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August 31, 2017

National Weather Service Hydrologic Model Calibration

Calibration of Flood Forecasting Models for Sub-basins of the San Antonio, Guadalupe, and Colorado Rivers 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. 1600012068

RTI
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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 23 sub-basins located in Central Texas in the Colorado, Guadalupe, and San Antonio River 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:

- <u>Pre-Calibration Data Analysis</u>: 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.

- <u>Unit Hydrograph Model Development</u>: 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.

- <u>Streamflow Routing Model Calibration</u>: Of the 23 sub-basins included in the hydrologic model calibration analysis, 17 are local areas where streamflow from upstream sub-basins must be accounted for when forecasting total flows at the forecast location. 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 17 modeled local areas, there are a total of 23 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.

- 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 23 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 irrigation, power generation, and municipal water supplies, 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 at either a fixed rate or defined as a percentage of the simulated streamflow volume. In some cases, the defined rate or percentage was varied by month. In addition, in sub-basins where there are losses to the local runoff due to karst geologic formations, the SAC-SMA parameter SIDE was utilized. Within the San Antonio River basin, the modeling of Salado Creek required a LOOKUP operation to most effectively model the net losses, which have a very large influence on total streamflow.

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 6-hour time step of the existing forecast models. This improvement is significant for modeling flood events in Central Texas, where peaks form extremely rapidly.

Within the Colorado River basin, the final calibrated models resulted in a correlation between the simulated and observed hourly total streamflow ranging from 0.817 to 0.999, an average peak flow simulation bias for the major floods of Oct 2013, May and October

2015, and May 2016, of -19% to 20%, and an average total streamflow volume bias ranging from -13% to 7%.

Within the Guadalupe River basin, the final calibrated models resulted in a correlation between the simulated and observed hourly total streamflow ranging from 0.802 to 0.975, an average peak flow simulation bias for the major floods of Oct 2013, May and October 2015, and May 2016, of -10%, and an average total streamflow volume bias ranging from -0.3% to 2.7%.

Within the San Antonio River basin, the final calibrated models resulted in a correlation between the simulated and observed hourly total streamflow ranging from 0.503 to 0.934, an average peak flow simulation bias for the major floods in the basin since 2013 of -55% to 49% (omitting two events with potentially underestimated precipitation or upstream flows for SSCT2), and an average total streamflow volume bias ranging from -3% to 174%.

1. INTRODUCTION

In recent years, a series of severe flooding events have occurred in Central Texas, resulting in loss of life and significant property damages. In the Colorado River basin, as much as 14 inches of rainfall fell southwest of Austin on October 31, 2013, prompting a flash flood along the Onion Creek tributary. In October 2015, the same area experienced a similar flood event. Within the Guadalupe and San Antonio River basins, rainfall totals as high as 24 inches were recorded on October 17 – 18, 1998, which resulted in flood peaks which exceeded the 100-year recurrence interval within both basins, and caused significant loss of life and over $750 million in property damages (USGS 1999). In an effort to improve the warning times of these extreme events, 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 Central 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 Colorado, Guadalupe, and San Antonio River 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 six (6) headwater basins and 17 local areas, development of 23 unit hydrograph models (UNIT-HG), and LAG/K routing model calibration for 23 river reaches. In addition, RTI investigated and accounted for streamflow diversions and gains/losses within the modeled areas.

Figure 1 shows a map of the project region, highlighting the modeled sub-basin areas. The WGRFC provided RTI with an initial delineation of the local drainage areas. These initial sub-basin delineations were refined by RTI during the course of the study in the Onion Creek area of the Colorado River basin. These revisions are reflected in the presented map. 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

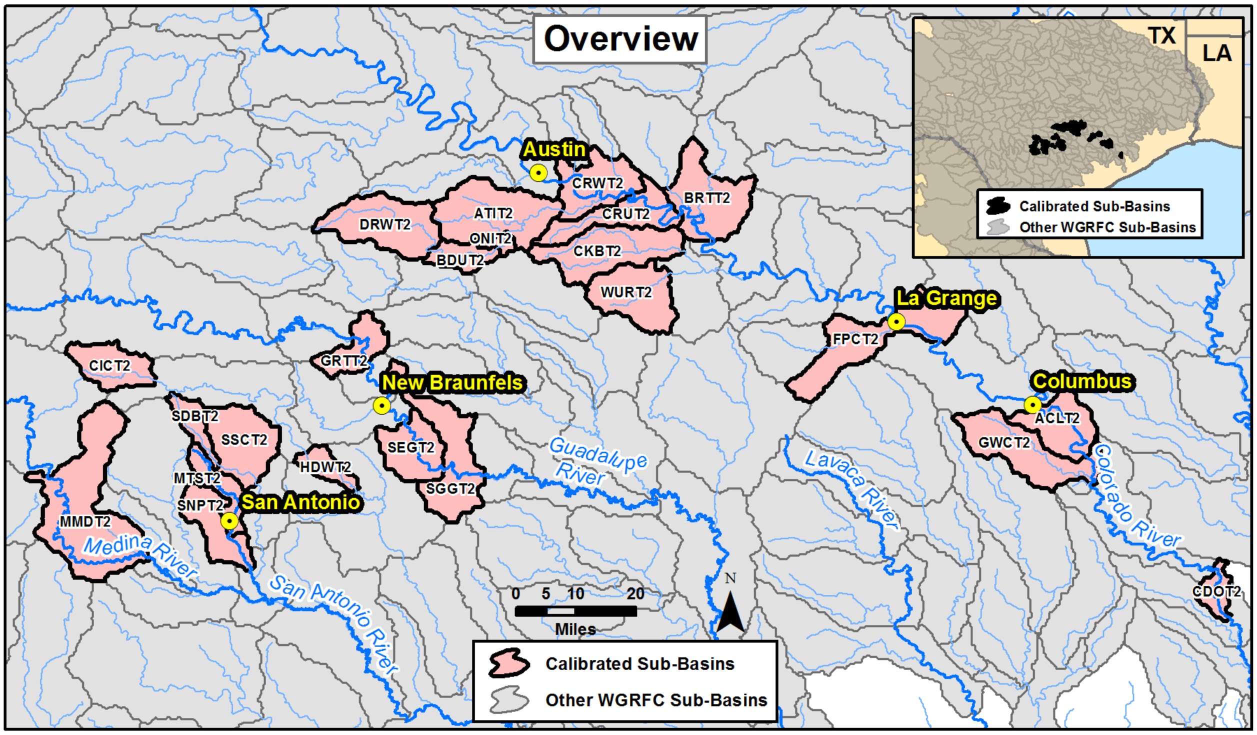


Table 1. List of Modeled Sub-basins

NWS ID	USGS/LCRA ID	Sub-basin Name	Sub-basin Type
		Colorado River	
DRWT2	08158700	Onion Creek near Driftwood	Headwater
BDUT2	4595	Onion Creek at Buda	Local Area
ONIT2	08158827	Onion Creek at Twin Cities Road near Manchaca	Local Area
ATIT2	08159000	Onion Creek at US 183, Austin	Local Area
CRWT2	5423	Colorado River at Webberville	Local Area
CRUT2	5450	Colorado River at Utley	Local Area
BRTT2	08159200	Colorado River at Bastrop	Local Area
CKBT2	5521	Cedar Creek Near Bastrop	Headwater
WURT2	5524	Walnut Creek near Rockne	Headwater
FPCT2	5635	Colorado River at FPP River Plant	Local Area
ACLT2	6377	Colorado River near Altair	Local Area
GWCT2	6399	Colorado River near Garwood	Local Area
CDOT2	6537	Colorado River near Lane City	Local Area
		Guadalupe River	
GRTT2	08167900	Guadalupe River at Third Crossing near Sattler	Local Area
SEGT2	08169760	Guadalupe River at Hwy 123 at Seguin	Local Area
SGGT2	08169792	Guadalupe River at FM1117 near Seguin	Local Area
		San Antonio River	
CICT2	08183900	Cibolo Creek near Boerne	Headwater
MMDT2	08180700	Medina River near Macdona	Local Area
SDBT2	08178593	Salado Creek at Blanco Rd, San Antonio	Headwater
MTST2	08178050	San Antonio River at Mitchell St, San Antonio	Headwater
SSCT2	08178700	Salado Creek at Loop 410, San Antonio	Local Area
SNPT2	08178565	San Antonio River at Loop 410, San Antonio	Local Area
HDWT2	08185065	Cibolo Creek near Saint Hedwig	Local Area

2. PROJECT DELIVERABLES

As is outlined in the project's scope of work, Exhibit B of the final contract (TWDB Contract No. 1600012068), RTI has delivered the following items to the TWDB and WGRFC upon completion of this study.

- *Final Task Report* - This report serves as a summary of the work performed for 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* – CHPS-FEWS configurations for each of the study areas (Colorado River, Guadalupe River, and San Antonio River) were provided by the WGRFC. RTI updated the configurations with final model parameters for the Lag/K, SAC-SMA, and UNIT-HG models as well as additional CHANLOSS and LOOKUP operations necessary to optimize simulations for some sub-basins. The configurations will allow the WGRFC to review the performance of the calibrations, as well as ease the transfer of necessary files to update 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, reports, and calibration tools and methodologies.

3. PRE-CALIBRATION DATA ANALYSIS

A thorough data analysis of sub-basin characteristics and model inputs was performed by RTI to identify potential issues that could impact the model calibration analysis. This 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

Initial sub-basin drainage area delineations were provided by the WGRFC. 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 2 through 4. Descriptions of each characteristic category are also provided.

Table 2. Physical/Hydrologic Characteristics of the Calibrated Colorado Sub-basins

NWSID	Local/Total Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
DRWT2	128 / 128	1624 / 1205 / 906	Edwards Plateau, Eastern Part	Clay Loam: 59% Loam: 39% Minor classes: 2%	A: 0%; B: 3%; C: 53%; D: 44%; W: 0%	Shrub/Scrub: 38% Evergreen Forest: 31% Grassland/Herbaceous: 17% Deciduous Forest: 11% Other: 3%
BDUT2	38 / 166	1115 / 846 / 653	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 93% Minor classes: 7%	A: 0%; B: 0%; C: 29%; D: 71%; W: 0%	Grassland/Herbaceous: 30% Shrub/Scrub: 26% Evergreen Forest: 18% Deciduous Forest: 14% Other: 12%
ONIT2	13 / 179	886 / 727 / 586	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 97% Minor classes: 3%	A: 0%; B: 1%; C: 30%; D: 69%; W: 0%	Shrub/Scrub: 26% Grassland/Herbaceous: 17% Developed, Open Space: 14% Deciduous Forest: 11% Other: 32%
ATIT2	146 / 326	1244 / 796 / 446	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 67% Clay Loam: 18% Loam: 12% Minor classes: 3%	A: 0%; B: 2%; C: 38%; D: 60%; W: 0%	Evergreen Forest: 20% Shrub/Scrub: 20% Developed, Open Space: 16% Grassland/Herbaceous: 11% Developed, Low Intensity: 10% Deciduous Forest: 10% Other: 13%
CRWT2	98 / 37110	705 / 489 / 390	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Loam: 29% Clay: 23% Sandy Clay Loam: 13% Other: 10% Silty Clay Loam: 10% Minor classes: 15%	A: 4%; B: 54%; C: 8%; D: 35%; W: 0%	Pasture/Hay: 19% Shrub/Scrub: 17% Developed, Open Space: 14% Other: 50%

(continued)

Table 2. Physical/Hydrologic Characteristics of the Calibrated Colorado Sub-basins (continued)

NWSID	Local/Total Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
CRUT2	89 / 37199	699 / 482 / 348	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Clay: 58% Loam: 11% Minor classes: 31%	A: 2%; B: 26%; C: 11%; D: 61%; W: 0%	Shrub/Scrub: 30% Pasture/Hay: 19% Deciduous Forest: 10% Grassland/Herbaceous: 10% Other: 31%
BRTT2	126 / 37551	643 / 454 / 341	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Sandy Clay Loam: 28% Clay Loam: 28% Minor classes: 44%	A: 8%; B: 33%; C: 9%; D: 51%; W: 0%	Pasture/Hay: 25% Shrub/Scrub: 17% Deciduous Forest: 13% Evergreen Forest: 13% Other: 32%
CKBT2	131 / 131	748 / 524 / 361	Texas Blackland Prairie, Northern Part	Clay: 59% Other: 19% Clay Loam: 15% Minor classes: 7%	A: 0%; B: 6%; C: 4%; D: 90%; W: 0%	Shrub/Scrub: 30% Deciduous Forest: 15% Pasture/Hay: 12% Grassland/Herbaceous: 11% Other: 32%
WURT2	107 / 107	663 / 490 / 351	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Clay: 56% Other: 24% Minor classes: 20%	A: 2%; B: 9%; C: 0%; D: 89%; W: 0%	Shrub/Scrub: 26% Deciduous Forest: 21% Pasture/Hay: 16% Developed, Open Space: 10% Other: 27%
FPCT2	156 / 38692	545 / 347 / 213	Texas Blackland Prairie, Southern Part; Texas Claypan Area, Southern Part	Clay: 53% Other: 24% Minor classes: 23%	A: 0%; B: 17%; C: 17%; D: 66%; W: 0%	Pasture/Hay: 35% Shrub/Scrub: 20% Deciduous Forest: 16% Other: 29%
ACLT2	87 / 39292	299 / 205 / 151	Gulf Coast Prairies; Texas Claypan Area, Southern Part	Clay: 50% Sandy Clay Loam: 15% Sandy Loam: 12% Clay Loam: 10% Minor classes: 13%	A: 0%; B: 9%; C: 11%; D: 80%; W: 0%	Pasture/Hay: 43% Deciduous Forest: 16% Evergreen Forest: 10% Other: 31%

(continued)

Table 2. Physical/Hydrologic Characteristics of the Calibrated Colorado Sub-basins (continued)

NWSID	Local/Total Drainage Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
GWCT2	131 / 39423	404 / 248 / 131	Gulf Coast Prairies; Texas Blackland Prairie, Southern Part; Texas Claypan Area, Southern Part	Clay: 41% Clay Loam: 20% Sandy Clay Loam: 16% Sandy Loam: 14% Minor classes: 9%	A: 0%; B: 5%; C: 39%; D: 55%; W: 0%	Pasture/Hay: 27% Deciduous Forest: 17% Evergreen Forest: 16% Shrub/Scrub: 14% Other: 26%
CDOT2	30 / 39635	102 / 90 / 72	Gulf Coast Prairies	Clay: 96% Minor classes: 4%	A: 0%; B: 6%; C: 0%; D: 93%; W: 0%	Cultivated Crops: 34% Pasture/Hay: 24% Deciduous Forest: 10% Other: 32%

Table 3. Physical/Hydrologic Characteristics of the Calibrated Guadalupe Sub-basins

NWSID	Local/Total Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
GRTT2	57 / 1508	1332 / 1006 / 722	Edwards Plateau, Eastern Part	Clay Loam: 37% Loam: 24% Clay: 20% Silty Clay: 17% Minor classes: 2%	A: 1%; B: 8%; C: 40%; D: 51%; W: 1%	Evergreen Forest: 60% Shrub/Scrub: 12% Other: 28%
SEGT2	82 / 1778	755 / 589 / 476	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Clay: 89% Minor classes: 11%	A: 0%; B: 19%; C: 10%; D: 71%; W: 0%	Cultivated Crops: 29% Shrub/Scrub: 22% Pasture/Hay: 15% Developed, Open Space: 12% Grassland/Herbaceous: 10% Other: 12%
SGGT2	133 / 1911	1001 / 578 / 443	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Clay: 66% Clay Loam: 10% Clay Loam: 10% Minor classes: 14%	A: 6%; B: 21%; C: 17%; D: 56%; W: 0%	Shrub/Scrub: 22% Cultivated Crops: 20% Pasture/Hay: 19% Developed, Open Space: 10% Other: 29%

Table 4. Physical/Hydrologic Characteristics of the Calibrated San Antonio Sub-basins

NWSID	Local/Total Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
CICT2	70 / 70	1985 / 1632 / 1302	Edwards Plateau, Eastern Part	Other: 35% Clay: 34% Loam: 22% Minor classes: 9%	A: 1%; B: 11%; C: 13%; D: 75%; W: 0%	Evergreen Forest: 38% Shrub/Scrub: 32% Grassland/Herbaceous: 12% Other: 18%
MMDT2	253 / 894	1837 / 1000 / 604	Edwards Plateau, Eastern Part; Northern Rio Grande Plain; Texas Blackland Prairie, Northern Part	Clay: 55% Other: 20% Loam: 16% Minor classes: 9%	A: 0%; B: 19%; C: 17%; D: 64%; W: 0%	Evergreen Forest: 26% Shrub/Scrub: 22% Cultivated Crops: 15% Grassland/Herbaceous: 12% Deciduous Forest: 10% Other: 15%
SDBT2	34 / 34	1417 / 1168 / 846	Edwards Plateau, Eastern Part	Other: 54% Clay: 45% Minor classes: 1%	A: 0%; B: 0%; C: 14%; D: 86%; W: 0%	Evergreen Forest: 44% Shrub/Scrub: 19% Developed, Open Space: 11% Other: 26%
MTST2	50 / 50	1122 / 815 / 610	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 78% Loam: 12% Minor classes: 10%	A: 0%; B: 14%; C: 36%; D: 50%; W: 0%	Developed, Low Intensity: 27% Developed, Open Space: 24% Developed, Medium Intensity: 22% Developed, High Intensity: 19% Other: 8%
SSCT2	106 / 140	1414 / 983 / 702	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 77% Other: 20% Minor classes: 3%	A: 0%; B: 3%; C: 23%; D: 73%; W: 0%	Developed, Open Space: 23% Developed, Low Intensity: 19% Developed, Medium Intensity: 17% Evergreen Forest: 16% Other: 25%

(continued)

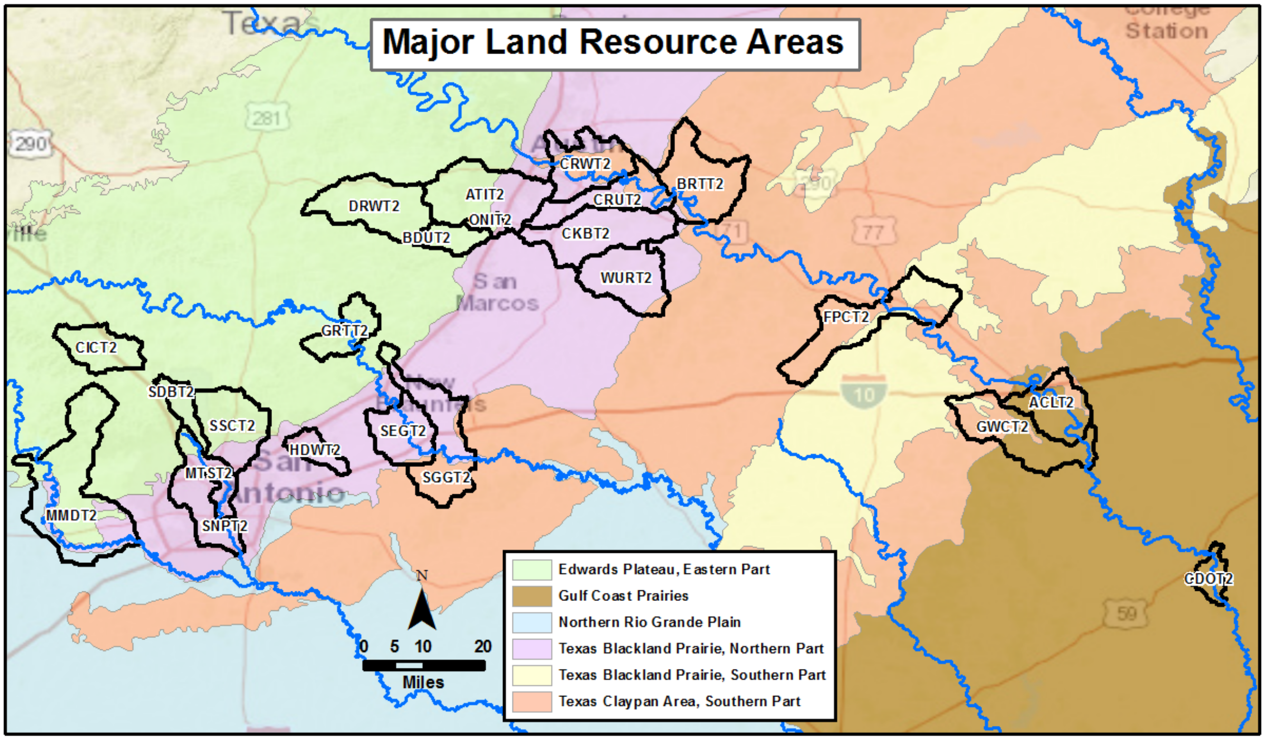
Table 4. Physical/Hydrologic Characteristics of the Calibrated San Antonio Sub-basins (continued)

NWSID	Local/Total Drainage Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
SNPT2	75 / 125	1014 / 693 / 505	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 85% Loam: 12% Minor classes: 3%	A: 0%; B: 32%; C: 15%; D: 53%; W: 0%	Developed, Low Intensity: 33% Developed, Open Space: 24% Developed, Medium Intensity: 22% Developed, High Intensity: 13% Other: 8%
HDWT2	32 / 308	899 / 734 / 607	Texas Blackland Prairie, Northern Part	Clay: 97% Minor classes: 3%	A: 0%; B: 26%; C: 14%; D: 60%; W: 0%	Developed, Open Space: 19% Cultivated Crops: 14% Developed, Low Intensity: 14% Developed, Medium Intensity: 14% Shrub/Scrub: 10% Other: 29%

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 6 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 (USDA-NRCS 2006).

