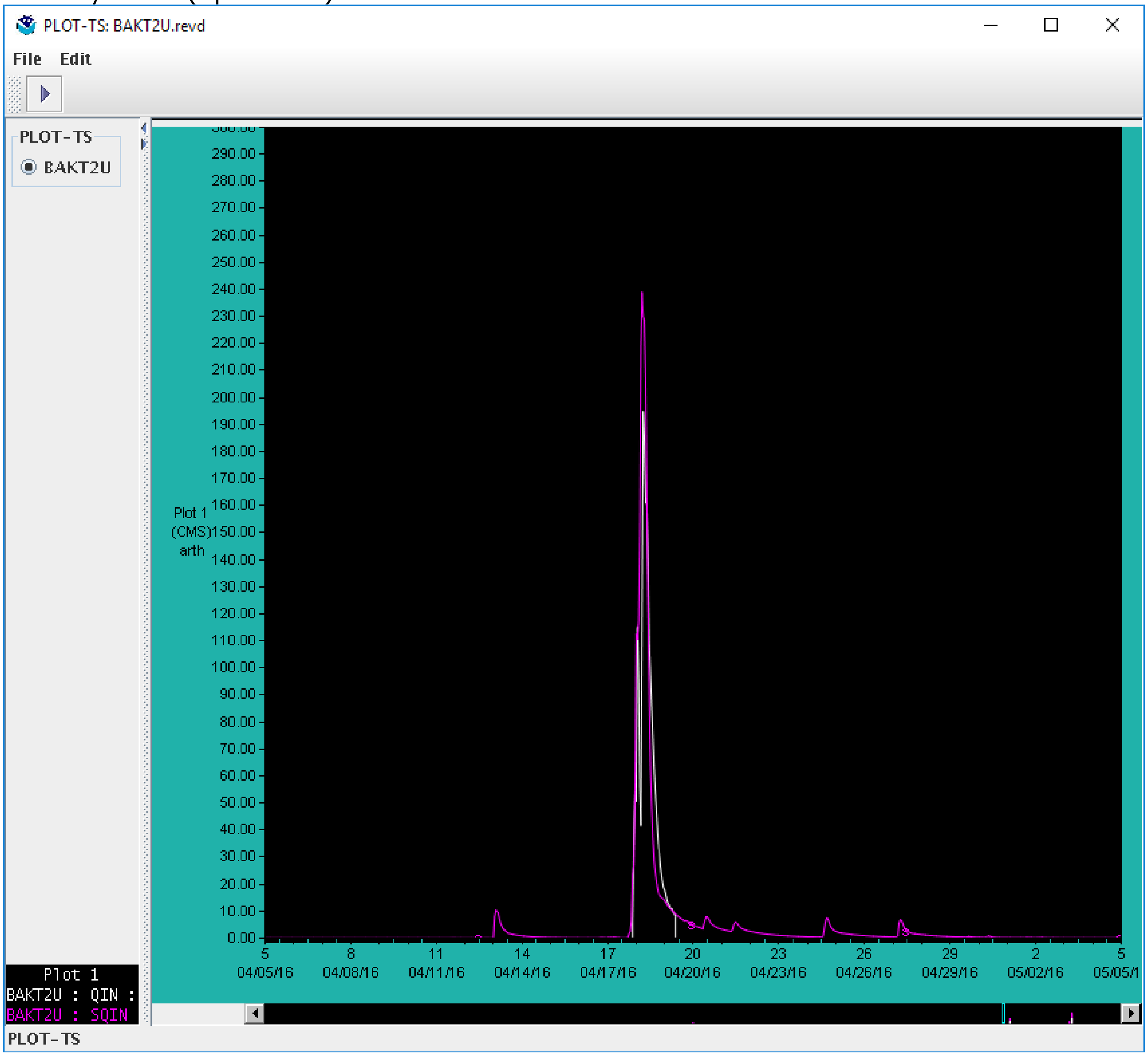
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

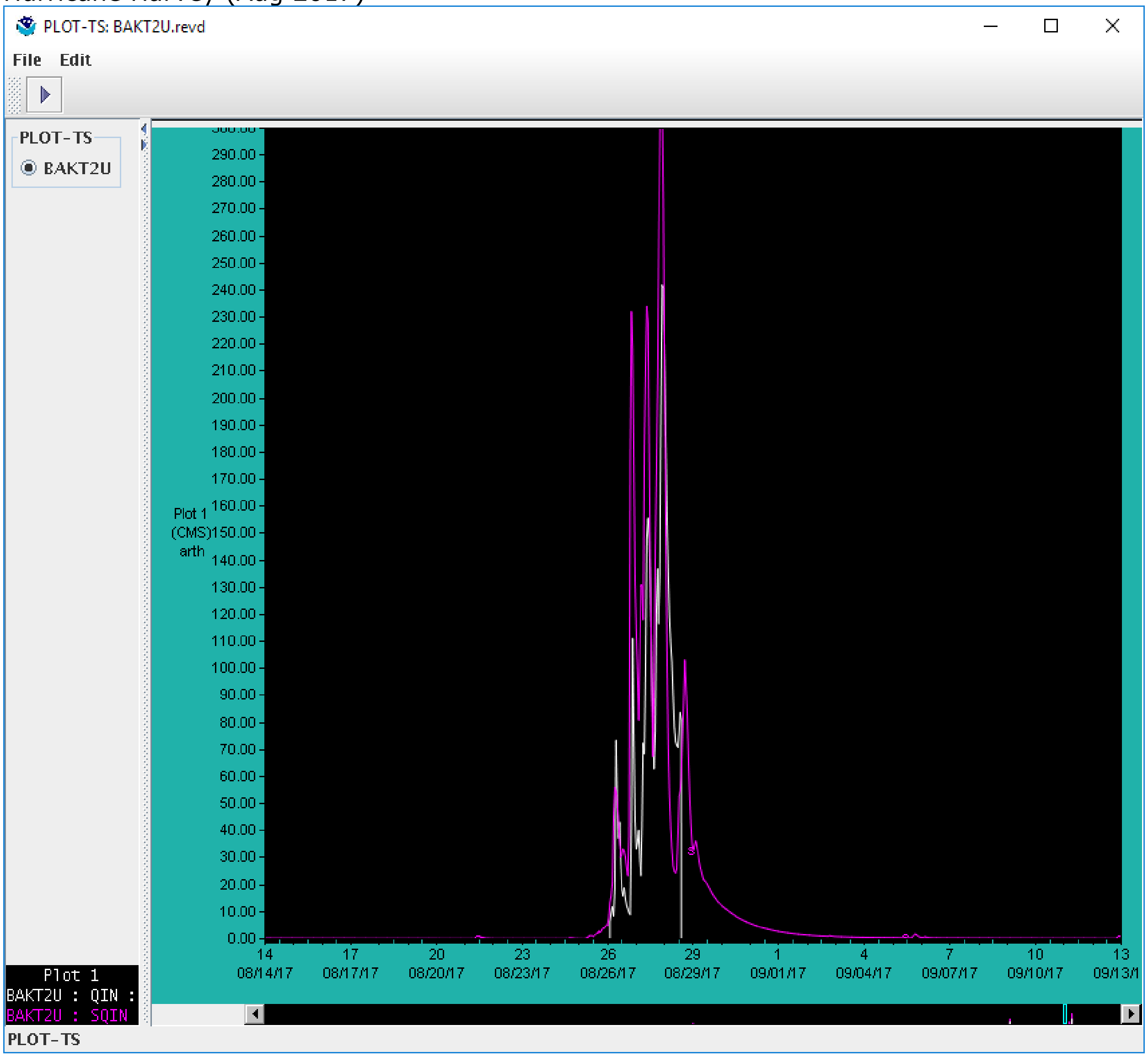
BAKT2U - Mason Creek at Prince Cr Dr abv Barker