Figure 2. Major Land Resource Areas in the Study Area



The MLRA data was obtained from 2006 MLRA Geographic Database, version 4.2 from United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) (USDA-NRCS 2006).

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 5 (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.

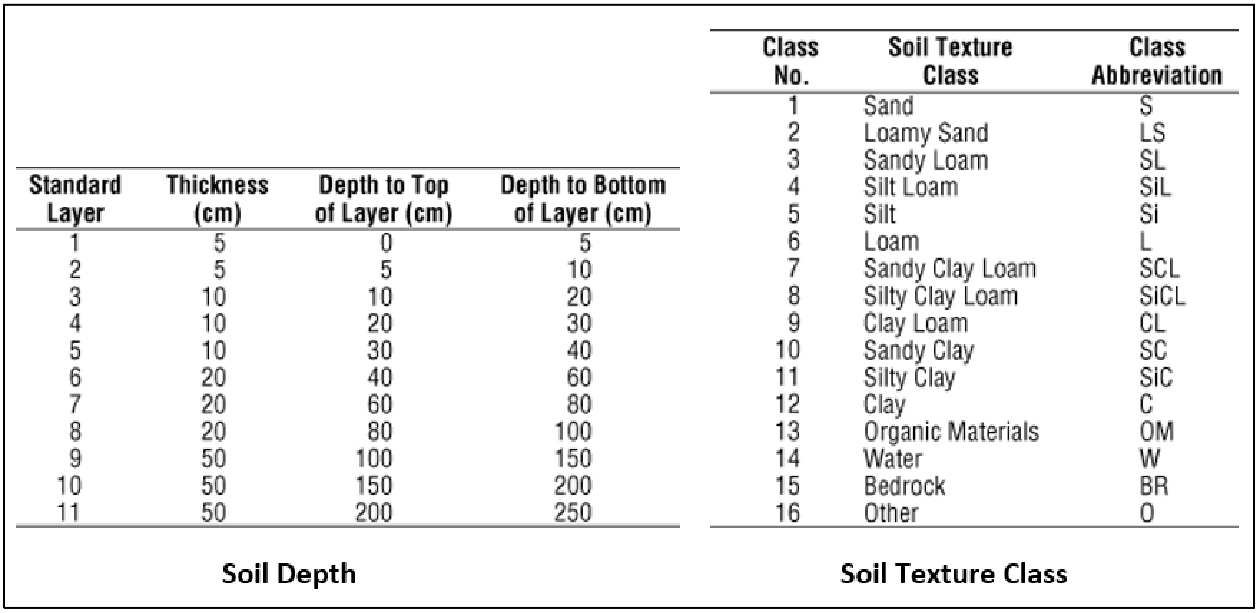
Table 5. SAC-SMA parameter ranges for varying soil types (Anderson 2002 Table 7-5-2)

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 US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) State Soil Geographic Database (STATSGO).

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 10% of the sub-basin area were grouped as "others".

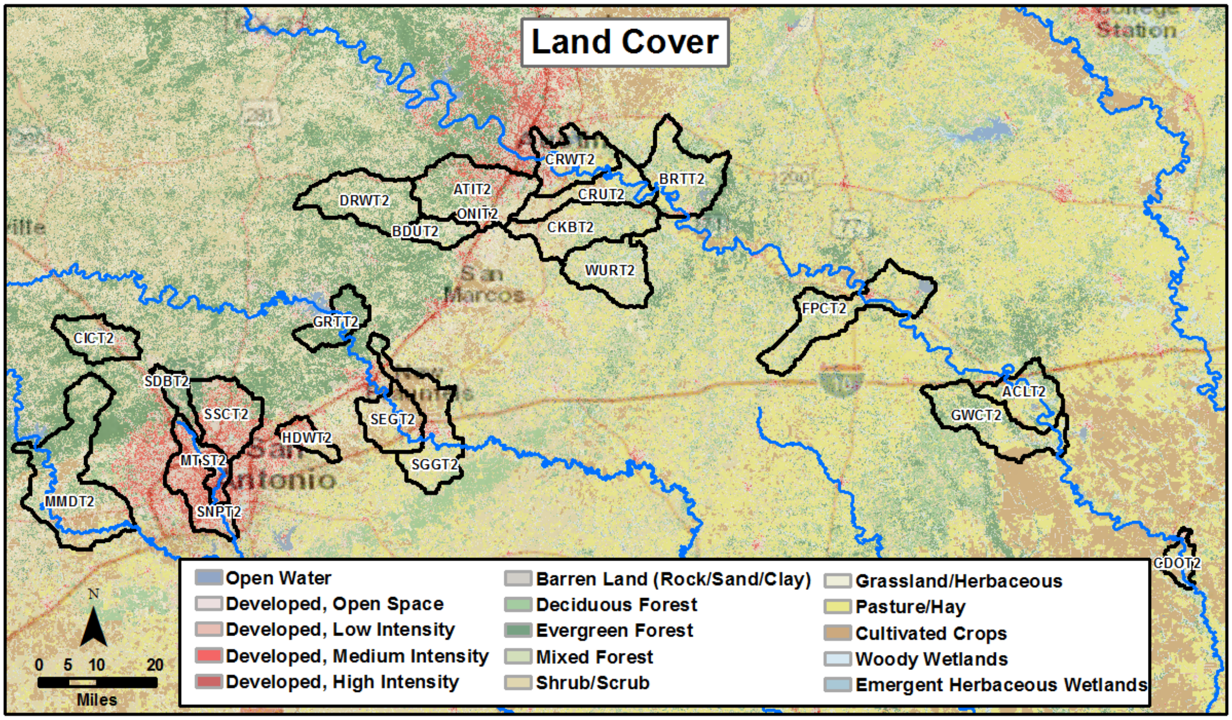
Figure 4 shows a map of the modeled sub-basins with the associated 15 LCLU classes in the region. Descriptions (from NLCD 2011 metadata information) of these classes are provided below:

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 gramanoid 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 cities of San Antonio and Austin, which are visible in red in Figure 4.

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 the Sabine, Neches, and Pecos river basins (Riverside 2013), 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 with the exception of ONIT2 and ATIT2. These sub-basins required a re-delineation and the mean areal precipitation was calculated from the raw gridded XMRG files. 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 16-year period 2000-2015 where the datasets overlap. Table 6 shows the percent difference between the annual average MAPX precipitation and the PRISM precipitation dataset over this period.

Table 6. Comparison of MAPX with PRISM 2000–2015

Sub-basin	MAPX (in)	PRISM (in)	% Diff
	Colorado River		
DRWT2	32.6	33.8	-3.5%
BDUT2	34.3	35.8	-4.3%
ONIT2	35.7	35.5	0.7%
ATIT2	35.1	35.5	-1.3%
CRWT2	33.7	33.9	-0.6%
CRUT2	33.4	34.0	-1.9%
BRTT2	34.3	34.7	-1.2%
CKBT2	32.8	34.3	-4.5%
WURT2	31.7	33.9	-6.5%
FPCT2	38.5	38.3	0.5%
ACLT2	42.1	42.5	-0.8%
GWCT2	42.5	42.5	0.1%
CDOT2	47.3	46.5	1.8%

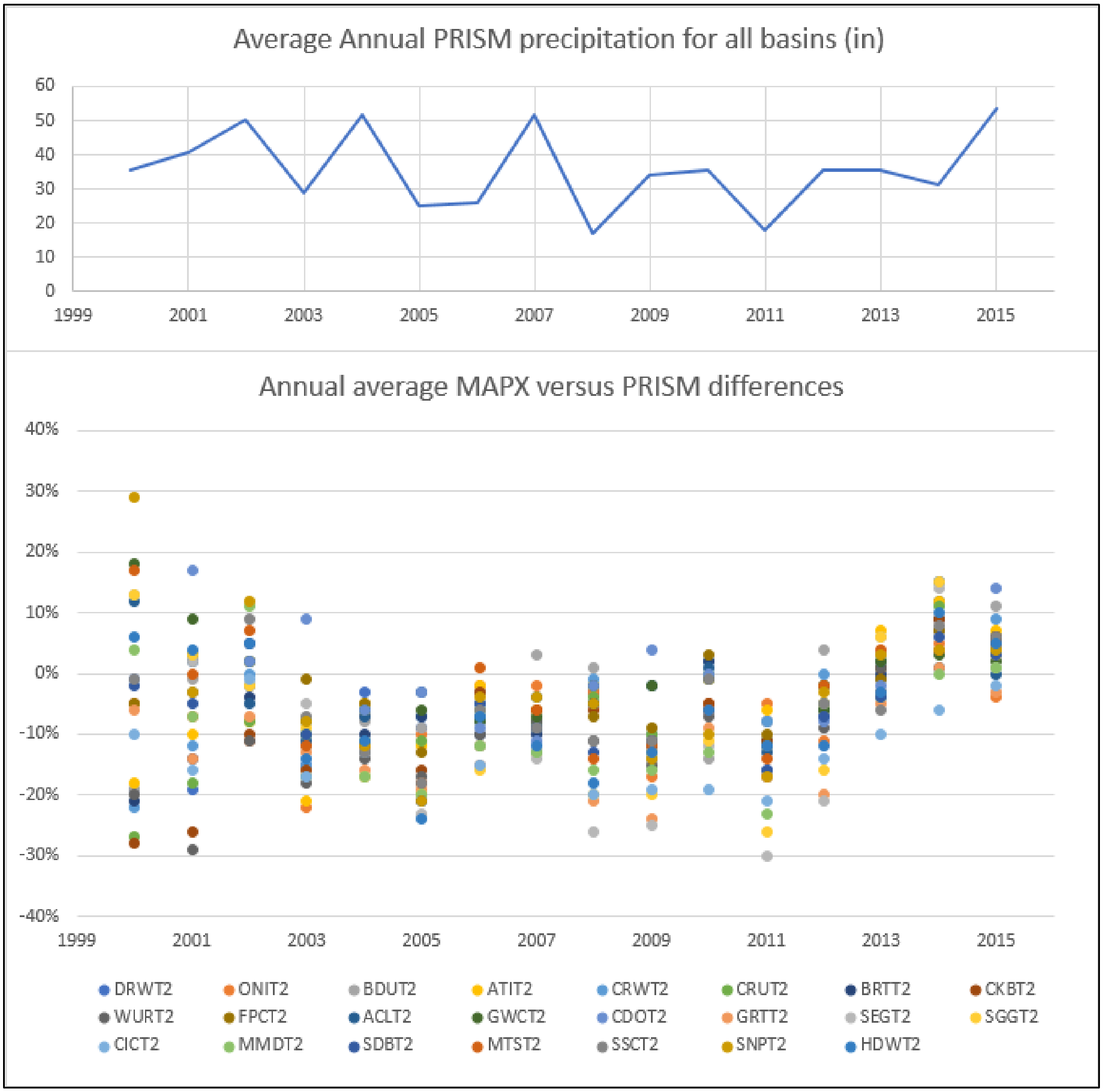
(continued)

Table 6. Comparison of MAPX with PRISM 2000–2015 (continued)

Sub-basin	MAPX (in)	PRISM (in)	% Diff
Guadalupe River			
GRTT2	33.4	36.8	-9.2%
SEGT2	31.2	32.9	-5.2%
SGGT2	31.0	32.7	-5.0%
San Antonio River			
CICT2	32.0	35.8	-10.6%
MMDT2	30.4	31.8	-4.5%
SDBT2	33.8	34.9	-3.0%
MTST2	33.7	33.7	-0.1%
SSCT2	34.0	34.3	-0.8%
SNPT2	32.8	32.1	2.2%
HDWT2	32.0	32.6	-1.9%

In this table, absolute differences greater than 5% are highlighted in red. These results show that the majority of MAPX differences with PRISM are negative. Five sub-basins indicate average MAPX values with an absolute difference with PRISM greater than 5%. To investigate these differences further, an analysis was done to compare the annual average difference for each year from 2000-2015 to identify any trends. 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 data sets.

Figure 5. **Average PRISM precipitation for all sub-basins and percent differences in MAPX versus PRISM for each year from 2000-2015**



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 16% and 11% in 2000 and 2001 respectively to ranges of 4 to 7% from 2002 to 2015. However, it is also clear from both Table 6 and Figure 5 that the radar-based MAPX data tends to under estimate the accumulated rainfall when compared with station-based PRISM data, particularly from 2003 to 2012. This aligns with similar observations RTI has observed in previous model calibration work for the WGRFC (Riverside 2013).

In addition, there does not appear to be a correlation with the level of rainfall and the observed percent difference. This is most evident when comparing 2007, which accumulated an average 52 inches of rainfall across the study sub-basins versus 2008 with an average of 17 inches. Despite the large difference in precipitation, both years show consistently negative percent differences with PRISM. However, there might be a correlation with greater rainfall resulting in a smaller standard deviation in percent difference, as some of the largest precipitation years (2004, 2007, 2015) also appear to have the smallest range in values.

After comparison of the MAPX data with PRISM, along with the limitations of instantaneous streamflow records (discussed further in Section 3.4), the model calibration period was selected as January 2011 through December 2016 for all sub-basins. This provides six (6) years of data (where streamflow observation are available) for calibration, and includes many of the largest flood events (occurring in 2013, 2015, and 2016). Furthermore, this period allows the calibration analysis to utilize the real-time precipitation forcings of the operational system without being significantly influenced by the historical negative biases of the previous decade. When comparing the percent differences of the average annual MAPX versus PRISM values from 2011 through 2015 in Table 7, the range and balance of positive versus negative percent differences is improved over those previously presented in Table 6. This offers more confidence in the development of the water balance (Section 3.5) and hydrologic model calibration (Section 4).

Table 7. Comparison of MAPX with PRISM 2011-2015

Sub- basin	MAPX (in)	PRISM (in)	% Diff
Colorado River			
DRWT2	33.8	34.3	1.4%
ONIT2	39.7	38.3	-3.6%
BDUT2	38.7	41.2	6.6%
ATIT2	38.9	40.6	4.4%
CRWT2	36.6	38.4	5.0%
CRUT2	35.3	36.2	2.4%
BRTT2	34.7	35.4	1.9%
CKBT2	35.8	36.3	1.3%
WURT2	34.0	33.7	-0.9%
FPCT2	35.9	36.3	1.1%
ACLT2	41.0	40.3	-1.7%
GWCT2	40.1	39.9	-0.6%
CDOT2	39.7	41.2	3.6%

(continued)

Table 7. Comparison of MAPX with PRISM 2011-2015 (continued)

Sub- basin	MAPX (in)	PRISM (in)	% Diff
Guadalupe River			
GRTT2	35.7	33.1	-7.4%
SEGT2	29.6	28.2	-4.8%
SGGT2	30.0	29.4	-2.1%
San Antonio River			
CICT2	31.4	28.7	-8.7%
MMDT2	27.4	26.3	-4.2%
SDBT2	32.7	32.0	-2.2%
MTST2	33.0	33.2	0.8%
SSCT2	33.0	32.9	-0.4%
SNPT2	31.0	30.9	-0.3%
HDWT2	30.4	30.0	-1.2%

3.3 Potential Evapotranspiration

The SAC-SMA model requires daily time series or average monthly estimates of potential evapotranspiration (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)

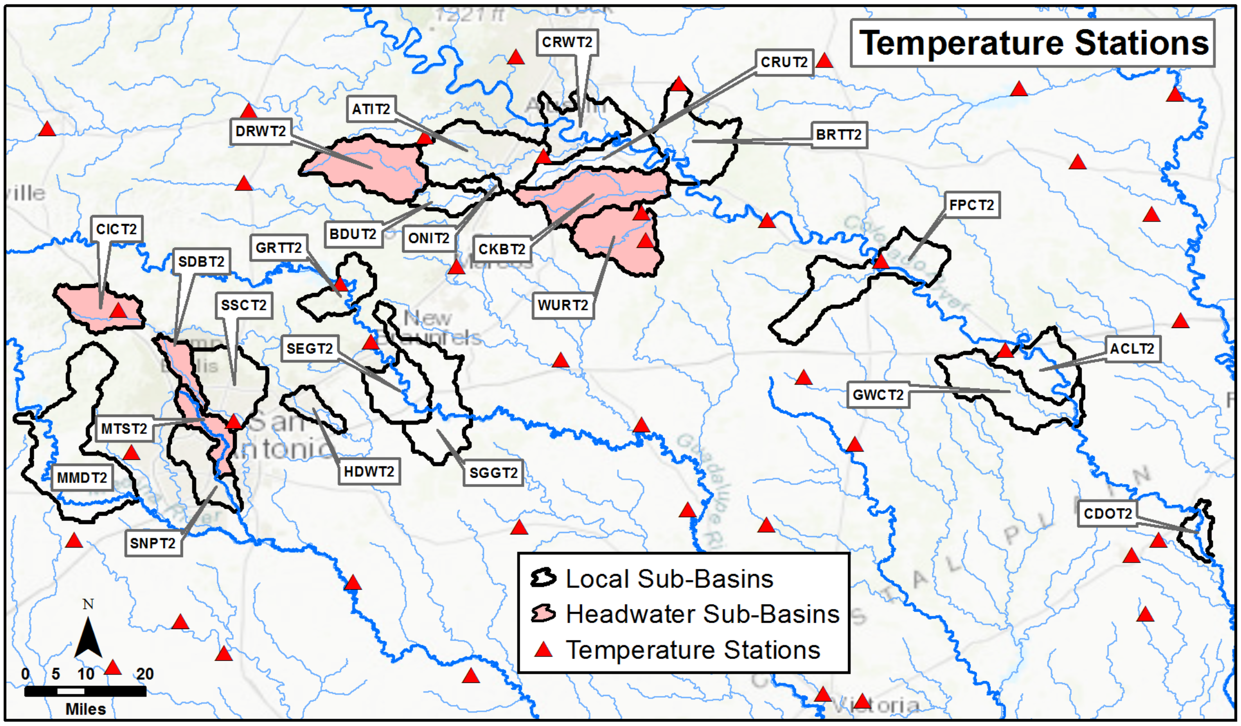
- Monthly Average Minimum Daily Temperature at each weather station to be included in the analysis (12 values per station)
- Temperature Station Latitude
- Temperature Station Longitude
- Temperature Station Elevation
- Sub-basin Centroid Latitude
- Sub-basin Centroid Longitude

An average wind speed of 7.5 miles per hour (3.3 m/s) was calculated from the average monthly reported measurements of three airport stations in the region (Austin – ID 13958; Houston - ID 12960; and San Antonio – ID 12291) with data obtained from the NOAA National Centers for Environmental Information (NCEI) (NCDC-NCEI 2017a).

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 42 stations in the study region as shown in Figure 6. These monthly maximum and minimum temperature normals were obtained from NOAA NCEI (NCDC-NCEI 2017b) based on data from the period 1981-2010. Once PET estimates were generated for the 42 temperature station locations, mean values for the modeled sub-basins were derived using inverse distance weighting techniques with the sub-basin centroids. The initial PET estimates were used in the development of the Water Balance calculation described in Section 3.3.1 but were refined in the final calibration as discussed in Section 3.3.2.

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 by MLRA as shown in Table 8. For sub-basins that include more than one MLRA, such as ATIT2, the predominant land cover was also considered in determining the groupings.
- 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 9) are specified in the SAC-SMA operation to convert the incoming PE datasets into values that emulate the calibrated PET curves.

Table 8. Grouping of Sub-basins by MLRA

	MLRA Name			
	Edwards Plateau	***Texas Blackland Prairie***	***Texas Claypan Area***	***Gulf Coast Prairies***
Sub-basins	CICT2	MTST2	CRWT2	ACLT2
	MMDT2	SNPT2	CRUT2	GWCT2
	SDBT2	HDWT2	BRTT2	CDOT2
	SSCT2	SEGT2	FPCT2	
	GRTT2	SGGT2		
	DRWT2	ONIT2		
	BDUT2	CKBT2		
	ATIT2	WURT2		

Table 9. 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**
ACLT2	1.33	1.40	1.20	1.06	0.97	0.87	1.01	0.99	1.14	1.31	1.42	1.58
ATIT2	1.04	0.97	0.93	0.88	0.83	0.92	0.98	0.95	1.11	1.26	1.56	1.26
BDUT2	0.89	0.87	0.80	0.76	0.72	0.81	0.86	0.83	0.98	1.08	1.39	1.12
BRTT2	1.05	1.06	0.97	0.94	0.87	0.81	0.85	0.82	0.92	1.10	1.22	1.31
CDOT2	1.21	1.30	1.13	1.00	0.92	0.85	0.98	0.95	1.05	1.25	1.29	1.46
CICT2	0.99	0.97	0.85	0.82	0.78	0.83	0.85	0.84	1.03	1.12	1.50	1.28
CKBT2	1.09	1.16	0.99	1.02	1.03	0.85	0.98	0.97	1.13	1.35	1.23	1.48
CRUT2	1.05	1.02	0.95	0.95	0.87	0.81	0.84	0.81	0.93	1.08	1.23	1.33
CRWT2	1.04	0.96	0.94	0.94	0.87	0.80	0.84	0.79	0.90	1.07	1.22	1.31
DRWT2	0.93	0.91	0.83	0.79	0.76	0.85	0.90	0.87	1.00	1.11	1.43	1.19

(continued)

Table 9. Monthly PE Adjustment Factors by Sub-basin for Use in the SAC-SMA Operation (continued)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
FPCT2	1.12	1.16	1.04	0.99	0.91	0.86	0.94	0.88	0.99	1.17	1.29	1.39
GRTT2	0.86	0.89	0.79	0.76	0.72	0.81	0.85	0.80	0.92	1.04	1.33	1.11
GWCT2	1.33	1.40	1.20	1.09	0.97	0.87	1.01	0.99	1.14	1.31	1.36	1.58
HDWT2	1.16	1.23	1.04	1.07	1.11	0.91	1.02	0.98	1.15	1.33	1.25	1.46
MMDT2	1.18	1.19	1.07	1.00	0.97	1.06	1.10	1.06	1.25	1.34	1.92	1.49
MTST2	1.17	1.26	1.05	1.08	1.11	0.91	1.01	0.98	1.16	1.32	1.30	1.56
ONIT2	0.90	0.93	0.82	0.86	0.88	0.73	0.83	0.82	0.94	1.09	1.02	1.19
SDBT2	1.17	1.18	1.05	1.00	0.97	1.06	1.10	1.07	1.28	1.38	1.89	1.48
SEGT2	1.09	1.20	1.00	1.02	1.08	0.89	1.04	0.98	1.15	1.33	1.24	1.44
SGGT2	1.16	1.20	1.03	1.05	1.11	0.91	1.05	1.00	1.16	1.38	1.25	1.45
SNPT2	1.18	1.25	1.02	1.06	1.11	0.91	1.03	0.99	1.17	1.33	1.32	1.57
SSCT2	1.05	1.11	0.94	0.91	0.85	0.93	0.97	0.94	1.11	1.23	1.61	1.33
WURT2	1.06	1.06	0.89	0.92	0.92	0.77	0.89	0.89	1.04	1.22	1.18	1.35

For the Gulf Coast MLRA, no consistent tendencies were evident in the average monthly volume bias values for the group of calibrated sub-basins. This group only has three sub-basins, and the available period of record for the observed streamflow data for one of the sub-basins (GWCT2) was very limited; therefore, no adjustments were applied to the initial PET curves for the Gulf Coast group. The final PET curves for all calibrated sub-basins are provided in Table 10. In addition, plots of the final PET curves, organized by river basin, are provided in Figures 7 to 9. A comparison plot of the average PET curve by river basin is given in Figure 10. As indicated in this comparison plot, the average PET is higher in the hotter and generally less humid San Antonio and Guadalupe river basins. In the Colorado river basin, which generally experiences higher humidity levels, and therefore slightly more resistance to evapotranspiration, the average PET curve is lower.

Table 10. Final Monthly PET Daily Rates (mm/day) by Sub-basin

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
ACLT2	2.12	2.51	3.24	4.03	4.47	4.97	5.34	5.54	4.89	3.94	2.85	2.21
ATIT2	1.98	2.33	2.98	3.78	4.25	5.82	5.98	6.10	5.19	4.03	3.58	2.01
BDUT2	1.78	2.10	2.65	3.36	3.75	5.13	5.26	5.38	4.58	3.58	3.19	1.80
BRTT2	1.88	2.23	2.90	3.85	4.33	4.92	4.93	4.90	4.14	3.31	2.56	1.96
CDOT2	2.06	2.47	3.16	3.91	4.34	4.75	5.00	5.12	4.51	3.75	2.84	2.18
CICT2	1.78	2.14	2.65	3.36	3.67	4.95	4.99	5.15	4.42	3.46	3.16	1.79

(continued)

Table 10. Final Monthly PET Daily Rates (mm/day) by Sub-basin (continued)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
CKBT2	2.08	2.56	3.06	4.20	5.15	5.21	5.75	5.99	5.08	4.18	2.71	2.22
CRUT2	1.90	2.24	2.93	3.88	4.36	4.94	4.96	4.92	4.16	3.33	2.59	1.99
CRWT2	1.87	2.21	2.92	3.87	4.37	4.93	4.97	4.89	4.13	3.31	2.57	1.96
DRWT2	1.77	2.10	2.67	3.41	3.80	5.20	5.32	5.45	4.62	3.55	3.14	1.78
FPCT2	2.01	2.33	3.02	4.06	4.56	5.17	5.27	5.19	4.34	3.52	2.70	2.09
GRTT2	1.63	1.96	2.45	3.12	3.51	4.84	4.93	5.09	4.24	3.31	2.93	1.66
GWCT2	2.13	2.52	3.25	4.04	4.48	4.98	5.36	5.55	4.88	3.94	2.85	2.21
HDWT2	2.33	2.94	3.43	4.69	5.67	5.65	6.13	6.34	5.40	4.52	2.99	2.48
MMDT2	2.37	2.85	3.53	4.51	4.97	6.71	6.73	6.80	5.75	4.57	4.22	2.38
MTST2	2.34	3.01	3.46	4.76	5.64	5.61	6.06	6.21	5.35	4.48	3.00	2.50
ONIT2	1.80	2.23	2.69	3.70	4.56	4.58	5.07	5.22	4.41	3.61	2.34	1.91
SDBT2	2.34	2.83	3.48	4.42	4.83	6.55	6.59	6.73	5.75	4.55	4.16	2.37
SEGT2	2.29	2.88	3.39	4.60	5.63	5.61	6.11	6.36	5.41	4.53	2.97	2.44
SGGT2	2.31	2.89	3.40	4.63	5.66	5.66	6.18	6.42	5.45	4.56	2.99	2.46
SNPT2	2.36	3.00	3.48	4.79	5.76	5.71	6.17	6.32	5.38	4.53	3.04	2.51
SSCT2	2.09	2.55	3.10	3.93	4.25	5.78	5.81	5.91	5.10	4.05	3.71	2.13
WURT2	1.91	2.33	2.75	3.79	4.58	4.69	5.14	5.44	4.68	3.78	2.49	2.03

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

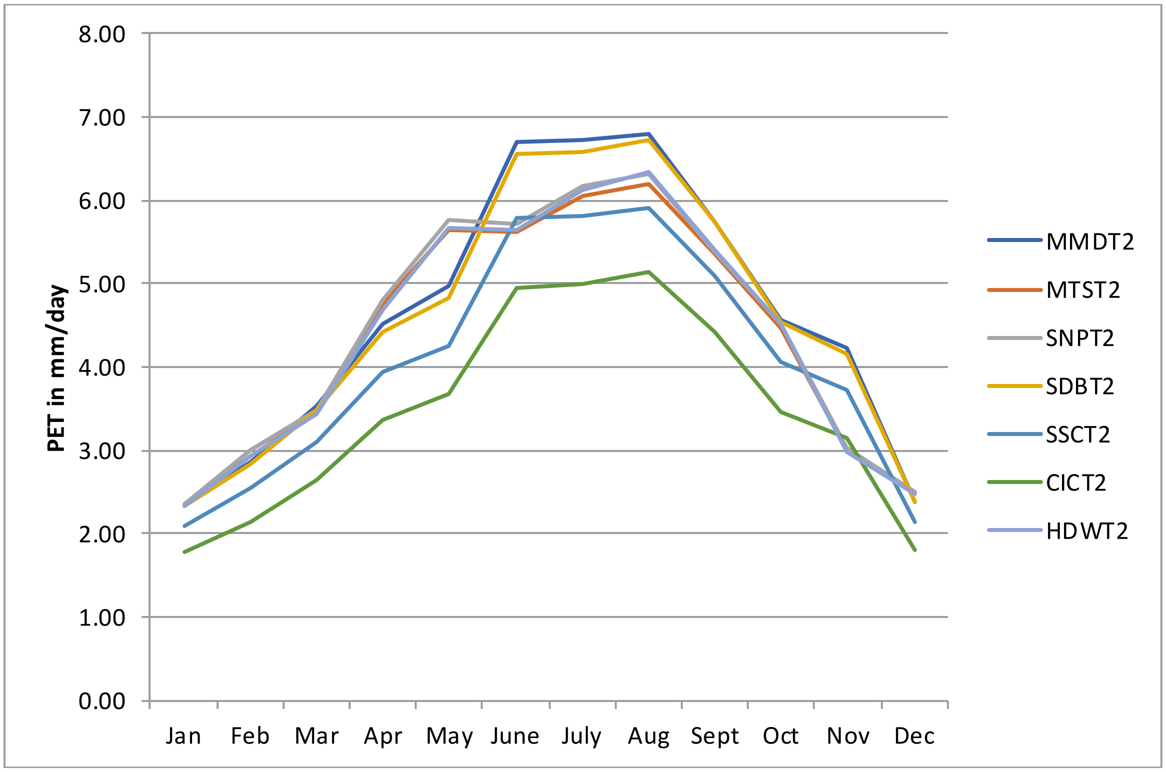


Figure 8. Final PET Curves for the Guadalupe River Basin

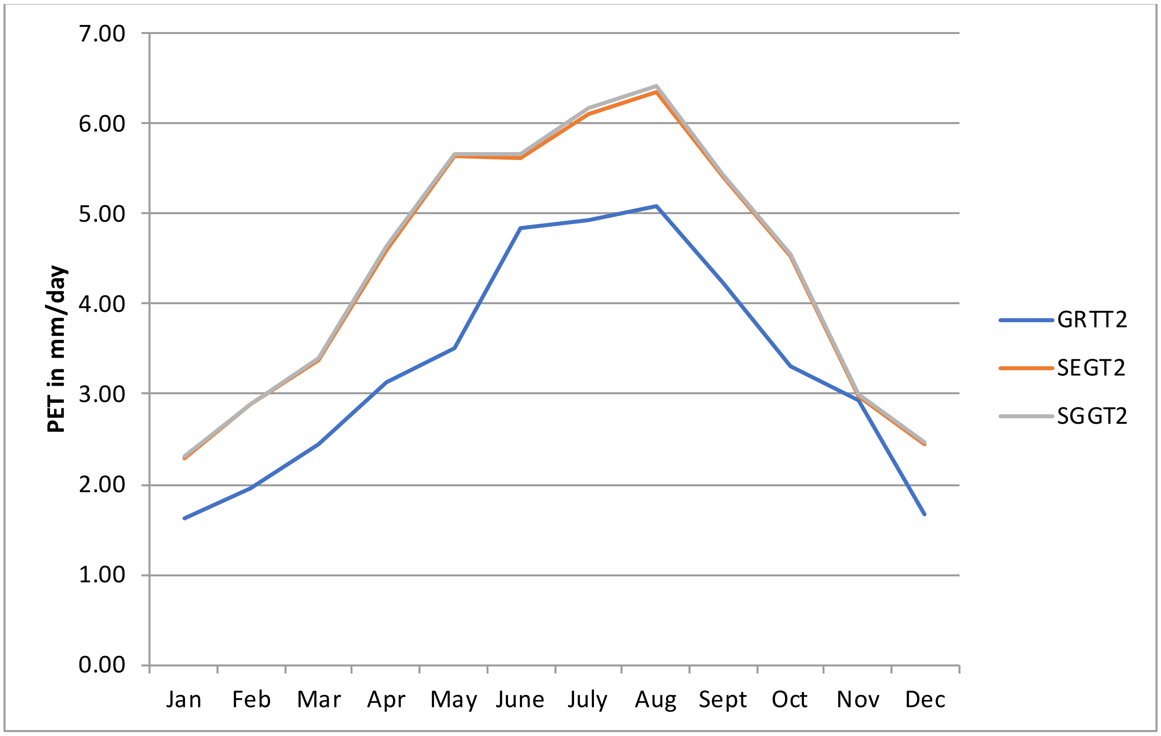


Figure 9. **Final PET Curves for the Colorado River Basin**

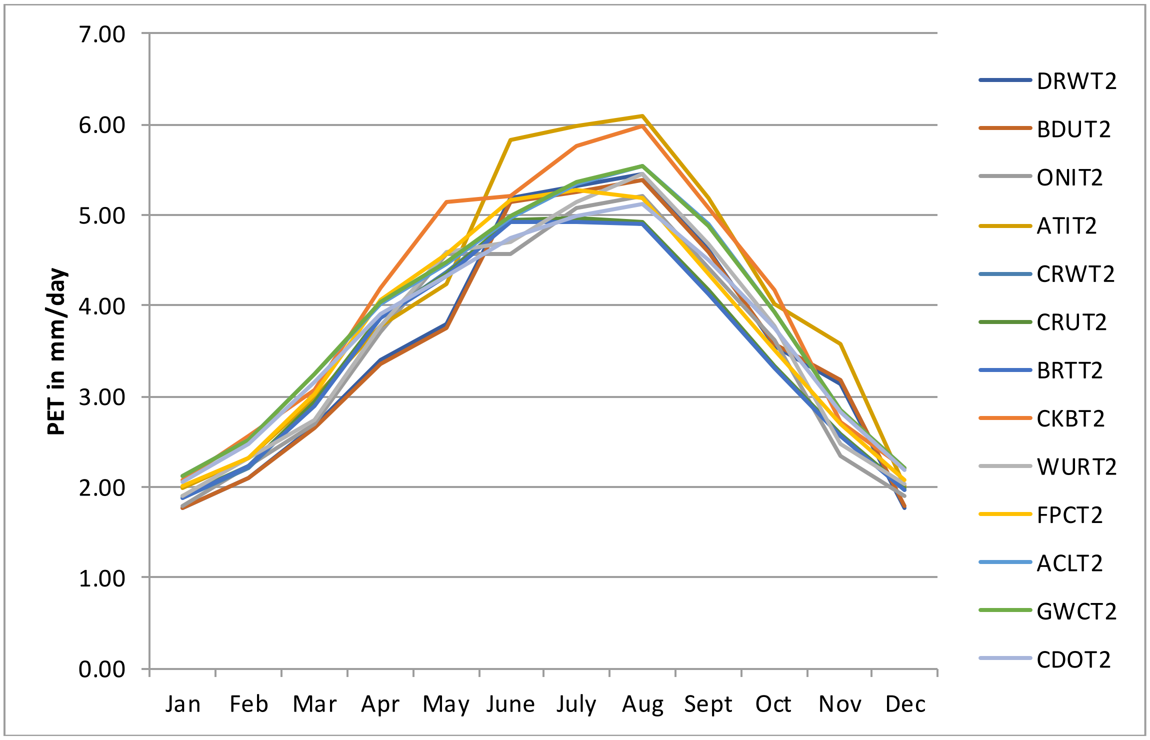
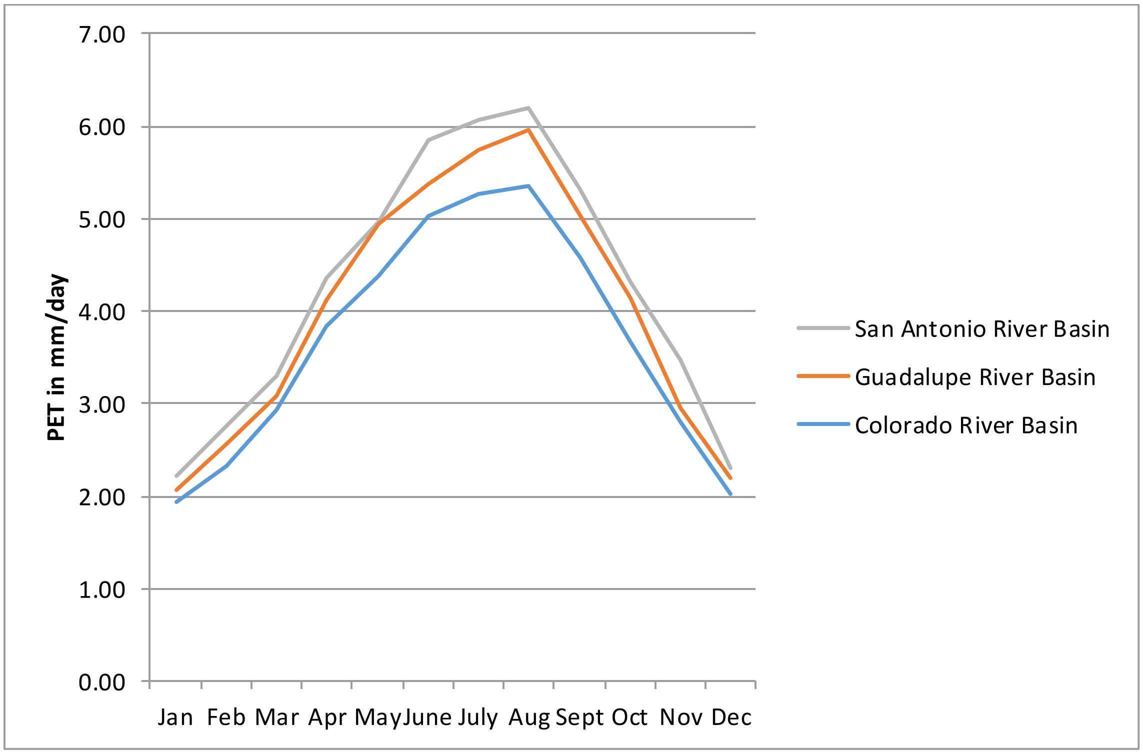


Figure 10. **Final Average PET Curves by River Basin**



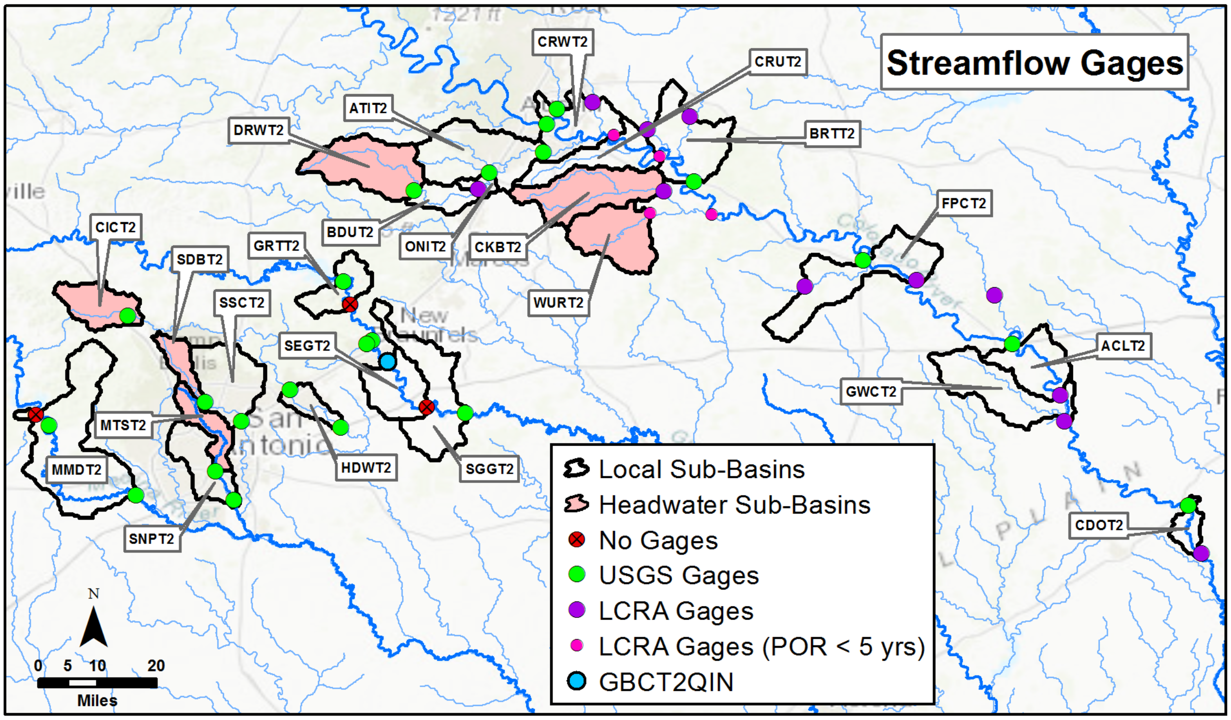
3.4 Streamflow Data

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 gauging 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 (measured as R2) over the common observed period 2000-2016.