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

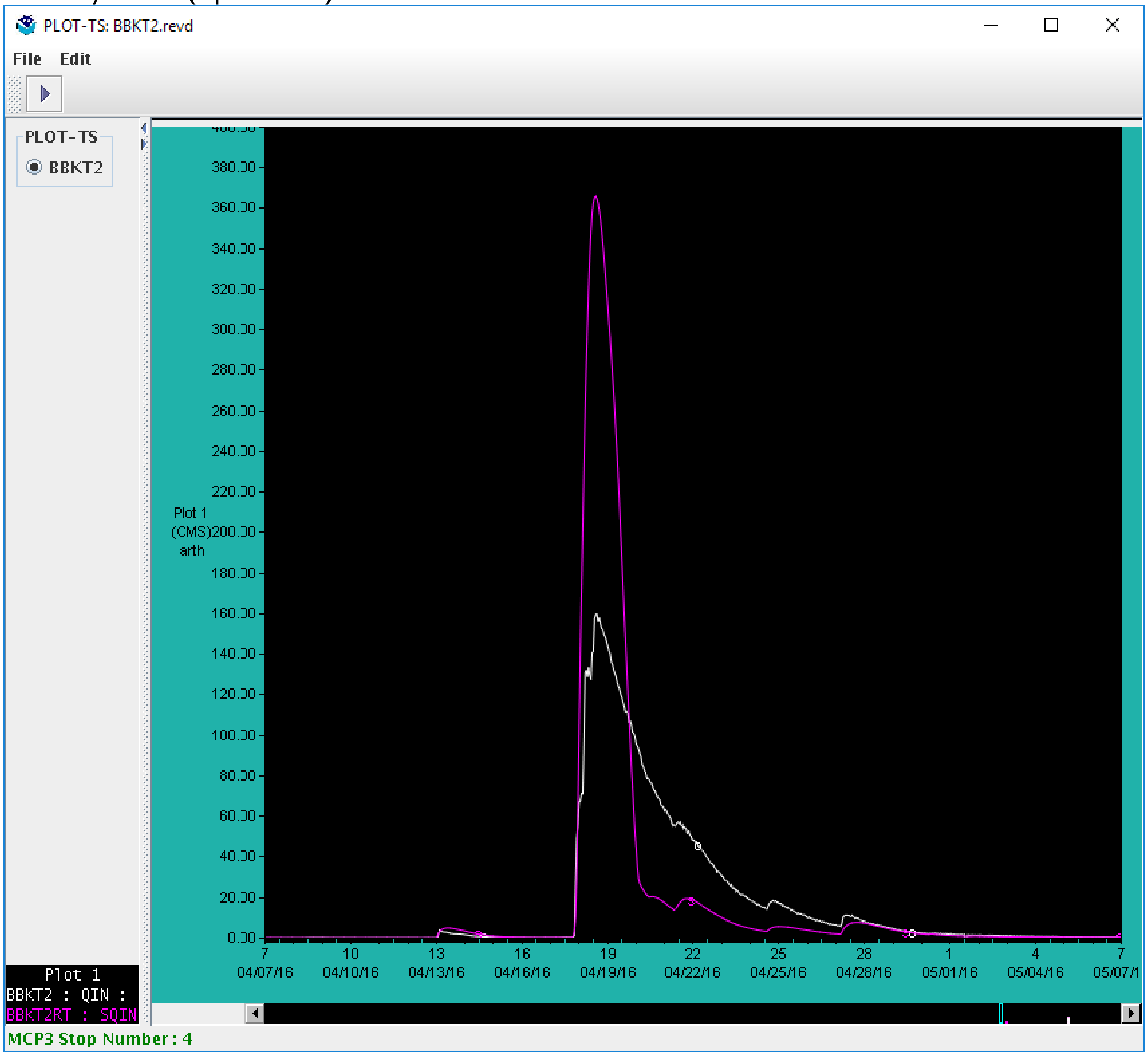
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

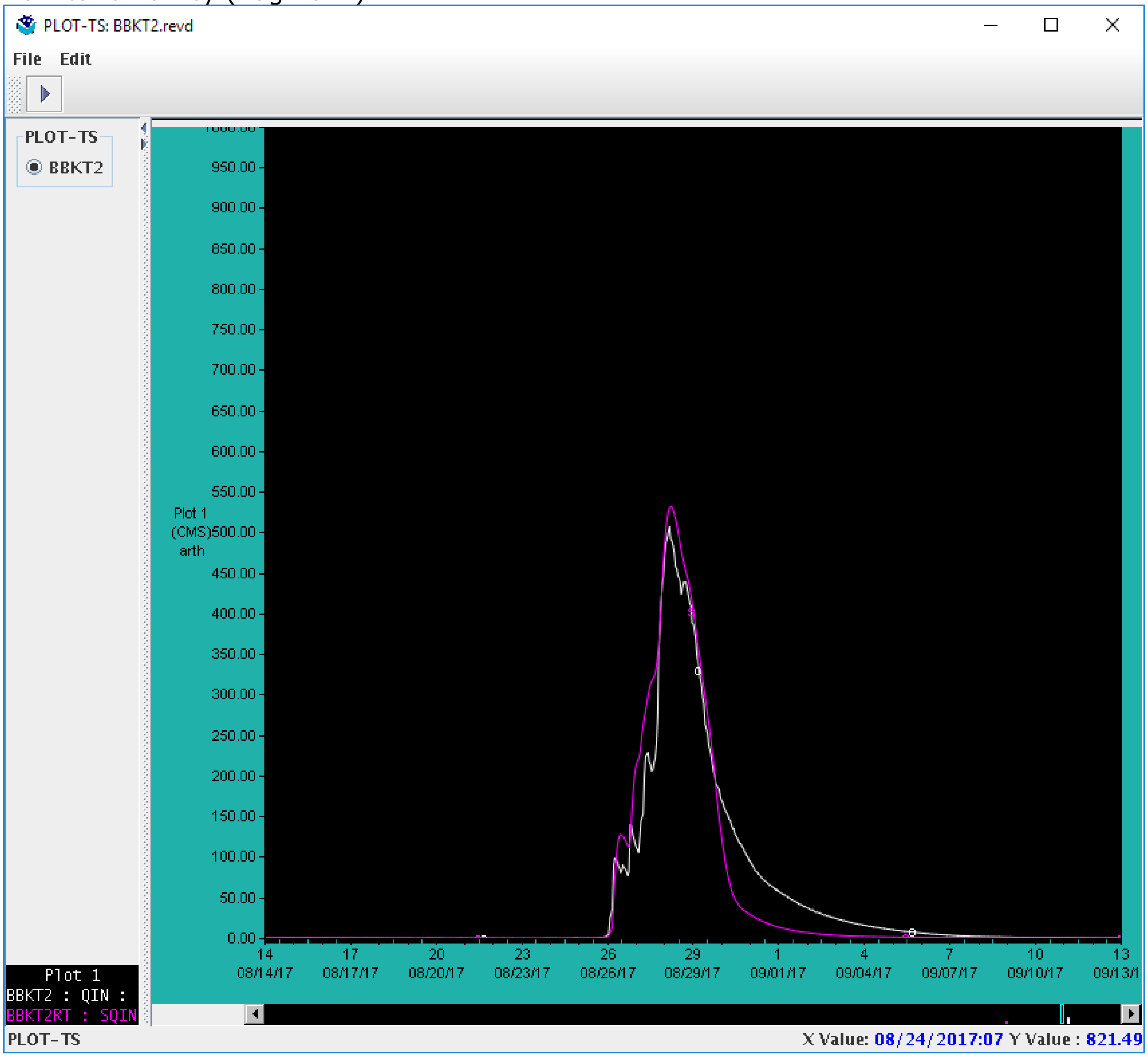
BBKT2 - Buffalo Bayou nr Katy, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

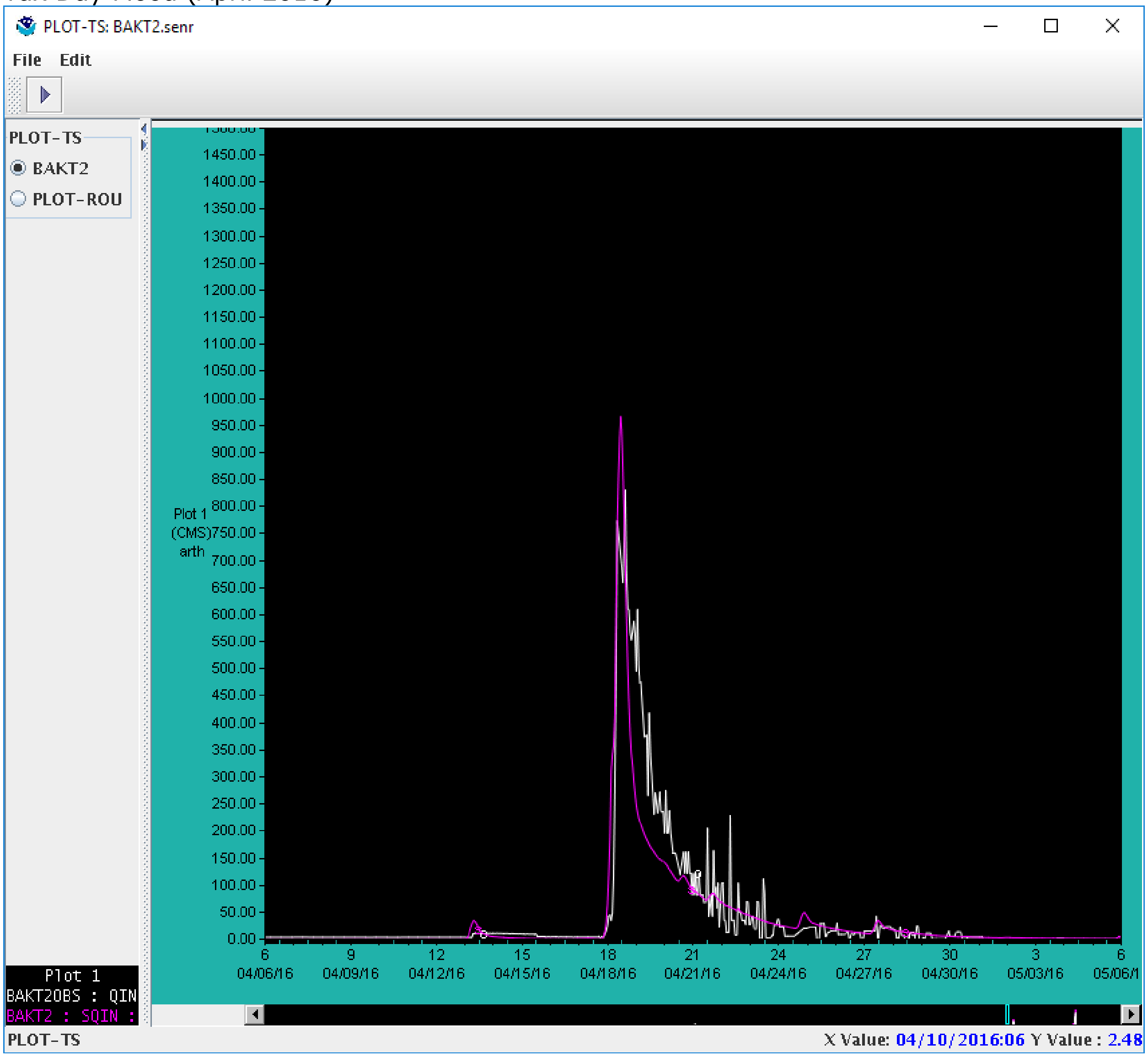
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