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 2017), or the Lower Colorado River Authority (LCRA) hydromet site (LCRA 2017). In addition, instantaneous data for sub-basin GBCT2 (upstream of SEGT2 in the Guadalupe) was provided by the WGRFC. All instantaneous data sets were converted to a uniform hourly time step for model calibration. Figure 11 presents a map of the study sub-basins and associated streamflow gage data sources.

Figure 11. Historical Observed Streamflow Gage Locations



Note from Figure 11 that no flow data were available for three important locations. These included the releases from Medina Lake upstream of sub-basin MMDT2 in the San Antonio River basin, the outlet of sub-basin GRTT2 in the Guadalupe River basin, and the outlet of sub-basin SEGT2 also in the Guadalupe. Each of these missing locations required scaling flows from nearby gages or combining the calibration with an adjacent sub-basin. The details of each of these unique cases are discussed further in the respective sub-basin descriptions in Section 4.

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 11. Additional information is provided under each sub-basin description in Section 4. The "Peak Flow Data" column denotes locations where reported peak flow values from USGS gages were retrieved (where available) to statistically assess the performance of the simulation to high flow events with respect to timing and magnitude.

Table 11. Streamflow Summary

Station ID	Station Name	Location	Mean Annual Flow (cfs)	Peak Flow (cfs)	Peak Flow Date	Peak Flow Data	Instantaneous Data POR
			Colorado Basins				
08158700	USGS - Onion Ck nr Driftwood, TX	DRWT2 outlet	53	16,600	2015-10-30	x	2007-10 to 2017-01
4595	LCRA - Onion Creek at Buda	BDUT2 outlet	70	28,640	2015-10-30		2000-02 to 2000-06 2002-10 to 2004-09 2006-10 to 2017-01
08158827	USGS - Onion Ck at Twin Creeks Rd nr Manchaca, TX	ONIT2 outlet	45	60,100	2013-10-31	x	2003-04 to 2017-01
08159000	USGS - Onion Ck at US Hwy 183, Austin, TX	ATIT2 outlet	81	138,000	1921-09-09	x	1991-06 to 2017-01
08158000	USGS - Colorado Rv at Austin, TX	near u/s of CRWT2	2,108	550,000	1869-07-07		1991-07 to 2017-01
08158600	USGS - Walnut Ck at Webberville Rd, Austin, TX	u/s of CRWT2	32	16,400	2007-01-13		2007-10 to 2017-01
5417	LCRA - Gileland Creek near Manor	u/s of CRWT2	28	17,747	2015-05-25		2000-01 to 2017-01
5423	LCRA - Colorado River near Webberville	CRWT2 outlet	2,810	30,171	2016-06-03		2015-12 to 2017-01
5450	LCRA - Colorado River near Utley	CRUT2 outlet	3,544	31,925	2016-05-27		2016-03 to 2017-01
5464	LCRA - Wilbarger Creek near Elgin	u/s of BRTT2	74	31,966	2015-05-26		2002-09 to 2017-01
5473	LCRA - Big Sandy Creek near Elgin	u/s of BRTT2	15	9,651	2015-10-30		2003-05 to 2017-01
08159200	USGS - Colorado Rv at Bastrop, TX	BRTT2 outlet	2,093	79,600	1960-10-29	x	1993-10 to 2017-01
5521	LCRA - Cedar Creek near Bastrop	CKBT2 outlet	60	30,573	2015-10-31		2009-01 to 2017-01
5524	LCRA - Walnut Creek near Rockne	WURT2 outlet	132	22,803	2016-05-27		2016-02 to 2017-01
5608	LCRA - Buckners Creek near Muldoon	u/s of FPCT2	32	16,857	2004-11-22		2000-01 to 2017-01
08160400	USGS - Colorado Rv abv La Grange, TX	u/s of FPCT2	2,349	89,800	1998-10-20		1993-10 to 2017-01
5635	LCRA - Colorado River at FPP River Plant	FPCT2 outlet	1,234	94,180	2016-05-28		2010-07 to 2017-01
08161000	USGS - Colorado Rv at Columbus, TX	u/s of ACLT2	2,997	190,000	1935-06-19		1990-10 to 2017-01

(continued)

Table 11. Streamflow Summary (continued)

Station ID	Station Name	Location	Mean Annual Flow (cfs)	Peak Flow (cfs)	Peak Flow Date	Peak Flow Data	Instantaneous Data POR
6377	LCRA - Colorado River near Altair	ACLT2 outlet	2,184	76,231	2004-11-25		2003-11 to 2017-01
6399	LCRA - Colorado River near Garwood	GWCT2 outlet	506	71,607	2016-04-19		2002-09 to 2017-01
08162000	USGS - Colorado Rv at Wharton, TX	u/s of CDOT2	2,654	159,000	1935-06-20		1988-06 to 1988-07 1990-10 to 2017-01
6537	LCRA - Colorado River near Lane City	CDOT2 outlet	2,226	72,541	2004-11-27		2000-06 to 2016-12
Guadalupe Basins							
08167800	USGS - Guadalupe Rv at Sattler, TX	near u/s of GRTT2	469	70,000	2002-07-06		1986-10 to 2017-01
08168500	USGS - Guadalupe Rv abv Comal Rv at New Braunfels, TX	near u/s of SEGT2	563	101,000	1935-06-15		1986-10 to 1990-05 1995-10 to 2017-01
08169000	USGS - Comal Rv at New Braunfels, TX	near u/s of SEGT2	299	73,500	1998-10-17		1986-10 to 1990-09 1992-10 to 2017-01
GBCT2QIN	Guadalupe River below Comal River at New Braunfels	u/s of SEGT2	579	58,263	2010-06-09		2007-10 to 2017-01
08169792	USGS - Guadalupe Rv at FM 1117 nr Seguin, TX	SGGT2 outlet	768	46,300	2010-06-09	x	2005-03 to 2017-01
San Antonio Basins							
08183900	USGS - Cibolo Ck nr Boerne, TX	near CICT2 outlet	30	36,400	1964-09-27	x	1991-12 to 1995-03 2011-10 to 2017-01
08180500	USGS – Medina Rv nr Riomedina, TX	near u/s of MMDT2	61	28,600	1973-07-15		2001-01 to 2017-01
08180700	USGS - Medina Rv nr Macdona, TX	MMDT2 outlet	181	55,400	2002-07-06	x	1987-05 to 1987-06 1991-12 to 1995-09 1997-05 to 2017-01
08178593	USGS - Salado Ck at Blanco Rd. San Antonio, Tx	SDBT2 outlet	1	3,490	2013-05-25	x	2009-10 to 2017-01

(continued)

Table 11. Streamflow Summary (continued)

Station ID	Station Name	Location	Mean Annual Flow (cfs)	Peak Flow (cfs)	Peak Flow Date	Peak Flow Data	Instantaneous Data POR
08178700	USGS - Salado Ck at Loop 410, San Antonio, TX	SSCT2 outlet	18	64,400	1998-10-17	x	1991-06 to 2006-12 2011-02 to 2017-01
08178050	USGS - San Antonio Rv at Mitchell St, San Antonio, TX	MTST2 outlet	77	22,400	2013-05-25	x	1992-12 to 2008-12 2010-04 to 2017-01
08178565	USGS - San Antonio Rv at Loop 410, San Antonio, TX	near SNPT2 outlet	129	81,400	2013-05-25	x	1989-10 to 2017-01
08185000	USGS - Cibolo Ck at Selma, TX	u/s of HDWT2	36	98,100	1998-10-17		1991-10 to 2017-01
08185065	USGS - Cibolo Ck nr Saint Hedwig, TX	HDWT2 outlet	36	20,100	2007-08-17	x	2005-12 to 2017-01

3.5 Water Balance Analysis

A water volume balance was computed for the study sub-basins over the common calibration period (2011 – 2016) to aid in model calibration and diversion modeling and for an overall consistency check of the required modeling data. The water balance analysis is useful in identifying potential problems in the observed data or problems with mean areal precipitation estimates or with potential evapotranspiration (PET) values or the magnitudes of the modeled gains and losses within the sub-basin. Water balance results from each sub-basin are compared to those of nearby sub-basins and potential problems in the recorded streamflow values or inconsistencies in precipitation or PET estimates are sometimes evident. 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 diversions or gains/losses.

3.5.1 Initial Water Balance Results

The initial water balance results are provided in Table 12. 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 average annual volumes shown in Table 12 (and subsequently in Table 13) were calculated for the common calibration period, which is January 2011 to December 2016; therefore, the values for precipitation (MAPX) and streamflow are slightly different than values provided elsewhere in this report.

Table 12. Initial Water Balance Results Based on Annual Volumes (2011 – 2016)

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
Colorado River Basin												
DRWT2	128	128	36.1	56	0	56	6.0	0.17	30.1	61.8	0.49	HW
BDUT2	38	166	39.8	26	0	-30	-10.6	-0.27	50.4	61.4	0.82	Local
ONIT2	13	179	43.1	56	0	30	31.7	0.73	11.5	61.9	0.19	Local
ATIT2	146	326	42.5	122	0	65	6.1	0.14	36.4	61.6	0.59	Local
CRWT2	98	37,110	40.4	1,119	0	207	28.8	0.71	11.6	62.2	0.19	Local
CRUT2	89	37,199	39.3	1,038	0	-81	-12.3	-0.31	51.6	62.4	0.83	Local
BRTT2	126	37,551	38.7	1,250	0	92	10.0	0.26	28.7	62.0	0.46	Local
CKBT2	131	131	39.5	80	0	80	8.3	0.21	31.2	62.9	0.50	HW
WURT2	107	107	36.9	103	0	103	13.1	0.35	23.8	64.1	0.37	HW
FPCT2	156	38,692	40.1	1,326	0	-342	-29.7	-0.74	69.8	61.6	1.13	Local
ACLT2	87	39,292	42.6	1,961	0	-94	-14.7	-0.34	57.2	61.2	0.94	Local
GWCT2	131	39,423	41.9	2,352	0	391	40.6	0.97	1.2	61.3	0.02	Local
CDOT2	30	39,635	43.8	2,018	0	-20	-9.3	-0.21	53.1	58.5	0.91	Local
Guadalupe River Basin												
GRTT2	57	1,508	35.3	340	0	85	20.2	0.57	15.1	57.3	0.26	Local
SEGT2+SGGT2	215	1,911	31.1	606	0	47	3.0	0.10	28.2	61.6	0.46	Local
San Antonio River Basin												
CICT2	70	70	30.8	31	0	31	6.1	0.20	24.7	64.0	0.39	HW
MMDT2	253	894	29.7	64	0	64	3.4	0.12	26.3	64.1	0.41	Local
SDBT2	34	34	34.8	1	0	1	0.3	0.01	34.5	63.1	0.55	HW
MTST2	50	50	35.7	42	0	42	11.4	0.32	24.4	61.7	0.40	HW
SSCT2	106	140	35.9	27	0	26	3.3	0.09	32.6	62.2	0.52	Local
SNPT2	75	125	34.7	108	0	66	12.0	0.35	22.7	62.4	0.36	Local
HDWT2	32	308	33.3	34	0	-27	-11.7	-0.35	45.0	61.8	0.73	Local

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 gives the ratio 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 diversions into or out of the sub-basin, poor streamflow records, or poorly computed MAP data sets. 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.

The initial water results revealed inconsistencies with AET/PET ratios in all three river basins. In the Colorado, there were several sub-basins (BDUT2, CRUT2, FPCT2, ACLT2, and CDOT2) with negative ROC values. This is often indicative of significant diversions or other losses that impact the measured streamflow at the sub-basin outlet. The three headwater sub-basins in the Colorado, however, showed consistent results, with AET/PET ratios ranging from 0.37 – 0.50. Within both the Guadalupe and San Antonio River basins, there was less variability in the initial water balance results, but a few issues, such as a negative ROC in sub-basin HDWT2, were evident. 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. The final water balance results are provided in Table 13.

Table 13. Final Water Balance Results Based on Annual Volumes (2011 – 2016)

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
Colorado River Basin												
DRWT2	128	128	36.1	56	0	56	6.0	0.17	30.1	51.4	0.59	HW
BDUT2	38	166	39.8	26	30	0	0.0	0.00	39.8	51.1	0.78	Local
ONIT2	13	179	43.1	56	0	30	31.7	0.73	11.5	50.6	0.23	Local
ATIT2	146	326	42.5	122	11	76	7.1	0.17	35.4	57.6	0.61	Local
CRWT2	98	37,110	40.4	1,119	-200	8	1.0	0.03	39.3	50.4	0.78	Local
CRUT2	89	37,199	39.3	1,038	0	-81	-12.3	-0.31	51.6	50.7	1.02	Local
BRTT2	126	37,551	38.7	1,250	166	258	27.8	0.72	10.9	50.3	0.22	Local
CKBT2	131	131	39.5	80	1	81	8.4	0.21	31.1	57.9	0.54	HW
WURT2	107	107	36.9	103	5	109	13.7	0.37	23.1	52.3	0.44	HW
FPCT2	156	38,692	40.1	1,326	176	-165	-14.4	-0.36	54.5	53.1	1.03	Local
ACLT2	87	39,292	42.6	1,961	28	-66	-10.3	-0.24	52.9	55.3	0.96	Local
GWCT2	131	39,423	41.9	2,352	-519	-128	-13.3	-0.32	55.2	55.5	1.00	Local
CDOT2	30	39,635	43.8	2,018	35	15	6.7	0.15	37.1	52.9	0.70	Local
Guadalupe River Basin												
GRTT2	57	1,508	35.3	340	-42	43	10.1	0.29	25.1	47.6	0.53	Local
SEGT2+SGGT2	215	1,911	31.1	606	0	47	3.0	0.10	28.2	62.9	0.45	Local
San Antonio River Basin												
CICT2	70	70	30.8	31	0	31	6.1	0.20	24.7	49.8	0.50	HW
MMDT2	253	894	29.7	64	0	64	3.4	0.12	26.3	66.5	0.40	Local
SDBT2	34	34	34.8	1	1	1	0.5	0.02	34.3	65.5	0.52	HW
MTST2	50	50	35.7	42	-5	36	9.9	0.28	25.8	62.9	0.41	HW
SSCT2	106	140	35.9	27	52	78	10.0	0.28	25.9	58.1	0.45	Local
SNPT2	75	125	34.7	108	0	66	12.0	0.35	22.7	63.7	0.36	Local
HDWT2	32	308	33.3	34	1	-26	-11.2	-0.34	44.5	63.1	0.71	Local

The final water balance results show improved consistency between sub-basins in all three river basins. Within the Colorado basin, there are still sub-basins where the calculated local runoff is negative (even with diversion modeling accounted for); however, the values are generally less extreme than the initial results. Table 14 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.

Table 14. Summary of Diversion and Gain/Loss Modeling

Sub-basin	Diversion/Loss (+) Return/Gain (-) [cfsd]	Diversion/Loss (+) Return/Gain (-) [cmsd]	Operation/Parameter Used in Model
ACLT2	28	0.790	LOOKUP
ATIT2	11	0.311	SIDE
BDUT2	30	0.845	CHANLOSS, SIDE
BRTT2	166	4.690	CHANLOSS, SIDE
CDOT2	35	0.996	CHANLOSS
CKBT2	1	0.023	SIDE
CRWT2	-200	-5.660	CHANLOSS
FPCT2	176	4.991	CHANLOSS
GRTT2	-42	-1.199	CHANLOSS
GWCT2	-519	-14.702	CHANLOSS
HDWT2	1	0.035	SIDE
MTST2	-5	-0.152	CHANLOSS
SDBT2	1	0.020	CHANLOSS
SSCT2	52	1.486	LOOKUP
WURT2	5	0.149	SIDE

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 calibrated include streamflow routing using Lag/K, the Sacramento Soil Moisture Accounting Model (SAC-SMA), and the Unit Hydrograph (UNIT-HG) described in Sections 4.1 - 4.3. These models and their associated parameters are used in sequence to produce a streamflow simulation that can be calibrated to best match historical observed conditions. 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. Although not explicitly described below, RTI also calibrated CHANLOSS and LOOKUP operations to capture associated reach gains and losses.

In general, RTI utilized the Interactive Calibration Program (ICP) for efficiencies in model calibration but all operations and parameters were converted to CHPS-FEWS configurations for ease of transfer to the operational forecasts system and model visualization by WGRFC. A primary focus of each sub-basin calibration was on achieving peakflows at an hourly time-step.

The introduction of each river basin in Sections 4.4, 4.5, and 4.6 provides a map of the calibrated sub-basins and summary tables of the Lag/K and SAC-SMA parameters as well tables summarizing the statistics of the final calibrated simulations. These sections are followed by individual write-ups of each sub-basin's characteristics, calibration challenges, statistics, and results.

4.1 Streamflow Routing using the Lag/K Method

Flow routing from upstream areas was performed for each of the 17 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 LCRA 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 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 the Interactive Calibration Program (ICP) but STAT-Q was utilized to check the hourly correlation coefficient as refinements became more tuned.

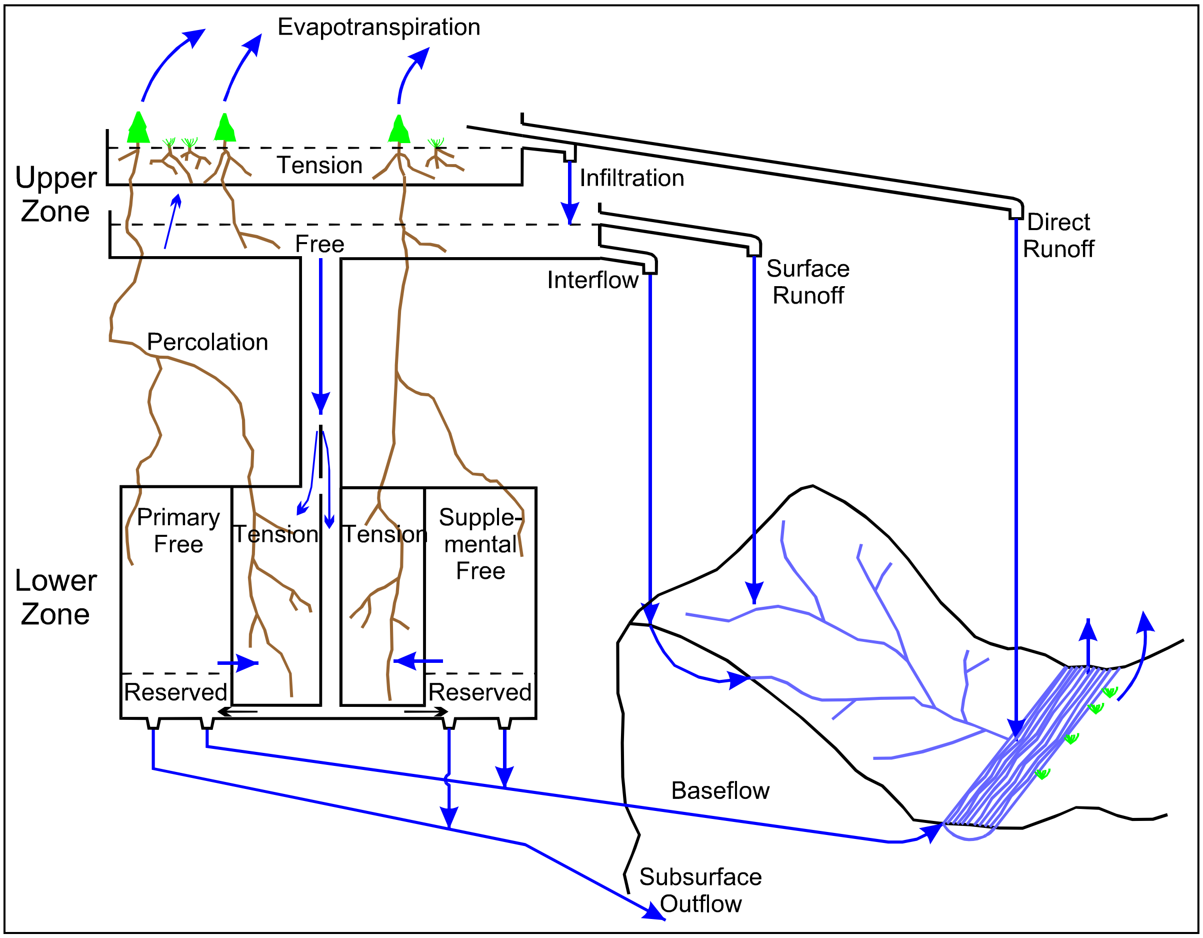
Following the initial assessment of the variable Lag parameters, the K parameter was expanded to incorporate variable characteristics and wave attenuation as needed. Subsequent adjustments of both the variable Lag and variable K parameters were made based on visual comparison and based on attempting 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 Lag-K 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 4.4, 4.5, and 4.6), as well as in each individual sub-basin description.

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 12 provides a conceptual schematic of these processes.

Figure 12. 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 23 study sub-basins utilizing the NWS Interactive Calibration Program (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 15. Exceptions included higher than normal values of PCTIM for some of the urbanized basins in the San Antonio region and higher than typical values for LZPK observed in the baseflow for the northern-most sub-basins in the Colorado River basin. Summary tables of the final SAC-SMA parameter sets are provided in subsequent sections (Sections 4.4, 4.5, and 4.6), as well as in each individual sub-basin description.

Table 15. 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 at the beginning of each river basin results section (Sections 4.4, 4.5, and 4.6). In addition, each sub-basin description provides a table of the STAT-Q statistics comparing results from the initial simulation (based on parameters extracted from the current WGRFC forecast system) to the final calibration.

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 a few of the study sub-basins (ACLT2, BRTT2, GRTT2, GWCT2, SEGT2, SGGT2), 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 Nation 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. Appendix B provides a description of the UNIT-HG development for each sub-basin including events analyzed in the manual procedure or channel characteristics defined for the GIS procedure.

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 their respective write-ups that follow.

4.4 Calibration Results for the Colorado River Basin

The sub-basins within the Colorado River basin that were included in this study are highlighted in Figure 13. A summary of the calibrated parameters from the LAG/K and SAC-SMA operations are provided in Tables 16 – 18. A summary of the hourly simulation statistics produced by the STAT-Q operation are provided in Table 19 (total flow) and Table 20 (local flow).

Figure 13. Calibrated Sub-basins in the Colorado River Basin

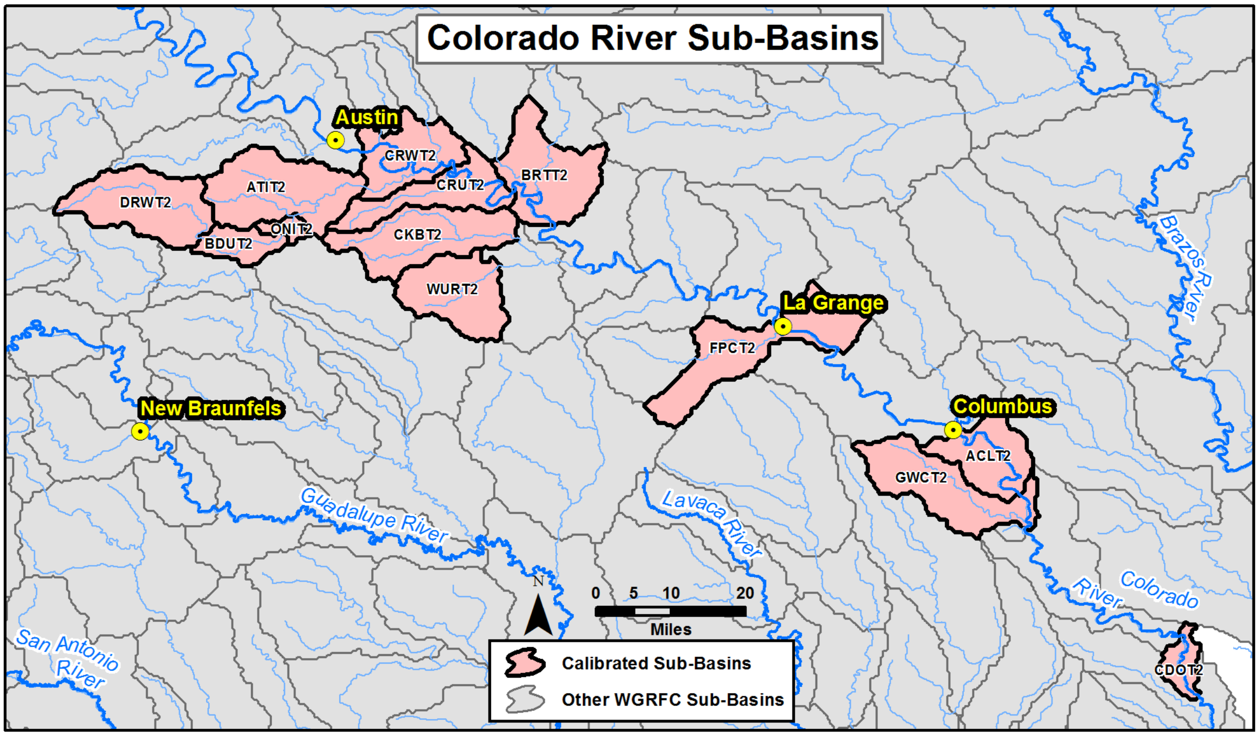


Table 16. Summary of Lag/Q Pairs for Modeled Reaches in the Colorado River Basin

Routing	Routing	Lag Parameters

to	from	Lag1 (hr)	Q1 (cfs)	Lag2 (hr)	Q2 (cfs)	Lag3 (hr)	Q3 (cfs)	Lag4 (hr)	Q4 (cfs)
BDUT2	DRWT2	2	450	3	1200	3	5000		
ONIT2	BDUT2	1	1400	0	7100				
ATIT2	ONIT2	4	2650	6	10500	3	17000		
CRWT2	ATIT2	7	2200	10	7100	8	22000	2	30000
CRWT2	ACRT2	9	700	6	3500	5	10600		
CRWT2	WWVT2	10	700	7	1800	6	3900		
CRWT2	MNGT2	3	350	4	1060	6	2500		
CRUT2	CRWT2	7	1060	5	1800	2	20000		
BRTT2	CRUT2	2							
BRTT2	EGYT2	0							
BRTT2	EGZT2	0							
FPCT2	MLDT2	2	700	4	1800	6	7000		
FPCT2	LGRT2	1							
ACLT2	CBST2	3.5	10600	1	35000	0	106000		
GWCT2	ACLT2	2							
CDOT2	WHAT2	2	20000	3	100000				

Table 17. Summary of K/Q Pairs for Modeled Reaches in the Colorado River Basin

Routing to	Routing from	Lag Parameters							
		Lag1 (hr)	Q1 (cfs)	Lag2 (hr)	Q2 (cfs)	Lag3 (hr)	Q3 (cfs)	Lag4 (hr)	Q4 (cfs)
BDUT2	DRWT2	3	450	1	1200	1	5000		
ONIT2	BDUT2	0	1400	0.25	7100				
ATIT2	ONIT2	0.5	2650	1	10500				
CRWT2	ATIT2	2.5	7100	8	20000	12	30000		
CRWT2	ACRT2	5	700	9	3500	8	10600		
CRWT2	WWVT2	5	700	4	1800	3	3900		
CRWT2	MNGT2	2	350	3	1060	6	2500		
CRUT2	CRWT2	2	1060	5	1800	8	20000	12	30000
BRTT2	CRUT2	3	12400	8	20000	12	30000		
BRTT2	EGYT2	9	5000	18	10000				
BRTT2	EGZT2	4	900	6	2650	8	10600		
FPCT2	MLDT2	2	700	4	1800				
FPCT2	LGRT2	7	3500	3	10000				
ACLT2	CBST2	4	10600	8	35000	30	106000		
GWCT2	ACLT2	0							
CDOT2	WHAT2	2	0	3	15900	5	100000		

Table 18. Calibrated SAC-SMA Parameters for Modeled Sub-basins in the Colorado River Basin

NWS Basin ID	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
DRWT2	1.0	1.0	20	30	0.25	0.025	0.05	0.01	240	2.20	150	25	85	0.070	0.009	0.50	0.3	0.20	2.52
BDUT2	1.0	1.0	30	30	0.20	0.005	0.05	0.02	70	2.00	150	30	45	0.100	0.007	0.15	0.3	0.00	3.32
ONIT2	1.0	1.0	60	25	0.50	0.015	0.09	0.01	300	2.50	75	30	70	0.150	0.030	0.05	0.3	0.00	6.60
ATIT2	1.0	1.0	60	45	0.50	0.010	0.02	0.02	200	3.50	235	30	140	0.100	0.020	0.05	0.3	1.50	5.80
CRWT2	1.0	1.0	30	60	0.40	0.010	0.10	0.01	150	2.30	150	50	200	0.130	0.010	0.30	0.3	0.00	8.50
CRUT2	1.0	1.0	90	45	0.30	0.015	0.10	0.01	100	2.50	150	20	150	0.060	0.002	0.10	0.3	0.00	1.50
BRTT2	1.0	1.0	75	75	0.50	0.010	0.05	0.01	100	2.50	175	40	175	0.080	0.011	0.05	0.3	1.00	5.13
CKBT2	1.0	1.0	60	15	0.50	0.000	0.05	0.04	150	2.50	250	15	40	0.100	0.001	0.05	0.3	1.00	1.54
WURT2	1.0	1.0	40	15	0.50	0.000	0.05	0.00	250	2.10	150	15	30	0.150	0.001	0.02	0.3	1.00	2.28
FPCT2	1.0	1.0	50	40	0.50	0.005	0.03	0.02	200	2.50	275	20	150	0.060	0.002	0.05	0.3	0.00	1.50
ACLT2	1.0	1.0	50	75	0.50	0.005	0.03	0.02	250	3.00	120	20	150	0.060	0.002	0.05	0.3	0.00	1.50
GWCT2	1.0	1.0	50	75	0.50	0.005	0.03	0.02	225	2.80	200	25	125	0.050	0.002	0.05	0.3	0.00	1.50
CDOT2	1.0	1.0	45	75	0.50	0.010	0.05	0.02	300	3.50	200	30	100	0.100	0.010	0.10	0.3	0.00	4.00

Table 19. Total Flow Simulation Statistics for Modeled Sub-basins in the Colorado River Basin

NWS Basin ID	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
DRWT2	-3.93	55.33	1.40	1.34	7.83	8.31	5.60	6.18	269.10	3.77	0.893	0.77	0.84	0.27	0.84
BDUT2	7.14	43.91	0.66	0.71	6.54	6.57	9.94	9.31	602.90	3.97	0.817	0.63	0.81	0.08	0.81
ONIT2	-2.11	38.39	1.04	1.02	8.05	6.92	7.75	6.81	304.60	3.16	0.922	0.85	0.79	-0.05	1.07
ATIT2	2.69	41.07	2.96	3.04	39.07	38.45	13.18	12.63	477.70	14.16	0.933	0.87	0.92	0.08	0.95
CRWT2	-1.79	7.25	76.72	75.34	149.30	142.10	1.95	1.89	15.36	11.78	0.998	0.99	0.95	-2.29	1.05
CRUT2	3.61	8.17	94.64	98.06	156.50	168.60	1.65	1.72	21.15	20.01	0.995	0.98	0.92	4.00	0.92
BRTT2	0.16	15.34	35.28	35.33	93.47	100.10	2.65	2.83	49.29	17.39	0.986	0.97	0.92	2.73	0.92
CKBT2	2.48	51.51	1.91	1.95	23.30	23.76	12.23	12.17	518.90	9.89	0.912	0.82	0.89	0.16	0.89
WURT2	-1.87	69.30	3.58	3.51	29.86	24.79	8.35	7.06	430.10	15.38	0.858	0.74	0.71	-0.05	1.03
FPCT2	-12.61	25.22	38.43	33.59	134.60	111.40	3.50	3.32	99.21	38.13	0.970	0.92	0.80	-0.97	1.17
ACLT2	3.52	11.78	61.43	63.59	142.00	142.50	2.31	2.24	24.36	14.97	0.995	0.99	0.99	-1.60	0.99
GWCT2	0.27	9.42	108.30	108.60	248.60	254.30	2.30	2.34	20.07	21.74	0.997	0.99	0.97	2.53	0.97
CDOT2	0.31	6.32	57.17	57.35	156.90	159.20	2.74	2.78	13.25	7.57	0.999	1.00	0.98	0.73	0.98

Table 20. Local Flow Simulation Statistics for Modeled Sub-basins in the Colorado River Basin

NWS Basin ID	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
BDUT2	-69.65	88.53	0.66	0.20	6.54	2.39	9.94	11.98	903.90	5.95	0.425	0.17	0.16	0.43	1.16
ONIT2	-70.21	85.19	1.04	0.31	8.05	1.63	7.75	5.28	697.30	7.24	0.592	0.19	0.12	0.14	2.92
ATIT2	-41.64	58.05	2.96	1.73	39.07	29.94	13.18	17.30	687.00	20.37	0.859	0.73	0.66	1.02	1.12
CRWT2	-95.19	95.19	76.72	3.69	149.30	10.22	1.95	2.77	213.40	163.70	0.310	-0.20	0.02	60.00	4.52
CRUT2	-95.67	95.67	94.64	4.10	156.50	20.87	1.65	5.09	186.10	176.10	0.325	-0.27	0.04	84.60	2.44
BRTT2	-95.57	95.67	35.28	1.56	93.47	12.02	2.65	7.69	269.30	94.98	0.443	-0.03	0.06	29.90	3.45
FPCT2	-95.98	96.09	38.43	1.55	134.60	11.79	3.50	7.62	347.10	133.40	0.577	0.02	0.05	28.20	6.59
ACLT2	-97.95	98.03	61.43	1.26	142.00	6.73	2.31	5.35	247.10	151.80	0.411	-0.14	0.02	50.50	8.67
GWCT2	-96.51	96.65	108.30	3.78	248.60	14.59	2.30	3.86	243.70	263.90	0.456	-0.13	0.03	78.90	7.77
CDOT2	-99.14	99.14	57.17	0.49	156.90	2.42	2.74	4.91	290.60	166.20	0.297	-0.12	0.00	47.70	19.30

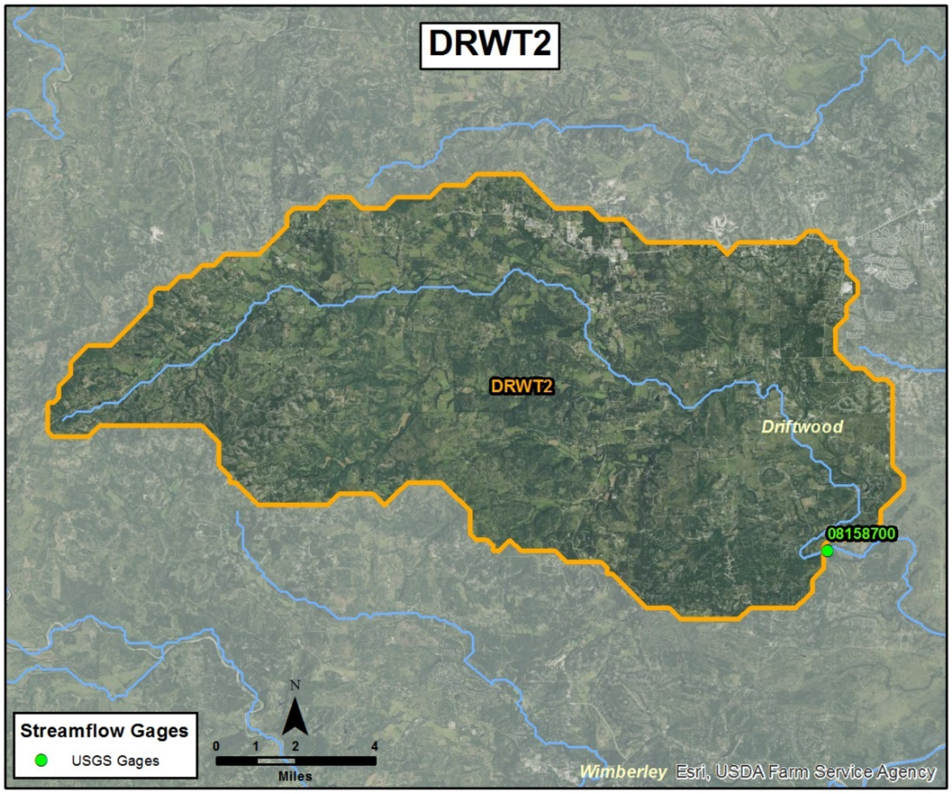
4.4.1 DRWT2: Onion Creek near Driftwood, TX

DRWT2 is a rural headwater sub-basin located in the Colorado River basin that drains approximately 128 mi^2. Residential/commercial development is relatively light, with only the towns of Driftwood (population 2,467) and Dripping Springs (1,870) contained within the sub-basin boundary. The dominant hydrologic soil groups are C and D which generally indicate low infiltration rates and high runoff potential. Table 21 summarizes the basin characteristics followed by Figure 14 which presents an aerial map of DRWT2.