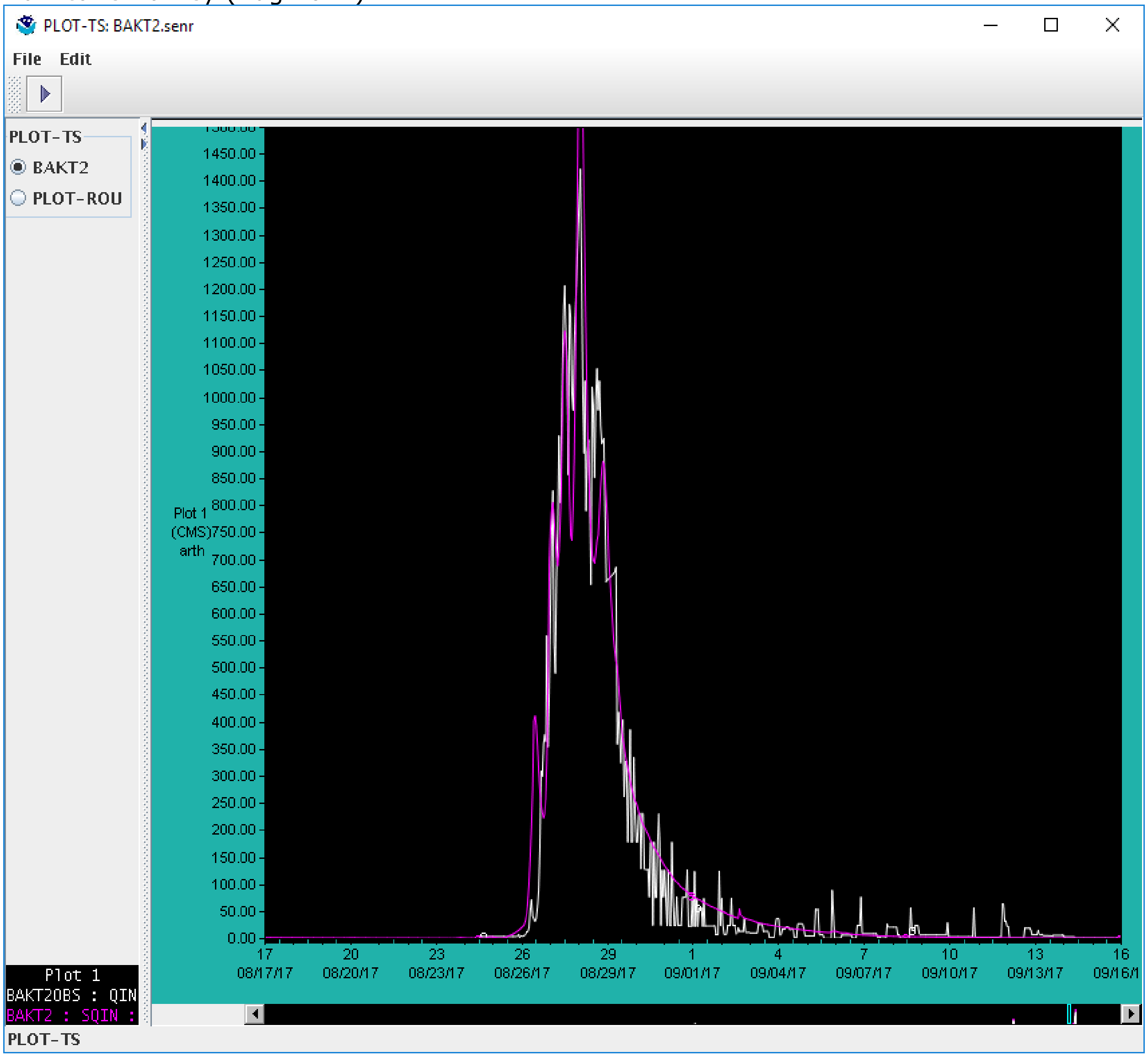
BAKT2 - Buffalo Bayou at State Hwy 6 nr Addicks, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

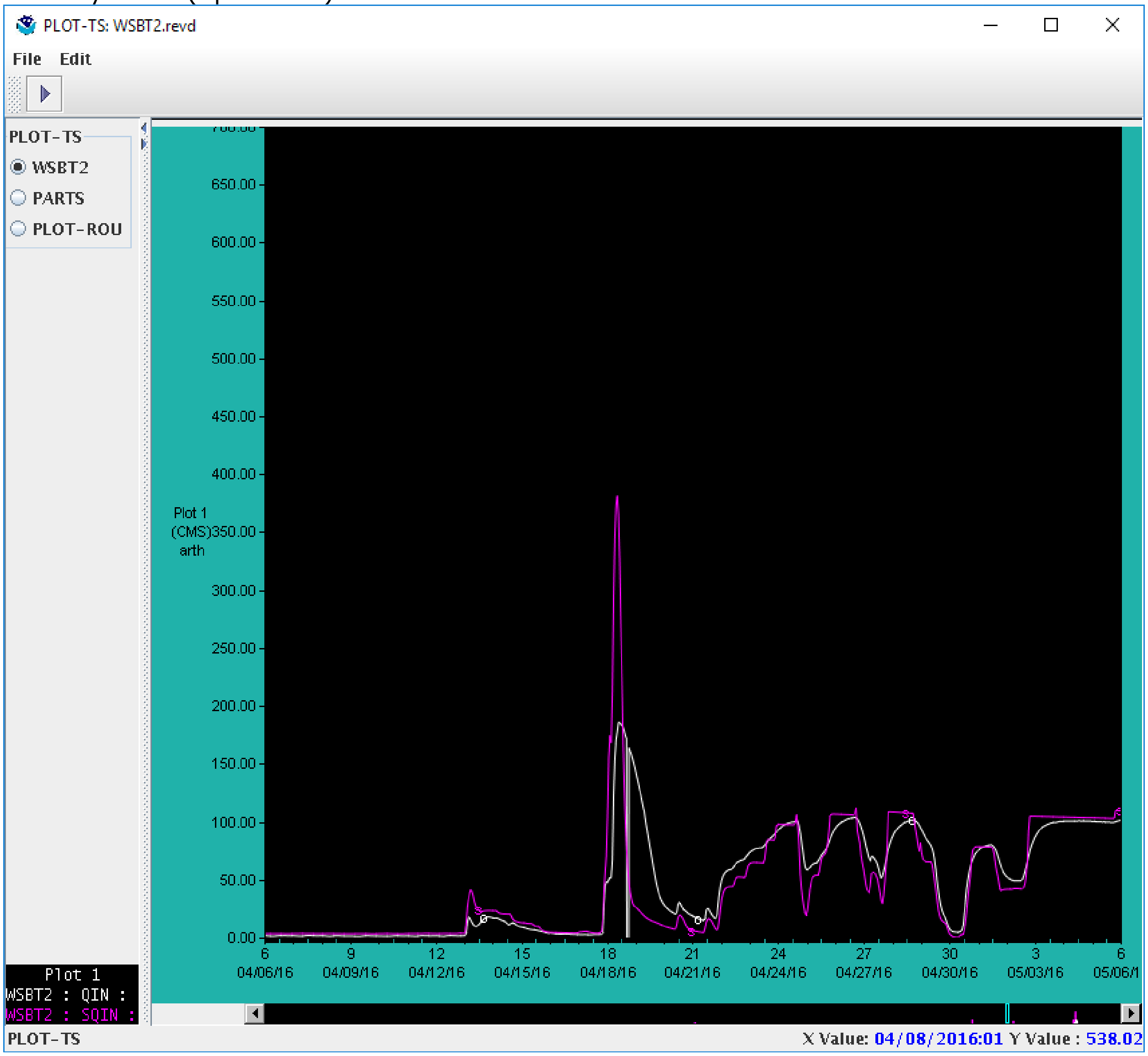
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

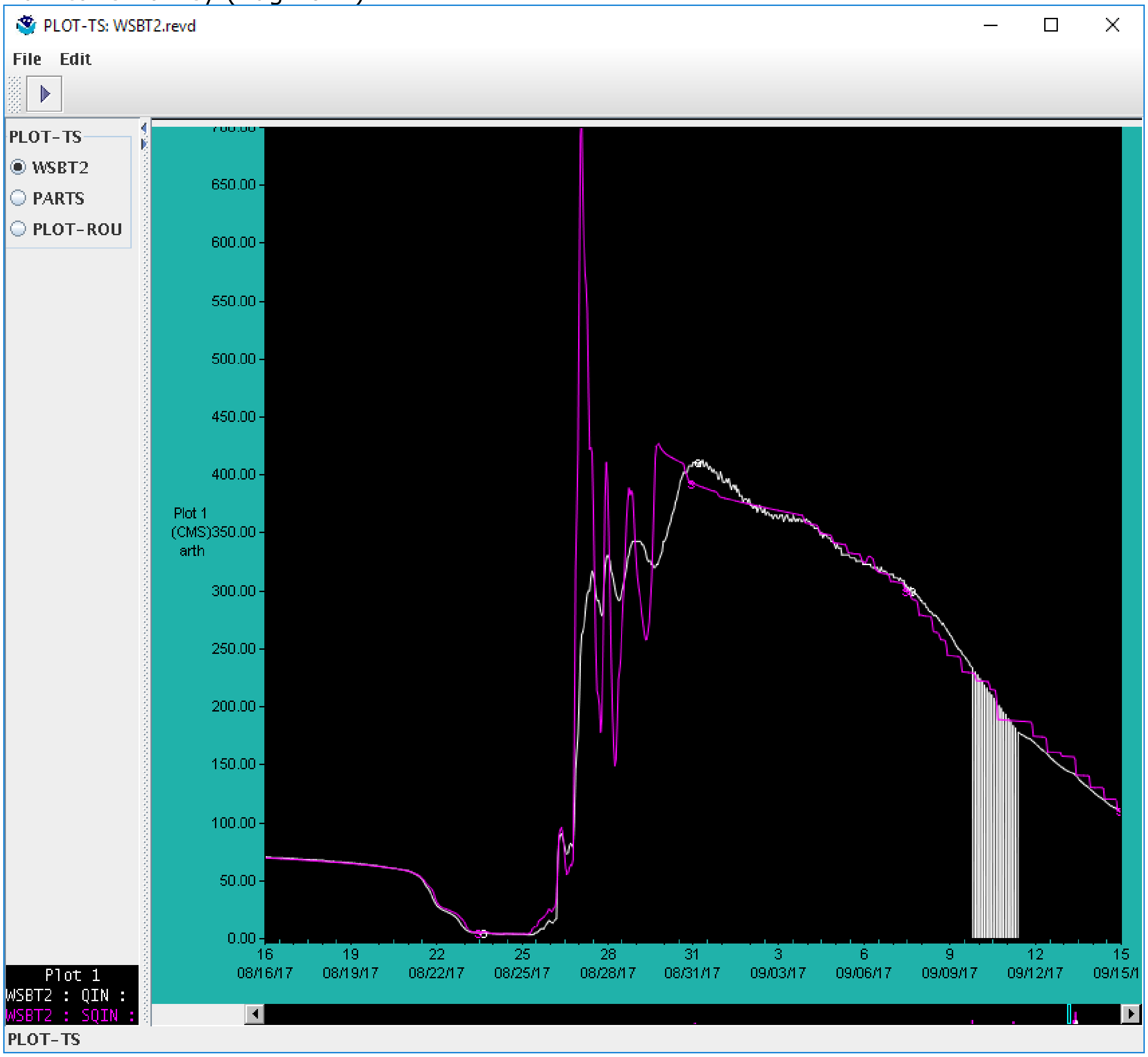
WSBT2 - Buffalo Bayou at W Belt Dr, Houston, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

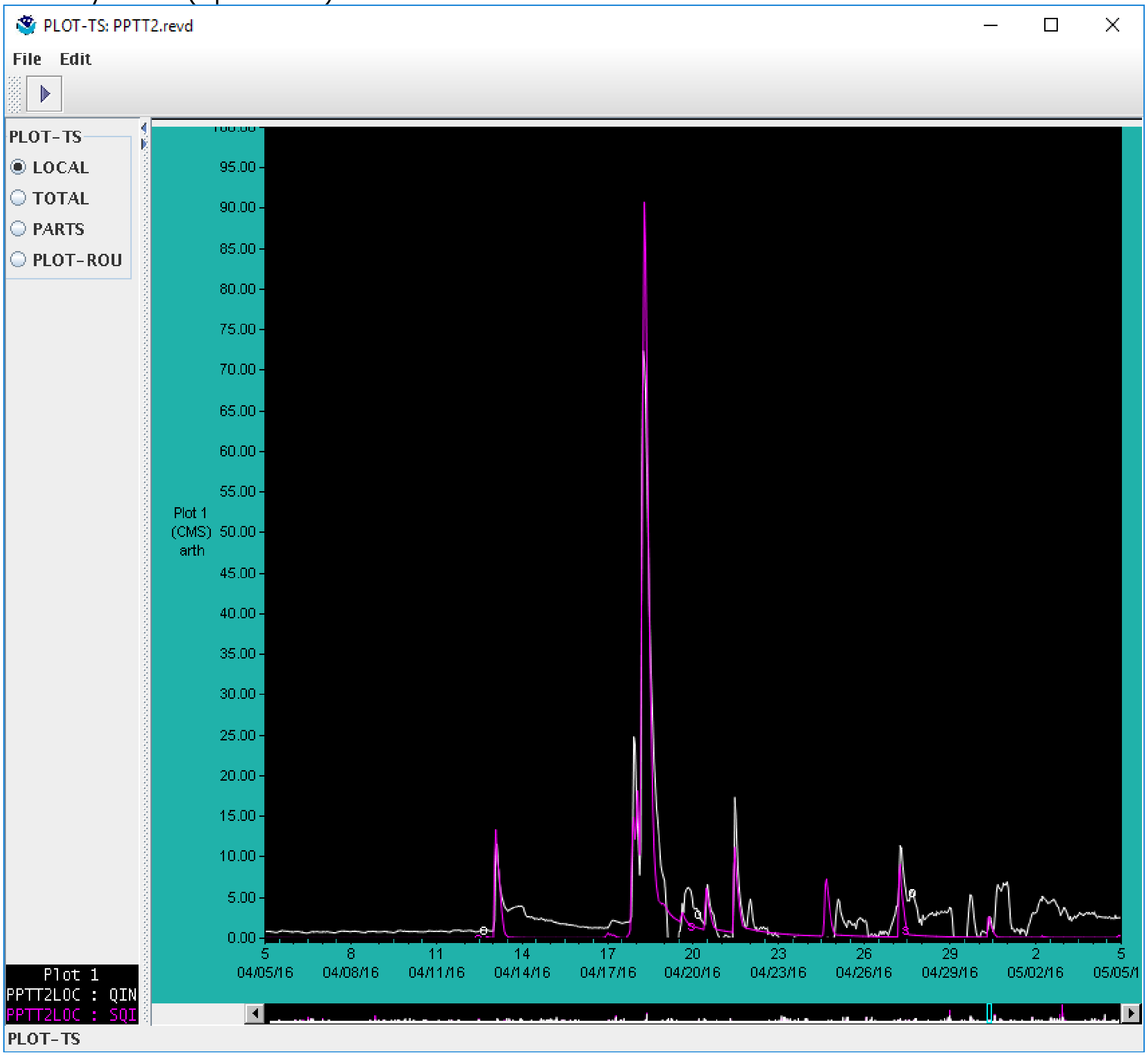
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

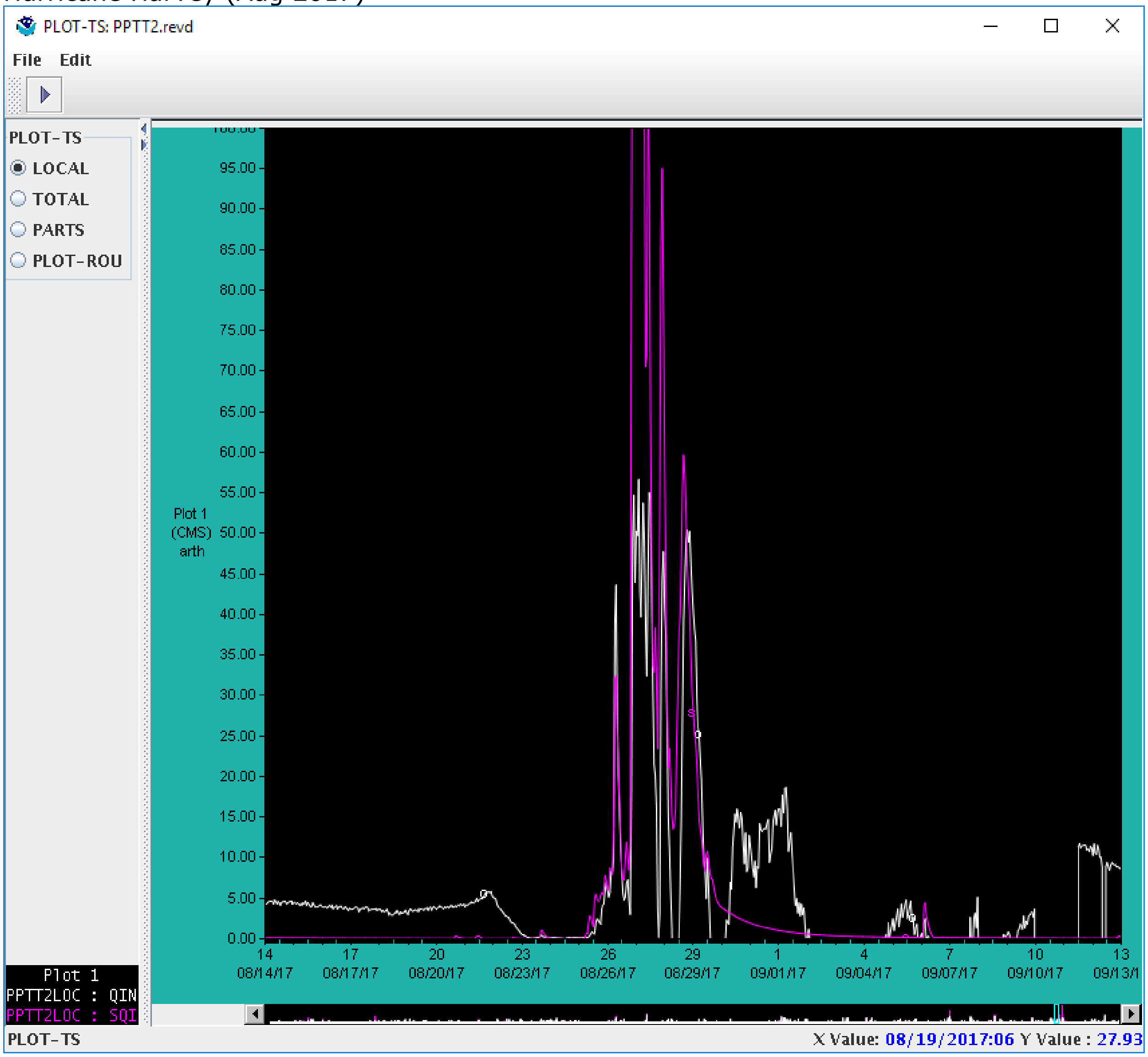
PPTT2 - Buffalo Bayou at Piney Point, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