Table 21. Basin Characteristics for DRWT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
128 / 128	1624 / 1205 / 906	Edwards Plateau, Eastern Part	Clay Loam: 59% Loam: 39% Minor classes: 2%	A: 0%; B: 3%; C: 53%; D: 44%; W: 0%	Shrub/Scrub: 38% Evergreen Forest: 31% Grassland/Herbaceous: 17% Deciduous Forest: 11% Other: 3%

Figure 14. DRWT2 sub-basin map



Observed streamflow data are available from July 1979 through January 2017 at USGS gage 08158700, Onion Creek near Driftwood, TX. The average observed streamflow over this period is 53 cfs. The typical event peaks within 4-5 hours, and takes approximately 11-14 hours to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 16,600 cfs in October 2015.

Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that peak flows tended to be significantly over-simulated using these values. The initial UZTWM value was lower than the typical range, and therefore was increased substantially during the calibration analysis. In addition, during calibration the initial PET estimates were lowered slightly in response to simulated volume bias over the calibration period from 2011 to 2016.

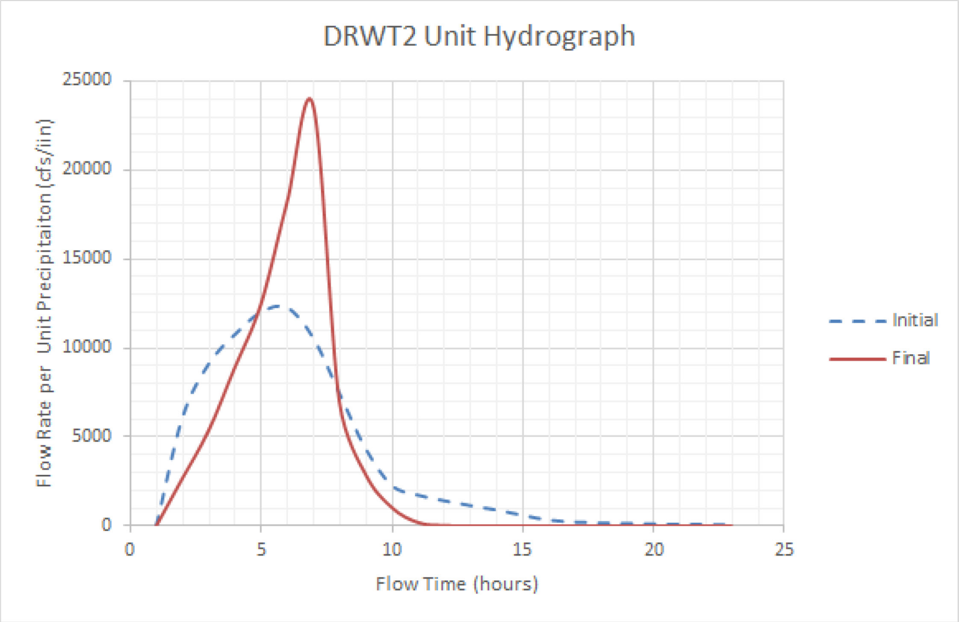
Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZFWM and UZK. Accordingly, emphasis was placed on refining these parameters. The baseflow parameter calibration was focused on the summer of 2014 with an effort to balance the over- and under- simulation of baseflow over the rest of the calibration period. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 22.

Table 22. Original Versus Calibrated SAC-SMA Parameters for DRWT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	20	30	0.25	0.025	0.05	0.010	240	2.20	150	25	85	0.070	0.009	0.50	0.3	0.25	2.52
Calib.	1.000	1.000	125	35	0.50	0.005	0.01	0.020	300	1.95	130	20	70	0.180	0.027	0.20	0.3	0.00	5.49

The ordinates for the initial UNIT HG were based on the October 2013 event with six (6) other events analyzed, as described in Appendix B. Figure 15 demonstrates the final adjustments made to the UNIT HG during calibration using both manual and optimizer techniques. The results suggested a much more dramatic peak with quicker baseflow recession, which was implemented into the final recommended UNIT-HG ordinates.

Figure 15. DRWT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set produces a significantly improved simulation when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models are presented in Table 23. These statistics demonstrate a large improvement to the water balance as seen in the reduced percent bias. The correlation coefficient and other statistics also show a significant improvement from the model calibration analysis.

Table 23. DRWT2 Original Versus Calibrated Simulation Statistics (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	144.5	179.3	1.4	3.4	7.8	26.2	5.6	7.7	1474.0	20.6	0.795	-5.9	0.2	0.59	0.24
Calib.	-3.9	55.3	1.4	1.3	7.8	8.3	5.6	6.2	269.1	3.8	0.893	0.8	0.8	0.27	0.84

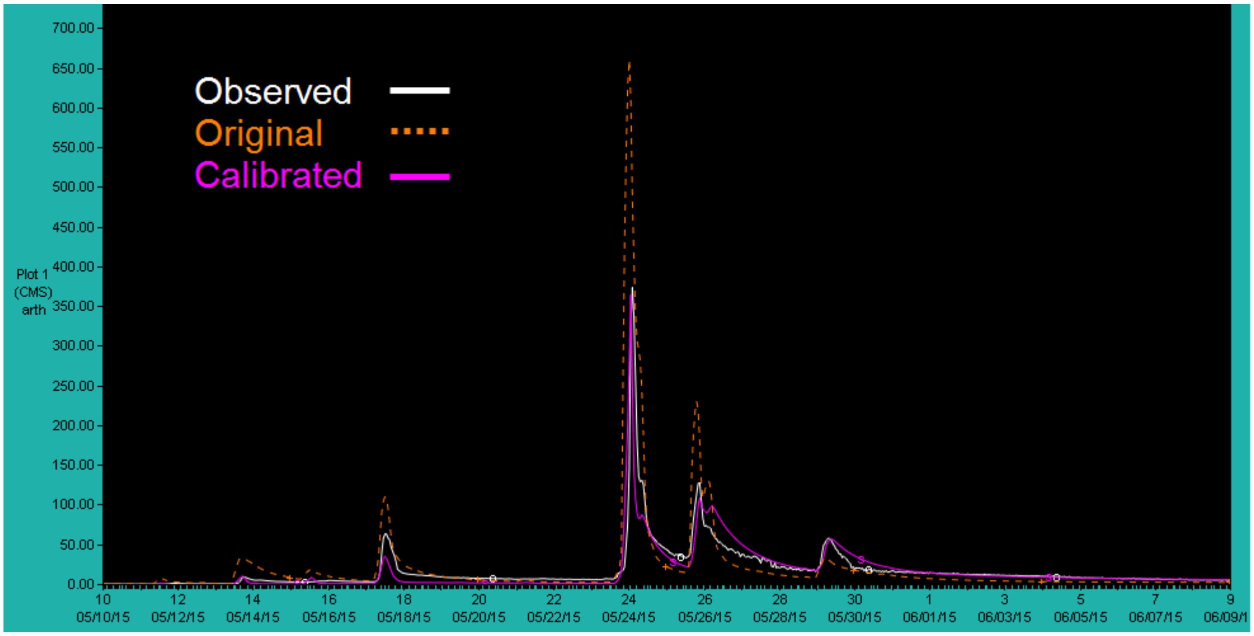
In addition to considering the STAT-Q output, the PEAKFLOW operation was used during the calibration analysis to evaluate model performance for the recent large flood events, as shown in Table 24. The PEAKFLOW operation uses observed instantaneous peak streamflow values as reported by the USGS. As seen in the table, these flood events are simulated well by the calibrated models, although there is a slight over-simulation during the 5/24/2015 event.

Table 24. DRWT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
365.0	10/31/2013	383.0	10/31/2013	0	18.0	1.05
377.0	5/24/2015	505.0	5/24/2015	0	128.0	1.34
470.0	10/30/2015	462.0	10/30/2015	0	-8.0	0.98

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 16. Overall, the final calibrated models should provide significantly improved predictive performance over those in the current forecast system.

Figure 16. Sample Plot Comparing the Original Versus Final Calibration Simulations for DWRT2



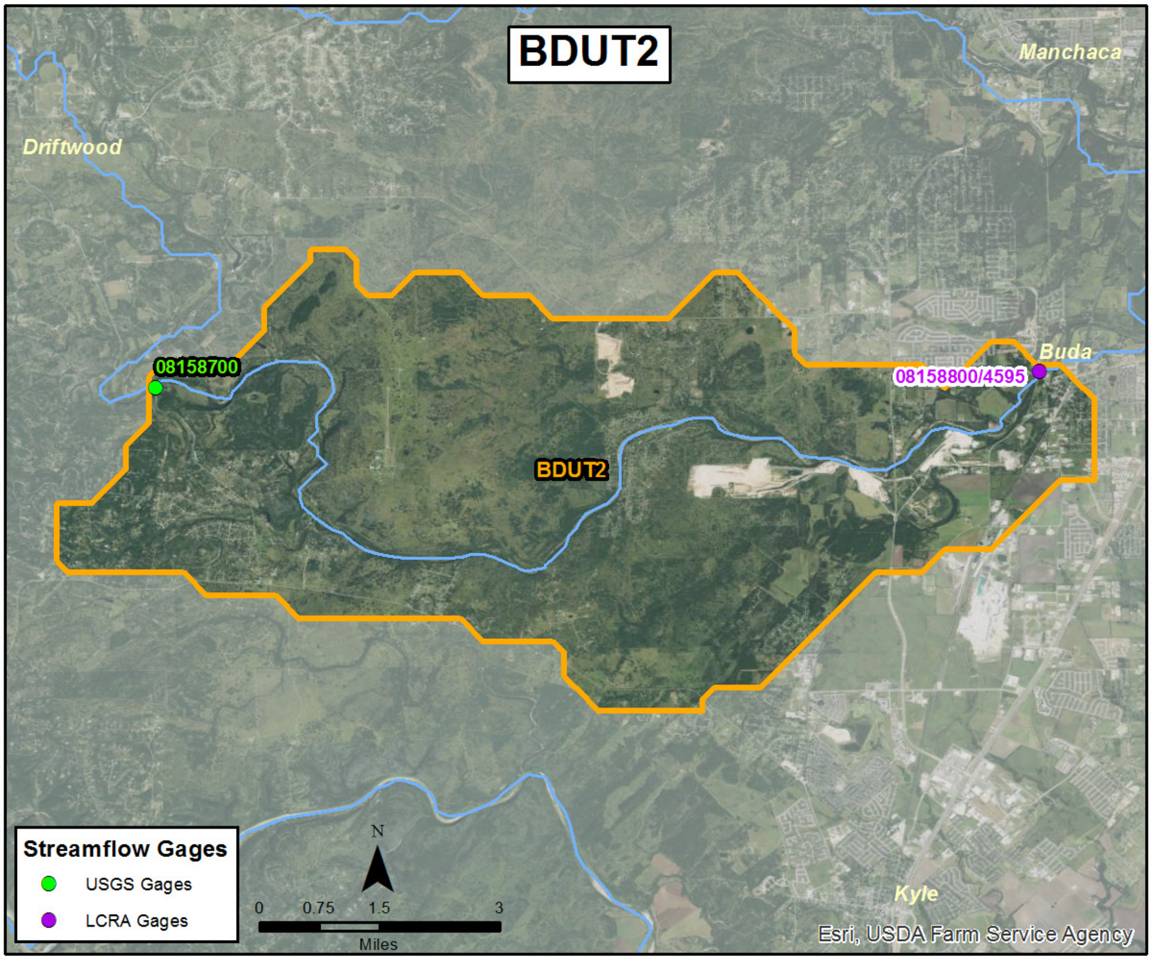
4.4.2 BDUT2: Onion Creek at Buda, TX

BDUT2 is a rural local sub-basin located at Colorado River basin that drains approximately 38 mi^2. Residential/commercial development is relatively light, with only the town of Buda (population 11,461) contained within the sub-basin boundary. The dominant hydrologic soil group within the local drainage area is type D, which indicates very low infiltration rates and very high runoff potential. Table 25 summarizes the basin characteristics followed by Figure 17 which presents an aerial map of BDUT2.

Table 25. Basin Characteristics for BDUT2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
38 / 166	1115 / 846 / 653	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 93% Minor classes: 7%	A: 0%; B: 0%; C: 29%; D: 71%; W: 0%	Grassland/Herbaceous: 30% Shrub/Scrub: 26% Evergreen Forest: 18% Deciduous Forest: 14% Other: 12%

Figure 17. BDUT2 Sub-basin Map



Observed streamflow data are available for LCRA gage 4595 (Onion Creek at Buda, TX) from February 2000 through January 2017 with some significant period of missing data from 2000 to 2006. The average observed streamflow over this period is 70 cfs. The typical event peaks within 2-4 hours, and takes approximately 9-10 hours to recede back to baseflow levels. The highest instantaneous flow ever recorded within the available period is 28,640 cfs in October 2015.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for upstream basin DRWT2. Table 26 compares the pre-existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 26. Lag/Q and K/Q Pairs for Routing Reach DRWT2 to BDUT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**
Lag	Orig.	1	1	1	5097	1	15741
	Calib.	2	450	3	1200	3	5000
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
K	Orig.	0	1	0	5097	0	24486
	Calib.	3	450	1	1200	1	5000

Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tend to significantly over-simulated peak flows when using the existing parameter values.

Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZFWM (which influences the timing and magnitude of the largest surface runoff events), and ZPERC and REXP (which together largely control the simulated percolation rate). Accordingly, emphasis was placed on refining these parameters during the calibration analysis.

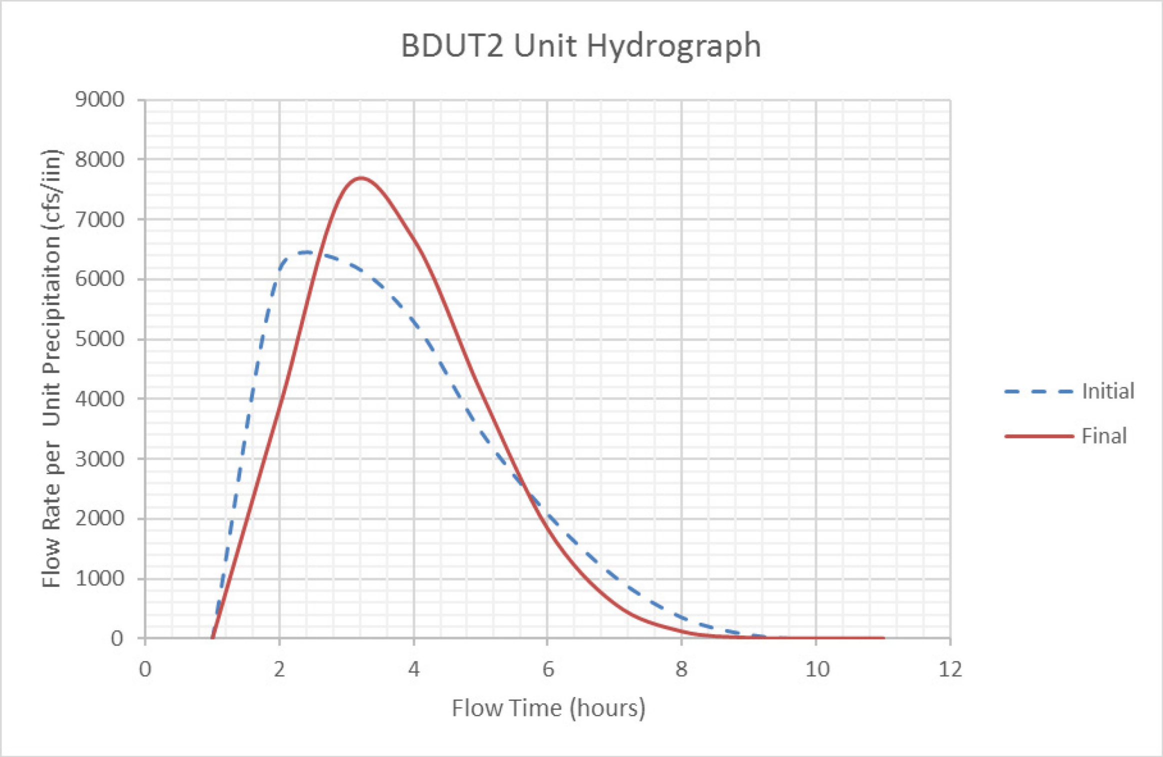
The initial water balance results indicated that there are significant losses (or observed data bias) between the upstream gage and streamflow measured at the BDUT2 outlet. Initial model calibration runs confirmed these issues, with the model significantly over-simulated the October 2013 and 2015 events because the upstream flows are much higher than the observed flow at the BDUT2 gage. The timing of the simulation of these peaks, however, was accurate. The baseflow periods showed similar issues with losses between the gages. To model these losses, which are likely related to karst geology in the region, the SIDE parameter and a CHANLOSS operation (with a constant rate that is varied monthly) were utilized. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 27.

Table 27. Original Versus Calibrated SAC-SMA Parameters for BDUT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	30	30	0.20	0.005	0.05	0.020	70	2.00	150	30	45	0.100	0.007	0.15	0.3	0.00	3.32
Calib.	1.000	1.000	125	30	0.50	0.002	0.01	0.010	335	3.00	240	30	115	0.080	0.010	0.05	0.3	1.00	3.55

The ordinates for the initial UNIT-HG model were based on three (3) historical events, as described in Appendix B. The initial model, however, was modified during the calibration analysis based on shape and timing of the simulated response. Figure 18 shows the final adjustments made to the UNIT-HG model.