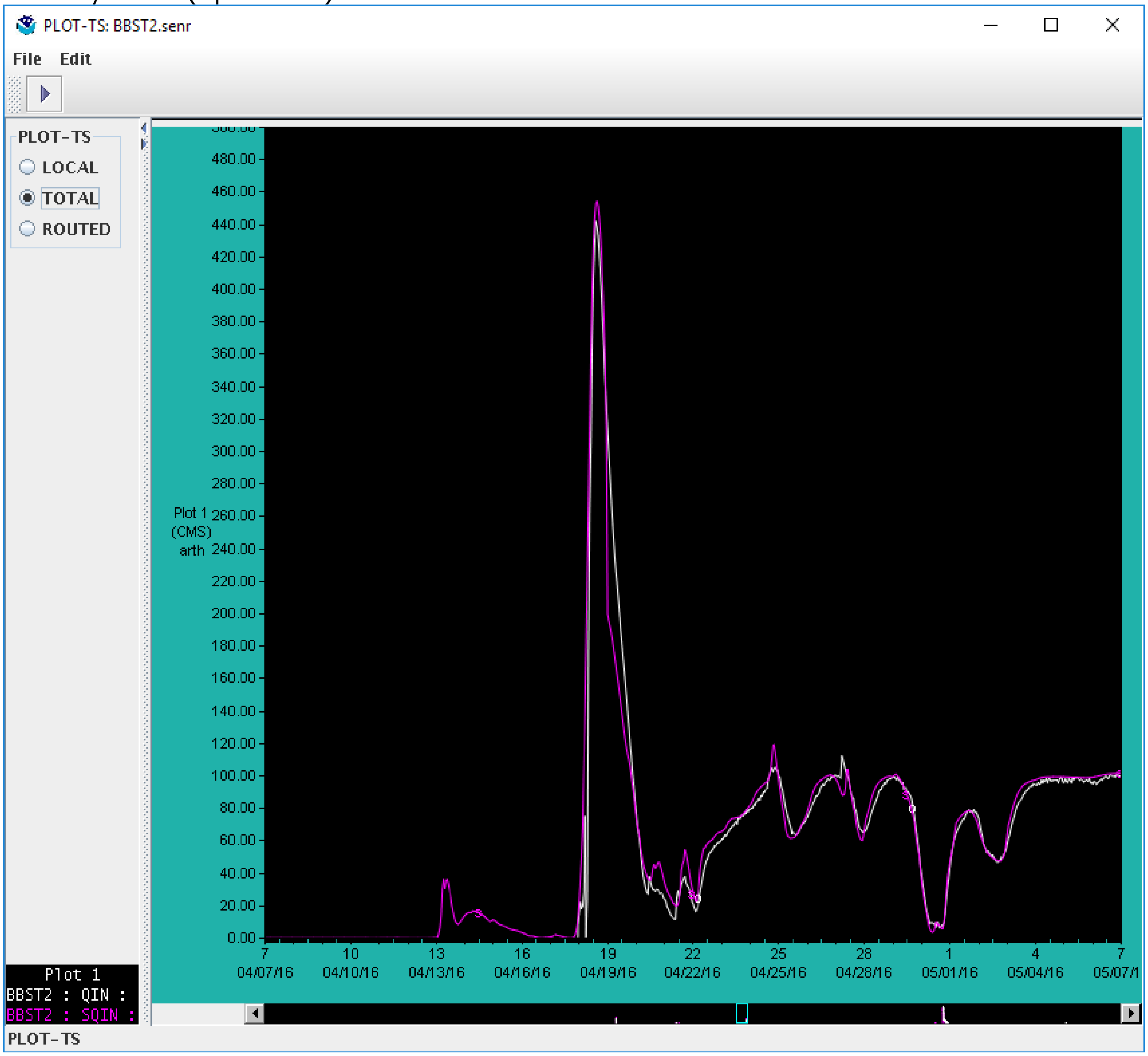
Hurricane Harvey (Aug 2017)



(Purple Line = Simulated, White Line = Observed)

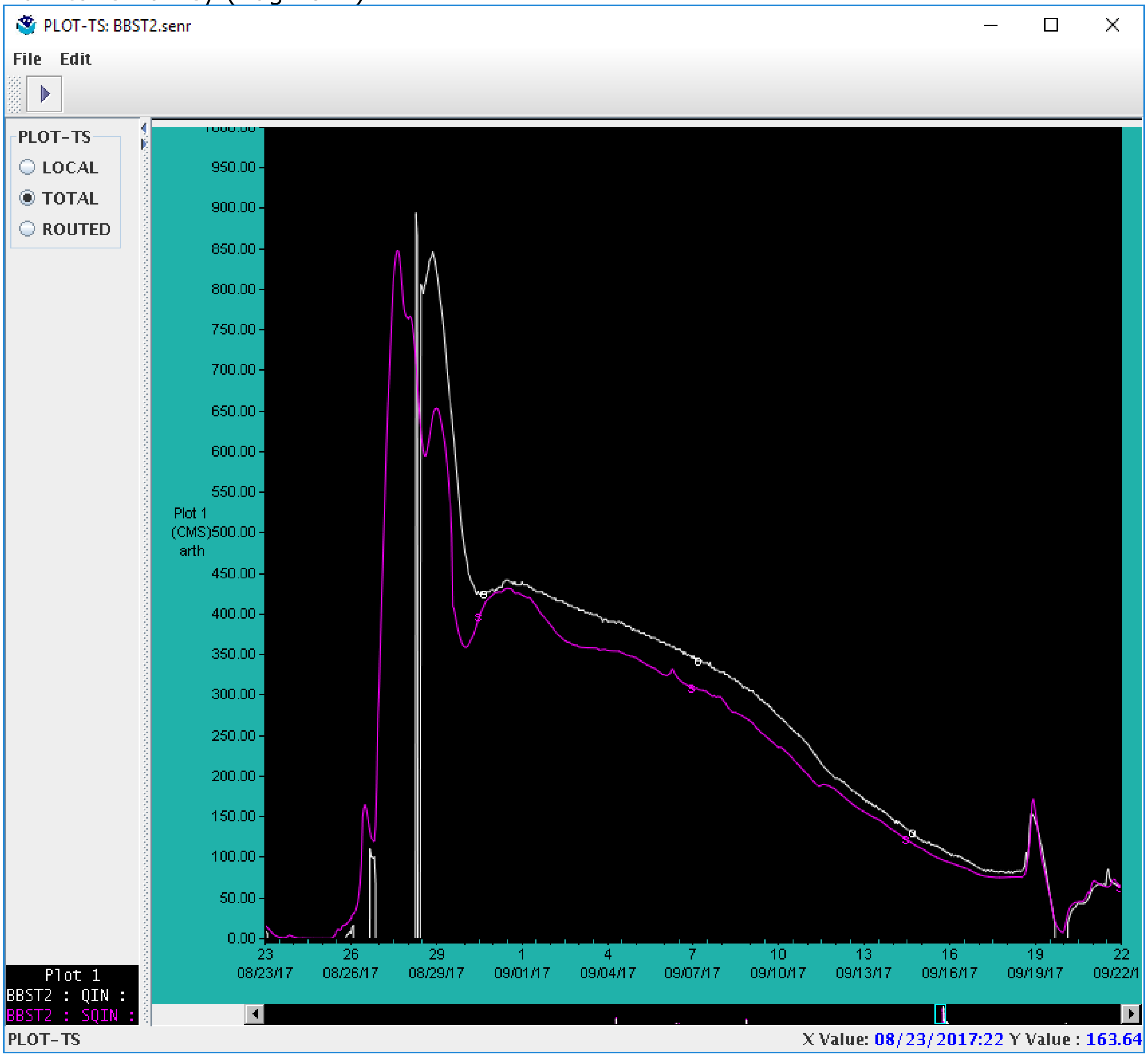
BBST2 - Buffalo Bayou at Houston, TX

Tax Day Flood (April 2016)



(Purple Line = Simulated, White Line = Observed)

Hurricane Harvey (Aug 2017)