Figure 18. BDUT2 Initial and Final Calibrated UNIT HG



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 28 and 29, respectively. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 28. BDUT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

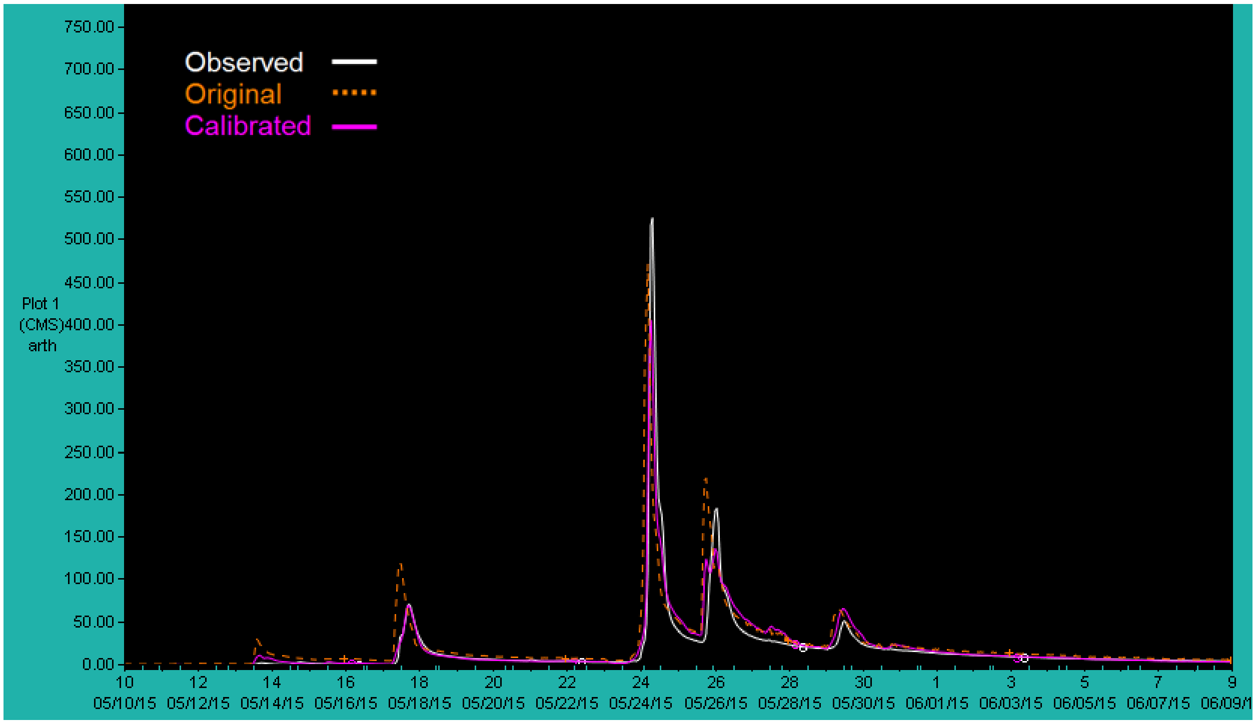
Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean CMS	Obs. std CMS	Sim. std CMS	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
Orig.	6.1	148.5	0.7	0.7	6.5	6.6	9.9	9.5	1270	8.4	0.196	-0.6	0.2	0.52	0.19
Calib.	-69.6	88.5	0.7	0.2	6.5	2.4	9.9	12.0	903.9	6.0	0.425	0.2	0.2	0.43	1.16

Table 29. BDUT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	200.1	224.2	0.7	2.0	6.5	9.4	9.9	4.8	1259.0	8.3	0.525	-0.6	0.4	-0.06	0.36
Calib.	7.1	43.9	0.7	0.7	6.5	6.6	9.9	9.3	602.9	4.0	0.817	0.6	0.8	0.08	0.81

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 19. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 19. Sample Plot Comparing the Original Versus Final Calibration Simulations for BDUT2



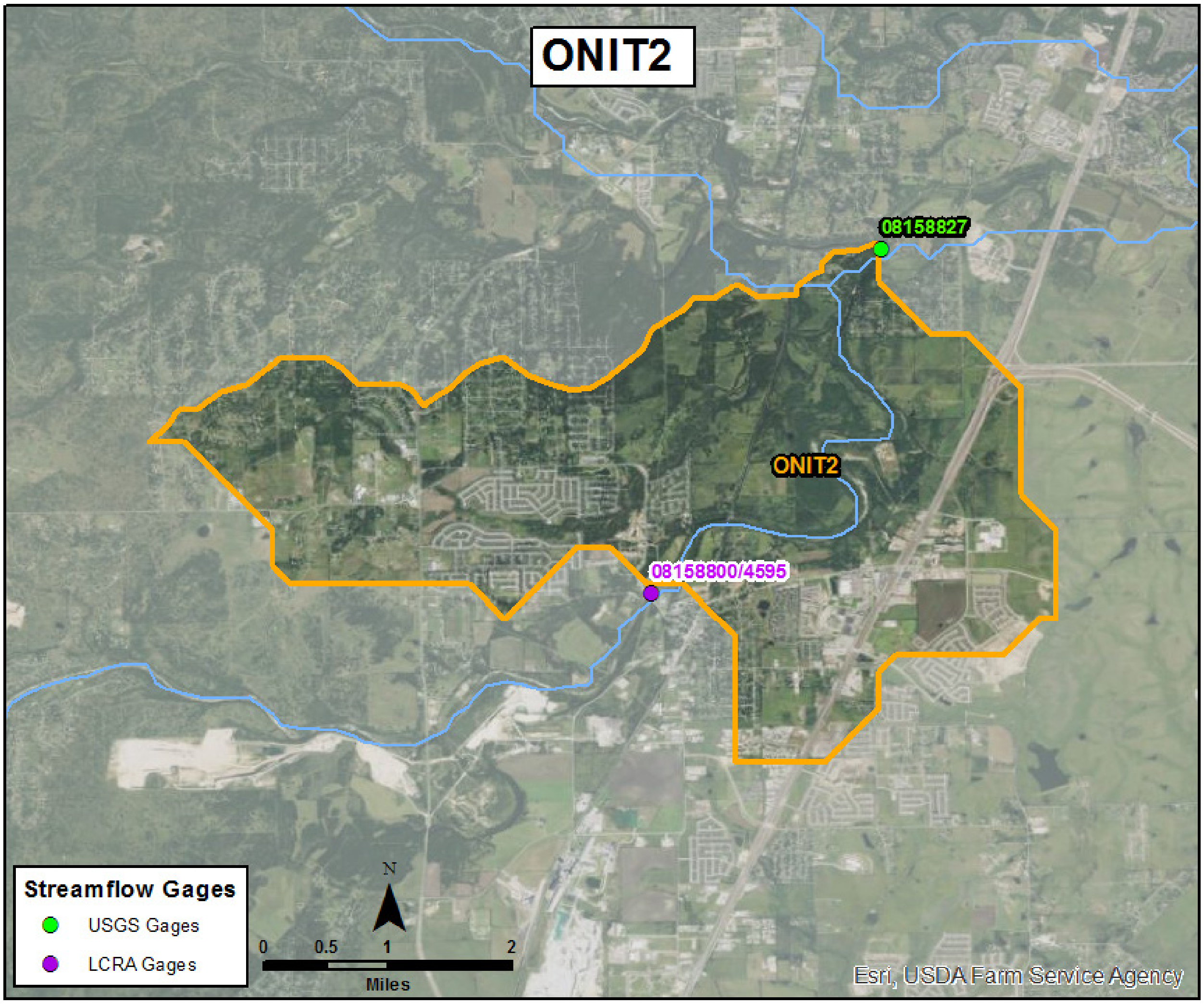
4.4.3 ONIT2: Onion Creek at Twins Creek Road near Manchaca, TX

ONIT2 is a suburban local sub-basin located in the Colorado River basin that drains approximately 13 mi^2. Residential/commercial development is high in the western and southern portions of the drainage area, with the majority of the town of Buda (population 11,461) contained within the sub-basin boundary. The dominant hydrologic soil groups are C and D which indicate low infiltration rates and high runoff potential. Table 30 summarizes the basin characteristics followed by Figure 20 which presents an aerial map of ONIT2.

Table 30. Basin Characteristics for ONIT2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
13 / 179	886 / 727 / 586	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 97% Minor classes: 3%	A: 0%; B: 1%; C: 30%; D: 69%; W: 0%	Shrub/Scrub: 26% Grassland/Herbaceous: 17% Developed, Open Space: 14% Deciduous Forest: 11% Other: 32%

Figure 20. ONIT2 Sub-basin Map



Observed streamflow data are available for USGS gage 08158827 (Onion Creek at Twins Creek Road near Manchaca, TX) from April 2003 through January 2017 with some missing data in 2004. The average observed streamflow over this period is 45 cfs. The typical event peaks within 3-4 hours, and takes approximately 6-8 hours to recede back to baseflow levels. The highest instantaneous flow recorded over this period is 60,100 cfs, which occurred in October 2013.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream sub-basin BDUT2. Table 31 compares the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 31. Lag/Q and K/Q Pairs for Routing Reach BDUT2 to ONIT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	Lag1	Q1	Lag2	Q2	Lag3	Q3
Lag	Orig.	2	1	2	5097	2	15741
	Calib.	1	1400	0	7100	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
K	Orig.	0	1	0	5097	0	24486
	Calib.	0	1400	0.25	7100	-	-

Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to over-simulate large peaks using these values.

Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be LZTWM, ZPERC, LZSK and LZPK. Accordingly, emphasis was placed on refining these parameters. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 32.

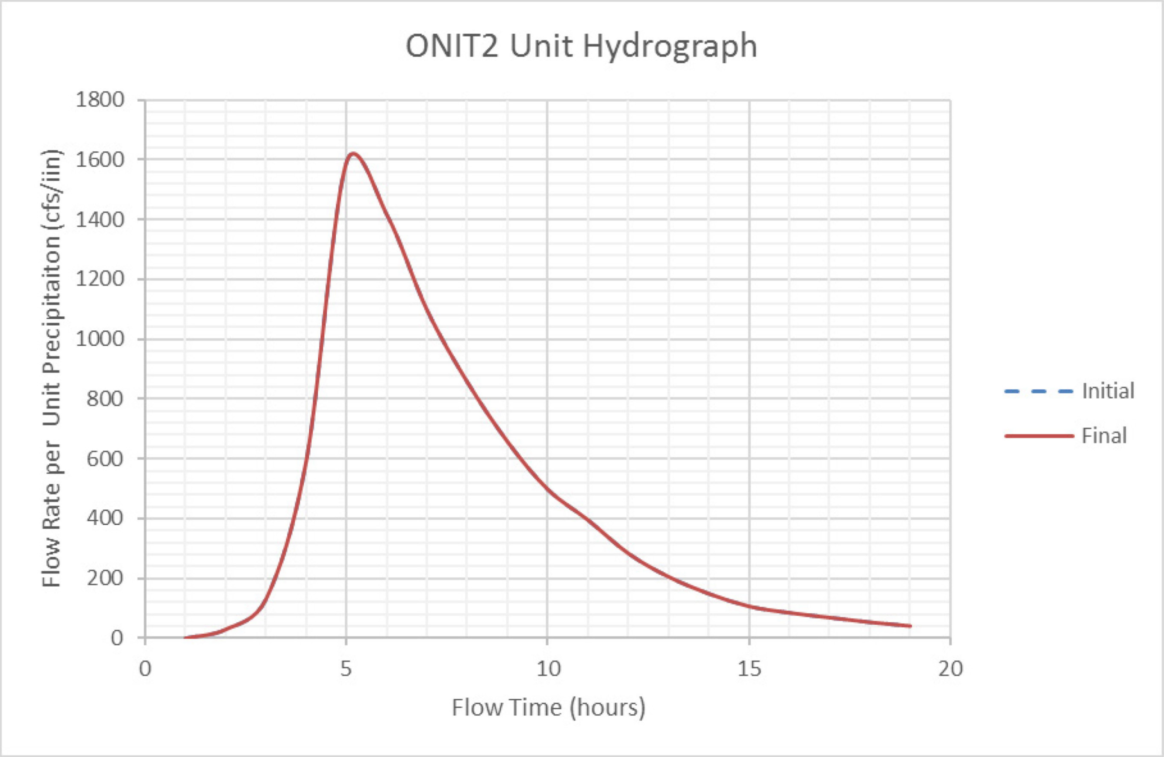
Table 32. Original Versus Calibrated SAC-SMA Parameters for ONIT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	30	30	0.20	0.005	0.05	0.020	70	2.00	150	30	45	0.100	0.007	0.15	0.3	0.00	3.32
Calib.	1.000	1.000	60	25	0.50	0.015	0.09	0.010	300	2.50	75	30	70	0.150	0.030	0.05	0.3	0.00	6.60

Observed streamflow records at the outlet of the upstream sub-basin BDUT2 were particularly noisy during the two large flood events in October 2013 and 2015. Because of this, the QINE time series (simulated flow adjusted to observed flow), which is typically used for upstream flows during calibration, caused the initial calibration simulations to excessively under-simulate the total flow for these two events. Therefore, the SQIN time series (simulated flow without adjustments to observed flow) from the calibrated BDUT2 model was used for the calibration analysis of ONIT2.

The UNIT-HG model, shown in Figure 21 was derived manually using five (5) historical events, as described in Appendix B. It performed well during model calibration runs and, therefore, was not altered during the calibration analysis.

Figure 21. ONIT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set produces a significantly improved simulation when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 33 and 34, respectively.

Table 33. ONIT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	49.4	140.1	1.0	1.6	8.0	14.6	7.8	9.4	1236	12.8	0.485	-1.5	0.3	0.62	0.27
Calib.	-70.2	85.2	1.0	0.3	8.0	1.6	7.8	5.3	697.3	7.2	0.592	0.2	0.1	0.14	2.92

Table 34. ONIT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	117.6	133.9	1.0	2.3	8.0	18.2	7.8	8.1	1354.0	14.1	0.687	-2.1	0.3	0.35	0.30
Calib.	-2.1	38.4	1.0	1.0	8.0	6.9	7.8	6.8	304.6	3.2	0.922	0.8	0.8	-0.05	1.07

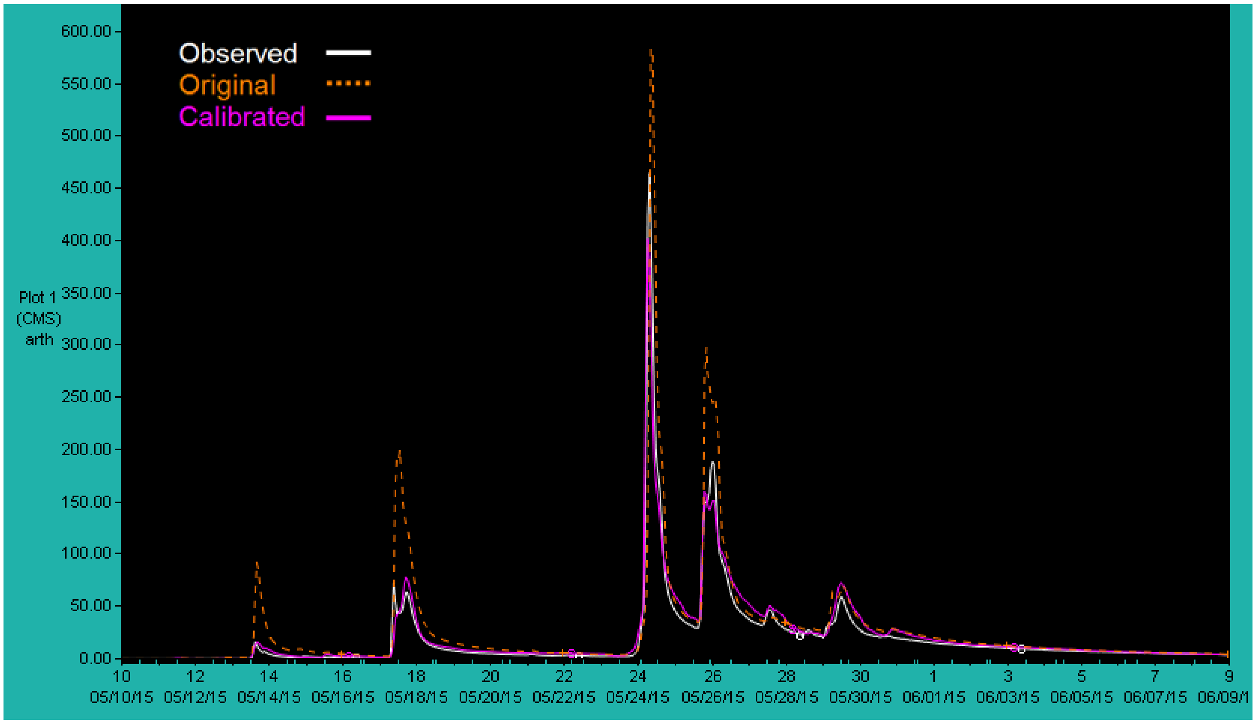
Output from the PEAKFLOW operation was used during the calibration analysis to further refine model parameters. Results of the final calibrated model simulation of the large, recent flood events is given in Table 35. The PEAKFLOW operation uses observed instantaneous peak streamflow values as reported by the USGS. As seen in the table, there are no timing errors recorded by the PEAKFLOW operation and the average peak during flood events is 91% of the observed peak.

Table 35. ONIT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
111.0	5/11/2012	101.0	5/11/2012	0	-10.0	0.91
1700.0	10/31/2013	1100.0	10/31/2013	0	-600.0	0.65
473.0	5/24/2015	401.0	5/24/2015	0	-72.0	0.85
1220.0	10/30/2015	1150.0	10/30/2015	0	-70.0	0.94

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 22. Overall, the final calibrated models should provide significantly improved predictive performance over those in the current forecast system.

Figure 22. Sample Plot Comparing the Original Versus Final Calibration Simulations for ONIT2



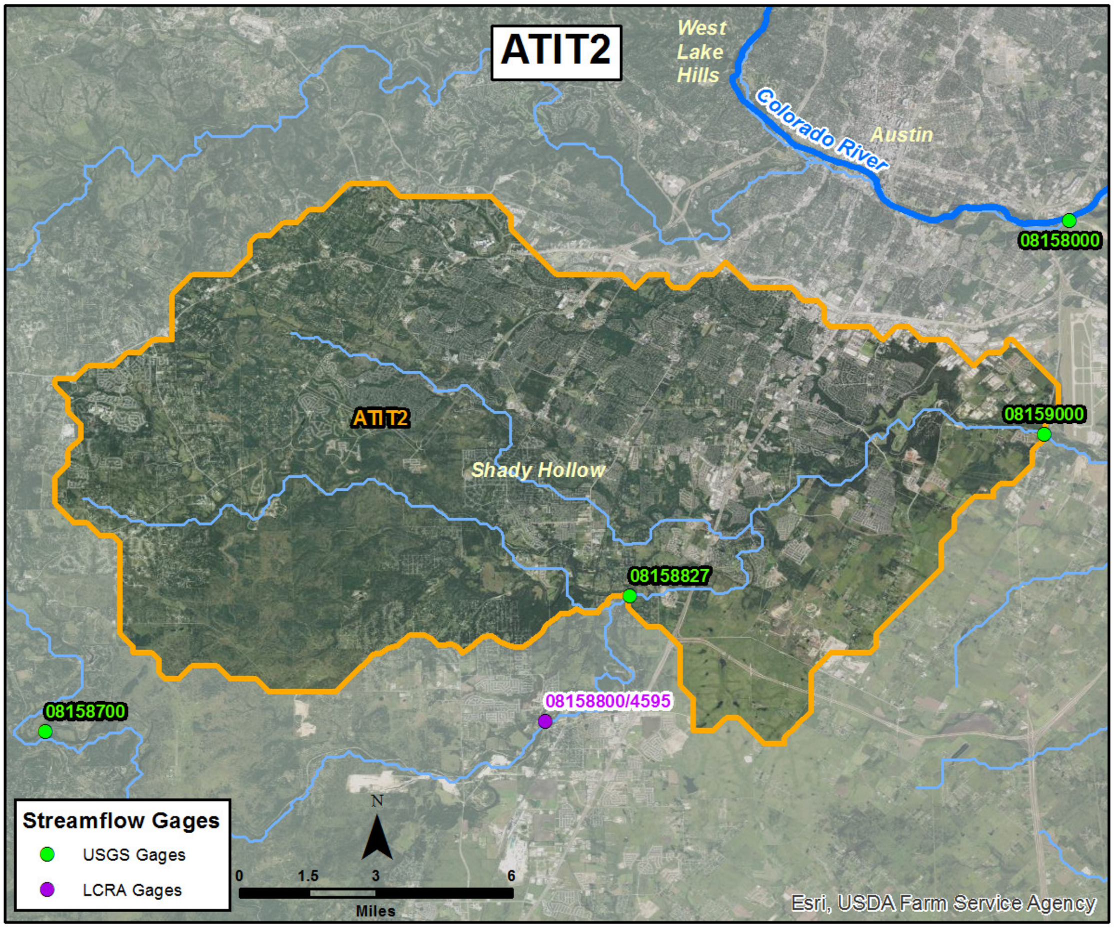
4.4.4 ATIT2: Onion Creek at US Hwy 183, Austin, TX

ATIT2 is a primarily suburban local sub-basin located 10 miles southwest of Austin in Travis and Hays counties that drains approximately 146 mi^2 locally and 326 mi^2 overall. The local area fully contains the Bear Creek and Slaughter Creek tributaries. Residential/commercial development is relatively dense with the southwest Austin suburbs, as well as the small towns of Manchaca, Sunset Valley, and Hays, contained within the sub-basin boundary. Although not a headwater basin, ATIT2's local area is nearly half of its total drainage area, and therefore it receives much of its total outflow locally. The dominant hydrologic soil groups are C and D which indicate low infiltration rates and high runoff potential. Table 36 summarizes the basin characteristics followed by Figure 23 which presents an aerial map of ATIT2.