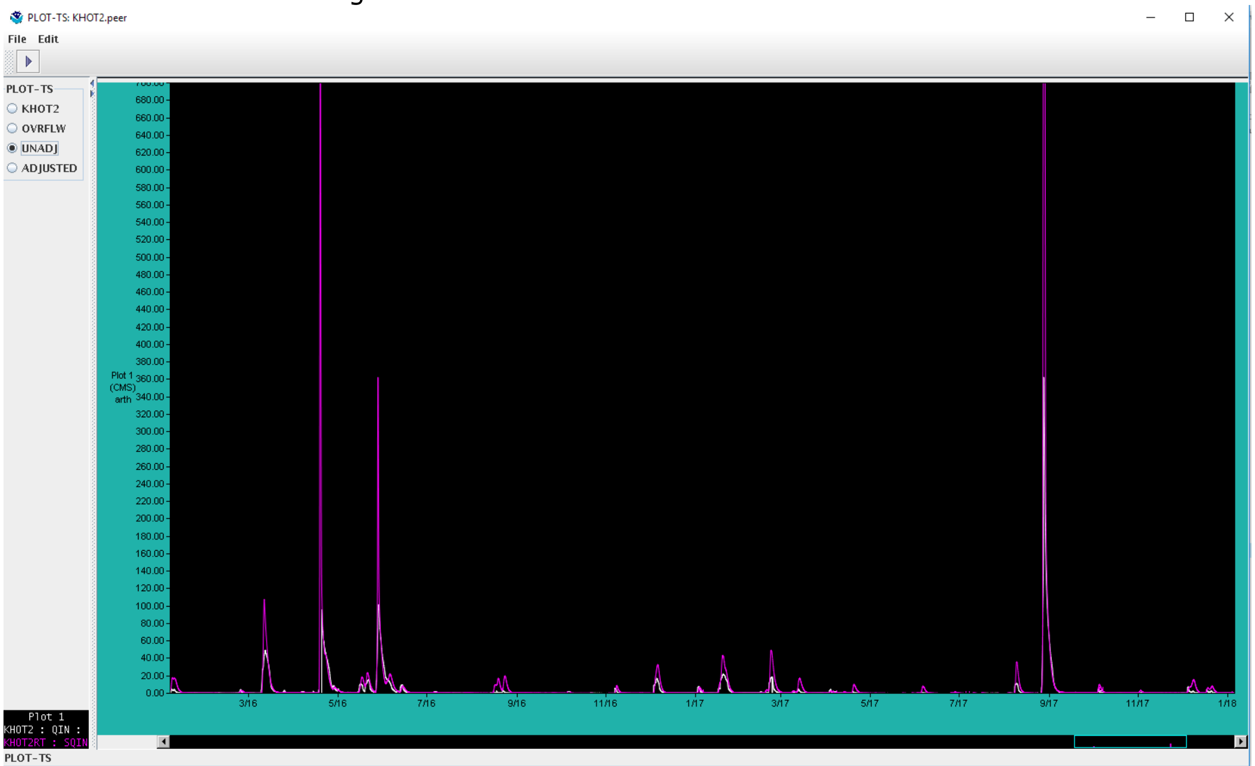


(Purple Line = Simulated, White Line = Observed)

Appendix E:
Cypress Creek Overflow Modeling Results

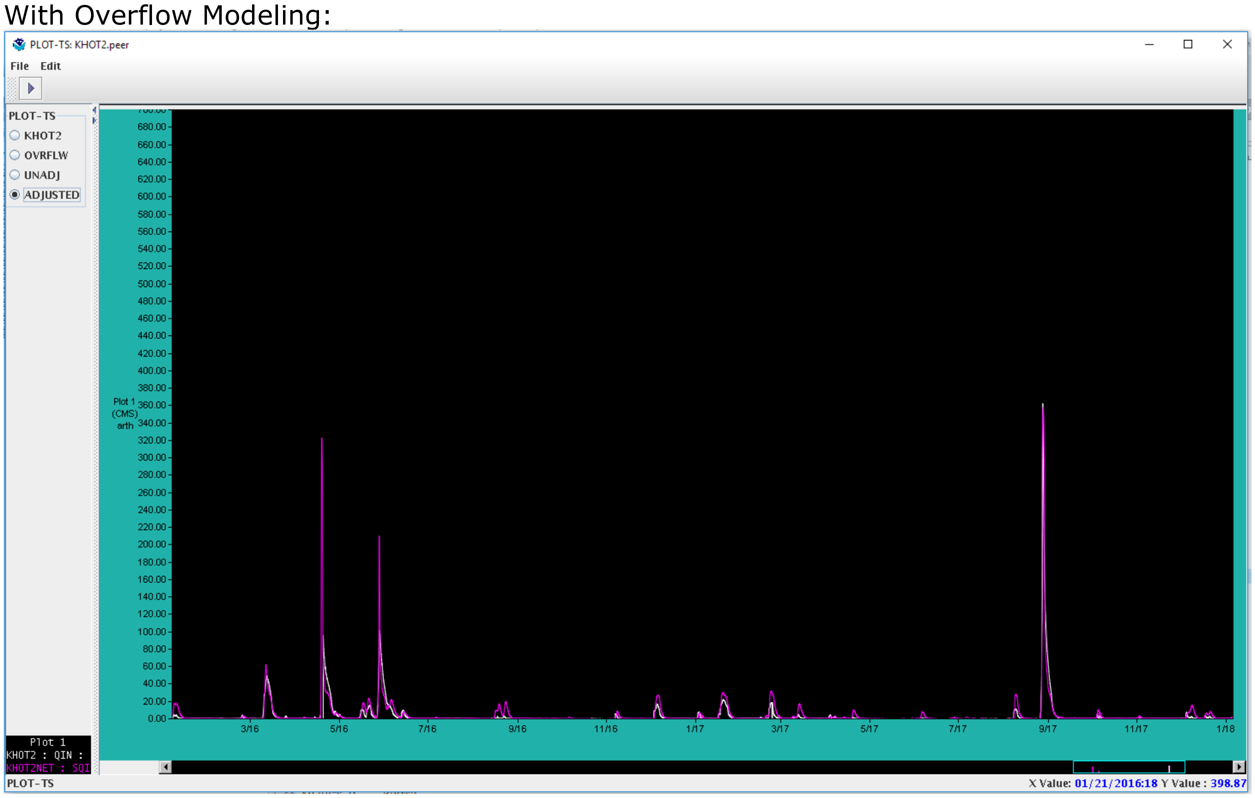
KHOT2 - Cypress Ck at Katy-Hockley Rd nr Hockley, TX

Without Overflow Modeling:



(Purple Line = Simulated, White Line = Observed)

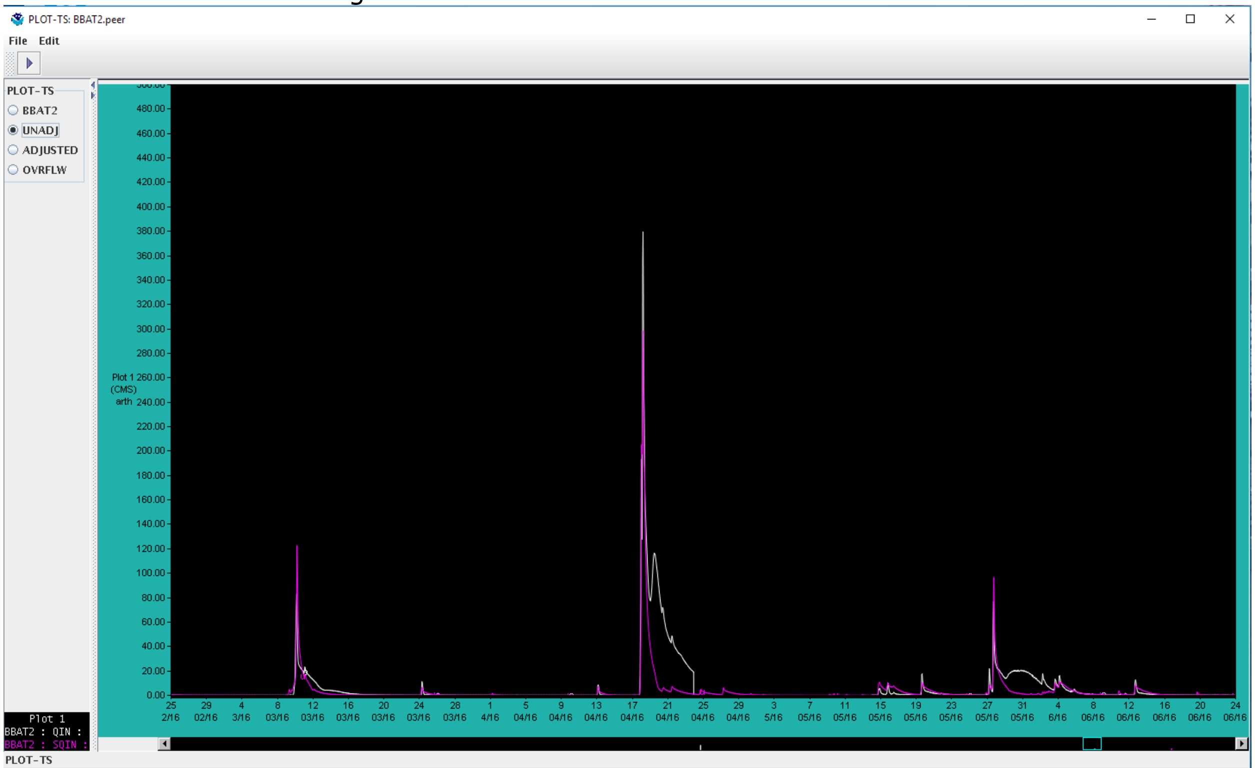
With Overflow Modeling:



(Purple Line = Simulated, White Line = Observed)

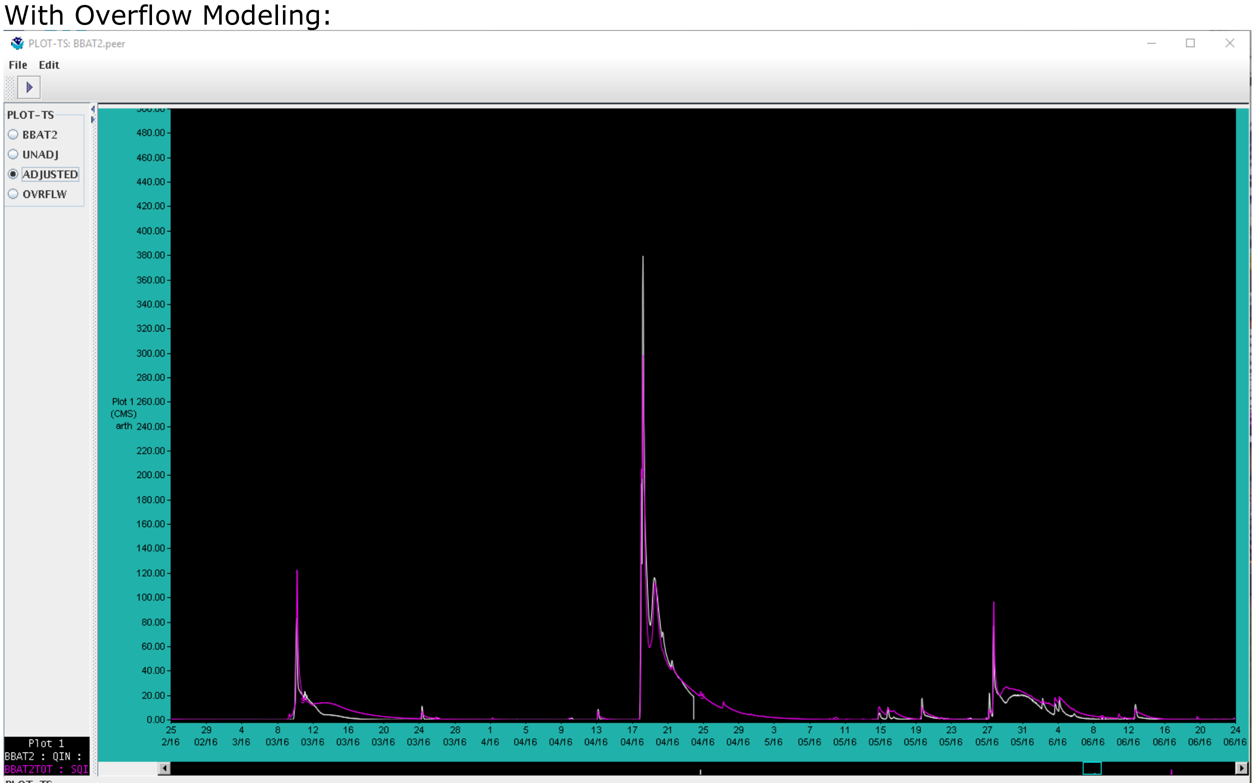
BBAT2 - Bear Ck nr Barker, TX

Without Overflow Modeling:



(Purple Line = Simulated, White Line = Observed)

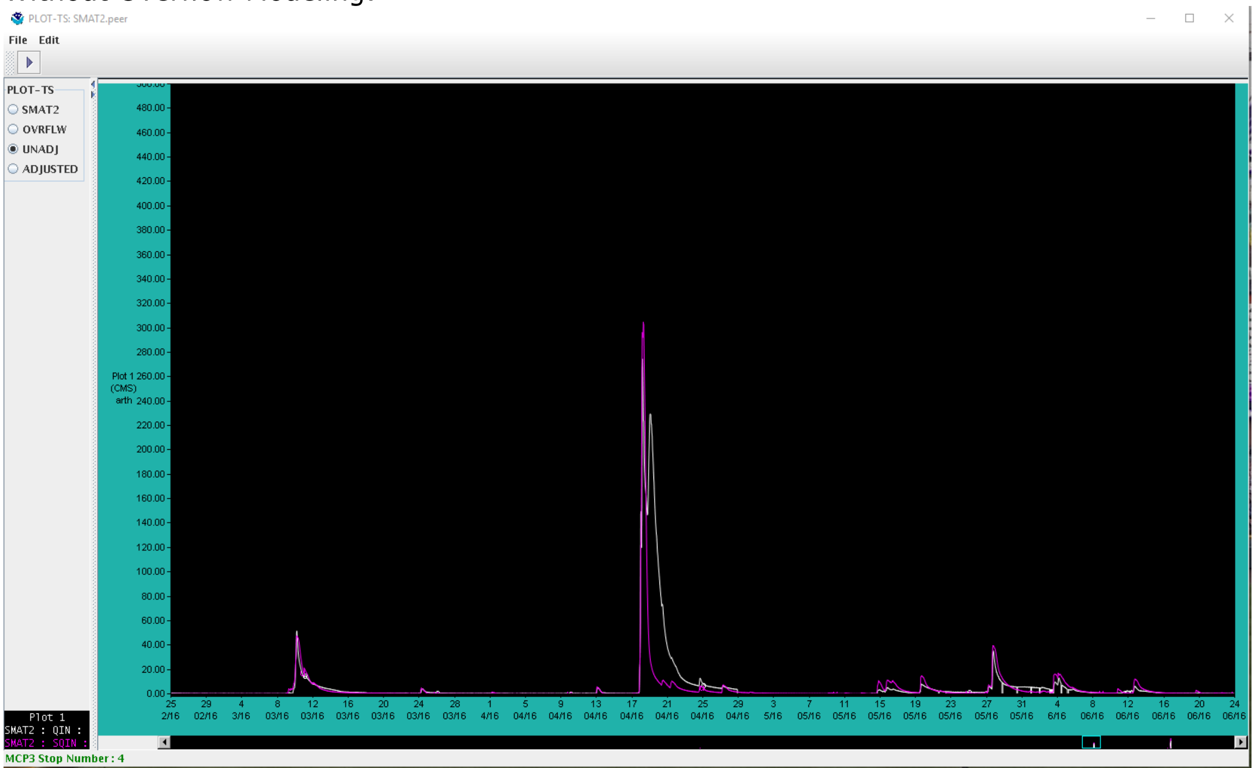
With Overflow Modeling:



(Purple Line = Simulated, White Line = Observed)

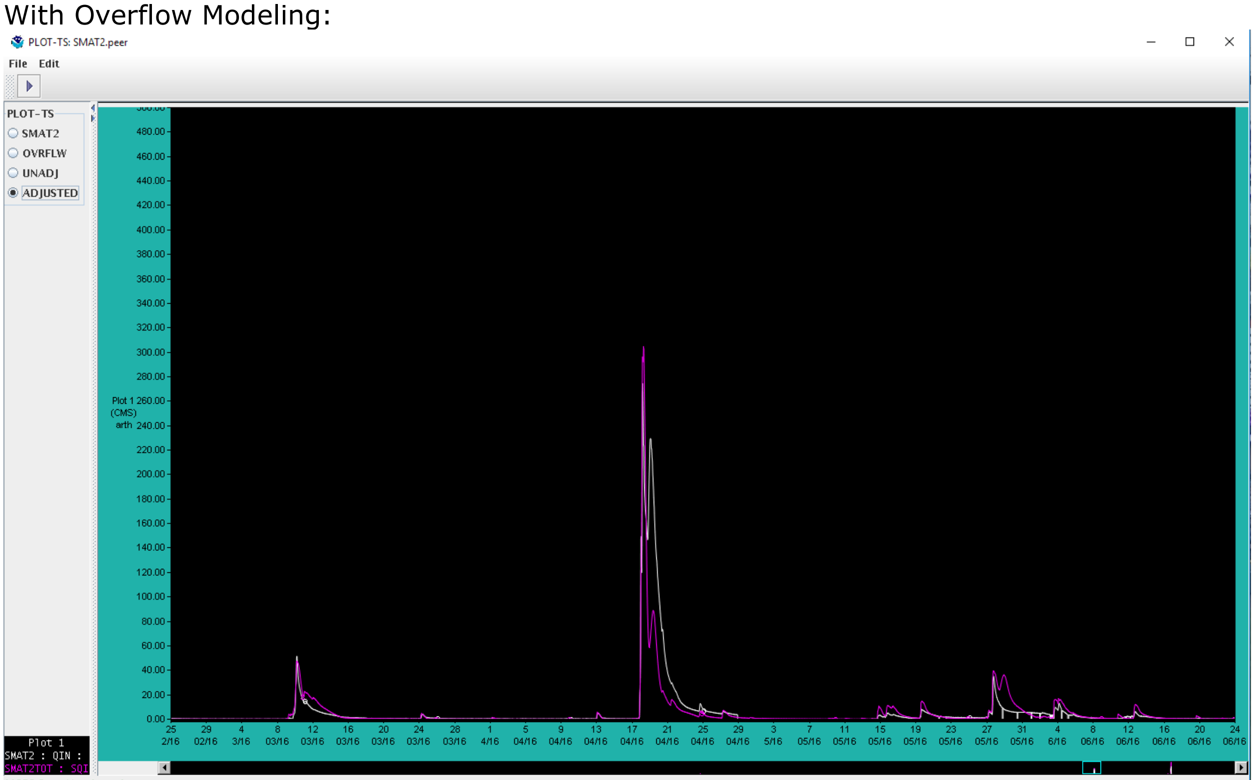
SMAT2 - S Mayde Ck at Heathergold Dr nr Addicks, TX

Without Overflow Modeling:



(Purple Line = Simulated, White Line = Observed)

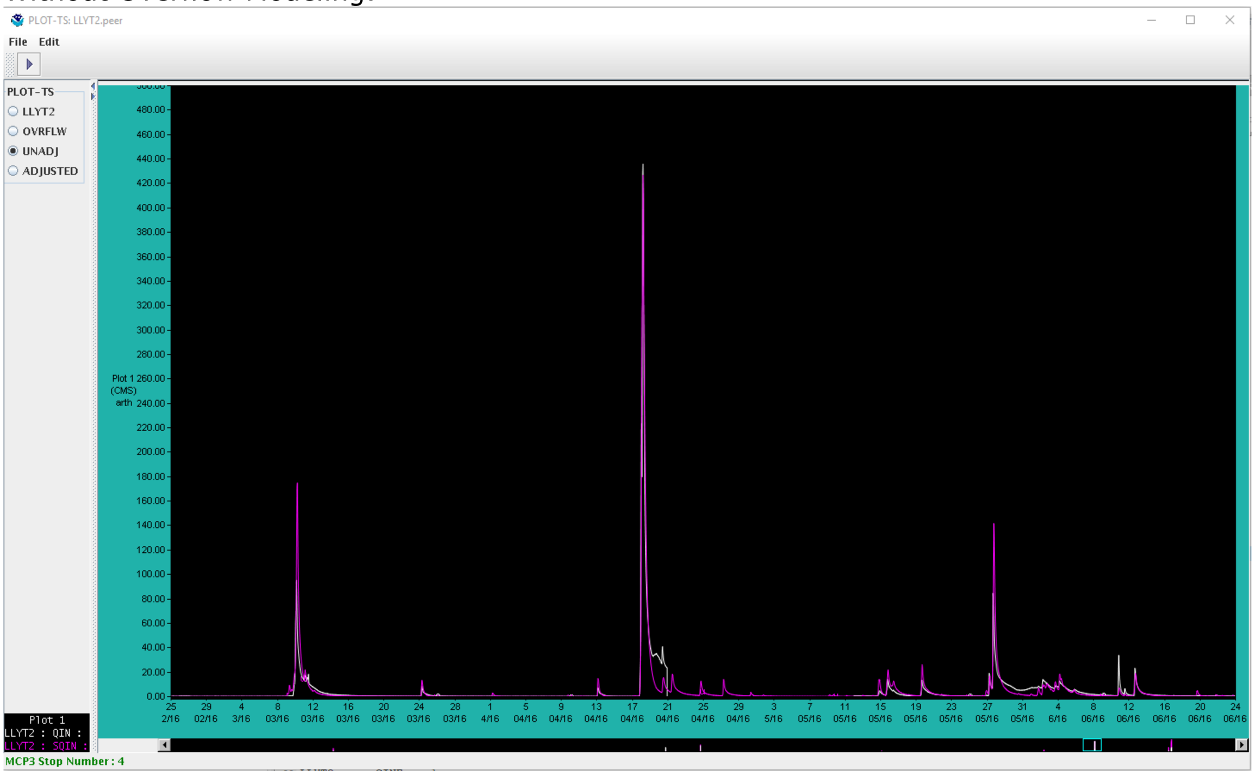
With Overflow Modeling:



(Purple Line = Simulated, White Line = Observed)

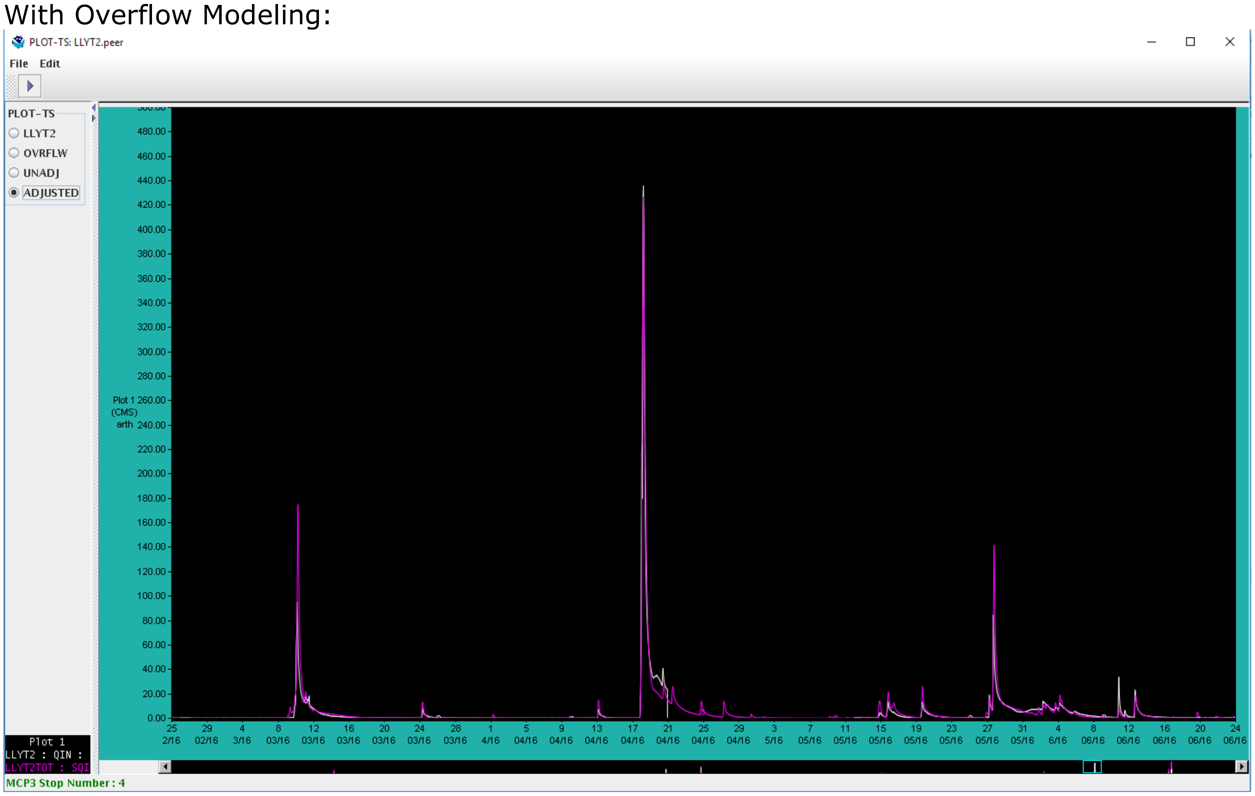
LLYT2 - Langham Ck at W Little York Rd nr Addicks, TX

Without Overflow Modeling:



(Purple Line = Simulated, White Line = Observed)

With Overflow Modeling:



(Purple Line = Simulated, White Line = Observed)

Appendix F:
TWDB Comments on Draft Report and RTI Responses

National Weather Service Hydrologic Model Calibration
Calibration of Flood Forecasting Models for Sub-basins of the San Jacinto River and Buffalo Bayou in Texas
Draft-final report to the Texas Water Development Board

Contract number 1800012243

The report documents a project to improve the flood forecasting capabilities of the National Weather Service's West Gulf River Forecast Center. During this project, the contractor (RTI International) calibrated hydrologic models for 28 sub-basins in the Houston area. As part of this project, RTI completed pre-calibration analysis, developed unit hydrographs, and calibrated rainfall runoff models for each sub-basin. For specific sub-basins where needed, RTI calibrated models to route flows through and between sub-basins and modeled diversions and channel gains and losses. RTI also evaluated the performance of existing models of the Addicks and Barker Reservoirs. Deliverables for this project included the draft final project report, calibration configuration files in two formats (both CHPS/FEWS and older NWSRFS formats), and additional supporting material.

General Draft Final Report Comments:
Overall, the report is well written and documents an effort that achieved the objectives of the Scope of Work.

REQUIRED CHANGES

1. Please recheck the document and correct typos such as the following:
    a. Page ES-2, 4th paragraph, 1st sentence, "existing WFRFC RES-J models" should be "existing WGRFC RES-J models".
    b. Page 3-2, Table 2a, 3rd row related to FCWT2, 4th column, "Western Costal Plain" should be "Western Coastal Plain".
    c. Page 3-7, Table 2a, 1st and 2nd rows related to WFDT2 and HMMT2, 4th column, "Gulf Coast Praries" should be "Gulf Coast Prairies".
    d. Page 4-7, 1st paragraph, last sentence, "Nation Hydrography Dataset" should be "National Hydrography Dataset".

    RTI Response: These items have been corrected.
2. Page 4-29, 2nd paragraph, 3rd sentence references Figure 16 while speaking about Hurricane Harvey. According to the title on Figure 16, this figure relates to the Tax Day Flood. Please provide a refence to Figure 16 in the appropriate location in the text on page 4-29. If there is a figure related to Barker Reservoir RES-J model performance for Hurricane Harvey, please provide it in the report (perhaps as Figure 17) and refer to it in the appropriate location in the text on page 4-29.
    RTI Response: The heading on Figure 16 was corrected to read "Barker Reservoir RES-J Model Performance for Hurricane Harvey". We did not include a figure showing the Tax Day Flood for this reservoir.
3. Several entries in the tables on pages A-3 and A-4 have entries of "####" (for example, the entry for "% Diff" for sub-basin BBAT2 for year 2008). Please provide valid entries for all cells of these tables.
    RTI Response: These items have been corrected.

SUGGESTED CHANGES

4. To emphasize the close cooperation between NWS-WGRFC and RTI during this project, please consider adding the following sentence as the 2nd sentence in the 1st paragraph on page 5-1: "This project was performed in cooperation with the NWS-WGRFC."
    RTI Response: This sentence has been added.