Table 36. Basin Characteristics for ATIT2

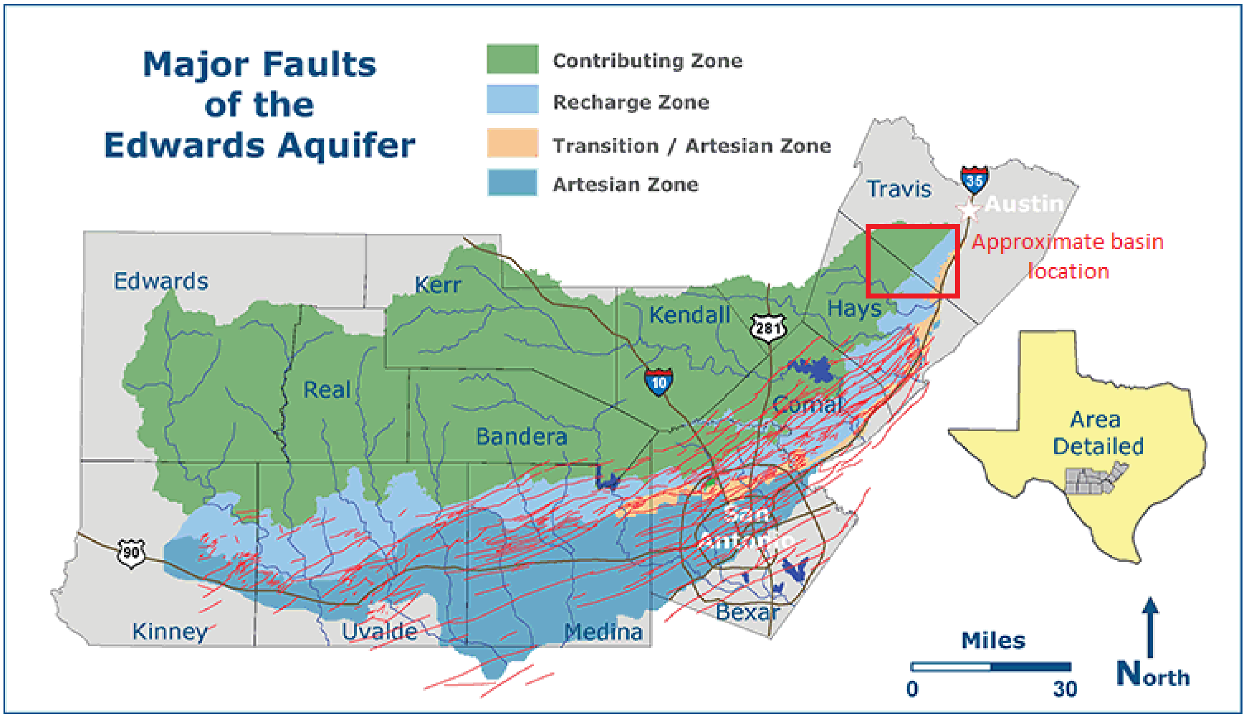
Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
146 / 326	1244 / 796 / 446	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 67% Clay Loam: 18% Loam: 12% Minor classes: 3%	A: 0%; B: 2%; C: 38%; D: 60%; W: 0%	Evergreen Forest: 20% Shrub/Scrub: 20% Developed, Open Space: 16% Grassland/Herbaceous: 11% Developed, Low Intensity: 10% Deciduous Forest: 10% Other: 13%

Figure 23. ATIT2 Sub-basin Map



Observed streamflow data are available from January 2000 through the present for USGS Gage 08159000 (Onion Creek at US Hwy 183, Austin, TX). The average observed streamflow over this period is 99 cfs. The typical event peaks within 6-7 hours, and takes approximately 14 hours to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 138,000 cfs, which occurred in September 1921. More recently, the recorded peak was 135,000 cfs for the October 2013 flood event. ATIT2 resides within the Balcones Fault Zone, where karst geologic features are prevalent. These features can cause local runoff losses, or gains when springs are present (see Figure 24).

Figure 24. Geologic Topography in the Basin Vicinity. ATIT2's Approximate Location Is Shown in Red.



Source: http://www.edwardsaquifer.net/faults.html

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream sub-basin ONIT2. Table 37 compares the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 37. Lag/Q and K/Q Pairs for Routing Reach ONIT2 to ATIT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**
Lag	Orig.	3	1	3	5097	3	15741
	Calib.	4	2650	6	10500	3	17000
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
K	Orig.	0	1	0	5097	0	24486
	Calib.	0.5	2650	1.00	10500	-	-

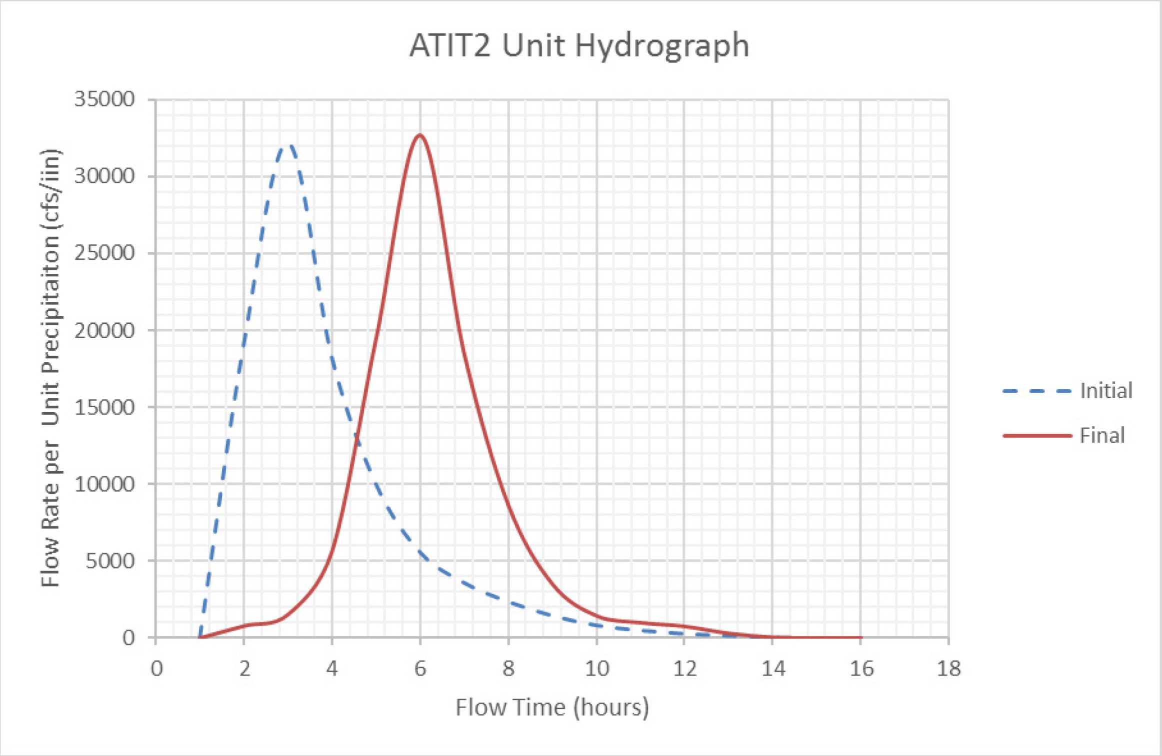
Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to over-simulate peaks and that the rising limb of the simulated response occurred too quickly. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZFWM (which influences the timing and magnitude of the largest surface runoff events) and LZSK (which controls the recession rate of the secondary baseflow component). Accordingly, emphasis was placed on refining these parameters during the calibration analysis. To account for suspected local runoff losses due to the karst formations mentioned previously, a high value of the SIDE parameter was specified. All other parameter values selected during the model calibration analysis are within the typical range of values. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 38.

Table 38. Original Versus Calibrated SAC-SMA Parameters for ATIT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	30	30	0.20	0.005	0.05	0.020	70	2.00	150	30	45	0.100	0.007	0.15	0.3	0.00	3.32
Calib.	1.000	1.000	60	45	0.50	0.01	0.02	0.020	200	3.50	235	30	140	0.100	0.020	0.05	0.3	1.50	5.80

The initially developed UNIT-HG model, described in Appendix B, performed well in simulating the observed peak magnitude; however, the timing of the simulated peak was too early based on inspection of hourly flows in PLOT-TS. The UNIT-HG ordinates were therefore manually adjusted to peak three (3) hours later. This adjustment provided improved timing of the simulated peak. The initially derived and final unit hydrographs are presented in Figure 25.

Figure 25. ATIT2 Initial and Final Calibrated UNIT HG



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 39 and 40, respectively.

Table 39. ATIT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	38.8	123.4	3.0	4.1	39.1	53.5	13.2	13.0	1650	48.9	0.477	-0.6	0.3	1.53	0.35
Calib.	-41.6	58.0	3.0	1.7	39.1	29.9	13.2	17.3	687	20.4	0.859	0.7	0.7	1.02	1.12

Table 40. ATIT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	83.0	109.6	3.0	5.4	39.1	57.7	13.2	10.6	1494.0	44.3	0.644	-0.3	0.4	0.60	0.44
Calib.	2.7	41.1	3.0	3.0	39.1	38.5	13.2	12.6	477.7	14.2	0.933	0.9	0.9	0.08	0.95

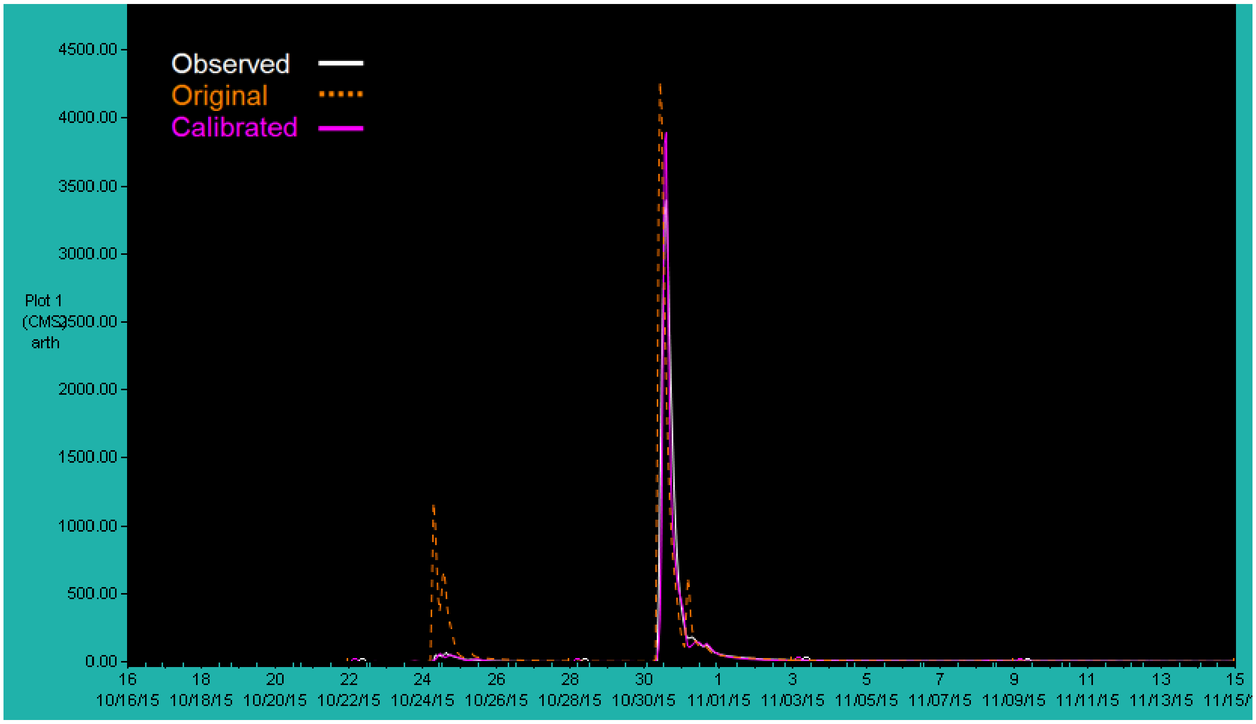
In addition to considering the STAT-Q output, the PEAKFLOW operation was used during the calibration analysis to evaluate model performance for the recent large flood events, as shown in Table 41. As seen in the table, these flood events are simulated well by the calibrated models, although there is timing error during the 5/24/2015 event. Timing errors such as this are sometimes due to the observed peak occurring near midnight, which can trigger an error despite the simulated peak actually being predicted relatively close to the actual observed time.

Table 41. ATIT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
3820.0	10/31/2013	2900.0	10/31/2013	0	-920.0	0.76
428.0	5/24/2015	742.0	5/25/2015	-1	314.0	1.73
3460.0	10/30/2015	3890.0	10/30/2015	0	430.0	1.12

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 26. Overall, the final calibrated models should provide significantly improved predictive performance over those in the current forecast system.

Figure 26. Sample Plot Comparing the Original Versus Final Calibration Simulations for ATIT2



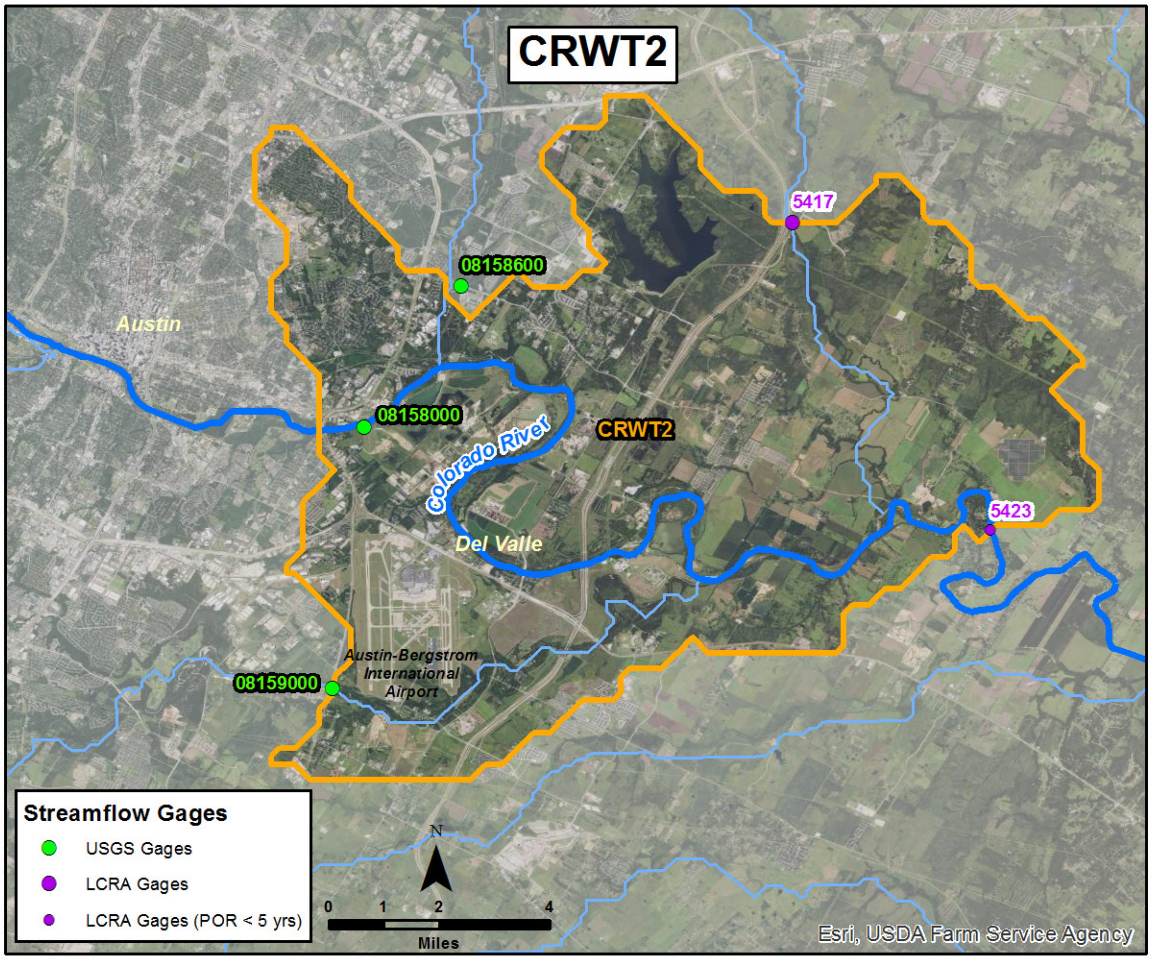
4.4.5 CRWT2: Colorado River near Webberville, TX

CRWT2 is a suburban/rural local sub-basin located just southeast of Austin that drains approximately 98 mi^2 locally and 37,110 mi^2 total. Residential/commercial development is dense in the western portion of the drainage area, with several Austin suburbs contained within the sub-basin boundary. The northern and eastern portions of the sub-basin are primarily rural. Walter E. Long Lake is situated at the upstream end of the basin, which stores cooling water pumped from the Colorado River for a nearby power plant. In addition, CRWT2 resides at the edge of the Balcones Fault Zone, where karst geologic features are prevalent. Local streamflow gains due to springs in the region are a likely influence on the total runoff. The dominant hydrologic soil groups are types B and D. Type B soils have a moderate, variable infiltration rate with average runoff potential. Type D soils have a low infiltration rate with high runoff potential. Table 42 summarizes the basin characteristics followed by Figure 27 which presents an aerial map of CRWT2.

Table 42. Basin Characteristics for CRWT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
98 / 37110	705 / 489 / 390	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Loam: 29% Clay: 23% Sandy Clay Loam: 13% Other: 10% Silty Clay Loam: 10% Minor classes: 15%	A: 4%; B: 54%; C: 8%; D: 35%; W: 0%	Pasture/Hay: 19% Shrub/Scrub: 17% Developed, Open Space: 14% Other: 50%

Figure 27. CRWT2 Sub-basin Map



Observed streamflow data are available for LCRA Gage 5423 (Colorado River near Webberville) from December 2015 through December 2016. The average observed streamflow over this period is 2,810 cfs. The typical event peaks within half a day, and takes approximately two (2) days to recede back to baseflow levels. The highest instantaneous flow recorded at the gage over the available period is 30,171 cfs in June 2016. CRWT2 is downstream of Lake Travis on the Colorado River, as well as several tributaries. Its local drainage area comprises less than 0.5% of the total contributing drainage area. Due to the short available period of record, the water balance at CRWT2 is difficult to assess. Over this period, the calibration analysis results indicated that there is a net gain of streamflow of about 200 cfs that cannot be accounted for through runoff modeling alone. Contributions from springs in the area are a likely source of these gains. In addition, it is possible that releases from Walter E. Lake storage occurred during the modeled period.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream basins ATIT2, ACRT2, WWVT2, and MNGT2. Tables 43 through 46 compare the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 43. Lag/Q and K/Q Pairs for Routing Reach ATIT2 to CRWT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**	**Lag4**	**Q4**	**Lag5**	**Q5**	**Lag6**	**Q6**
	Orig.	6	0	6	1400	6	9500	4	100000	6	500000	4	999999
Lag	Calib.	7	2200	10	7100	8	22000	2	30000	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
	Orig.	6	0	6	100000	6	999999	-	-	-	-	-	-
K	Calib.	2.5	7100	8.00	20000	12	30000	-	-	-	-	-	-

Table 44. Lag/Q and K/Q Pairs for Routing Reach ACRT2 to CRWT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**	**Lag4**	**Q4**	**Lag5**	**Q5**	**Lag6**	**Q6**
	Orig.	10	0	8	1400	6	3500	4	100000	9	500297	3	1000594
Lag	Calib.	9	700	6	3500	5	10600	-	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
	Orig.	6	0	6	3500	6	500297	-	-	-	-	-	-
K	Calib.	5.0	700	9.00	3500	8	10600	-	-	-	-	-	-

Table 45. Lag/Q and K/Q Pairs for Routing Reach WWVT2 to CRWT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**	**Lag4**	**Q4**
	Orig.	12	5	9	1000	6	3000	12	10000
Lag	Calib.	10	700	7	1800	6	3900	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**
	Orig.	3	5	3	3000	3	10000	-	-
K	Calib.	5.0	700	4.00	1800	3	3900	-	-

Table 46. Lag/Q and K/Q Pairs for Routing Reach MNGT2 to CRWT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**	**Lag4**	**Q4**
	Orig.	12	5	9	200	6	500	12	5000
Lag	Calib.	3	350	4	1060	6	2500	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**
	Orig.	8	5	6	500	6	5000	-	-
K	Calib.	2.0	350	3.00	1060	6	2500	-	-

Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to under-simulate baseflow and runoff events and simulate flood peaks which occur too early compared to the observed.

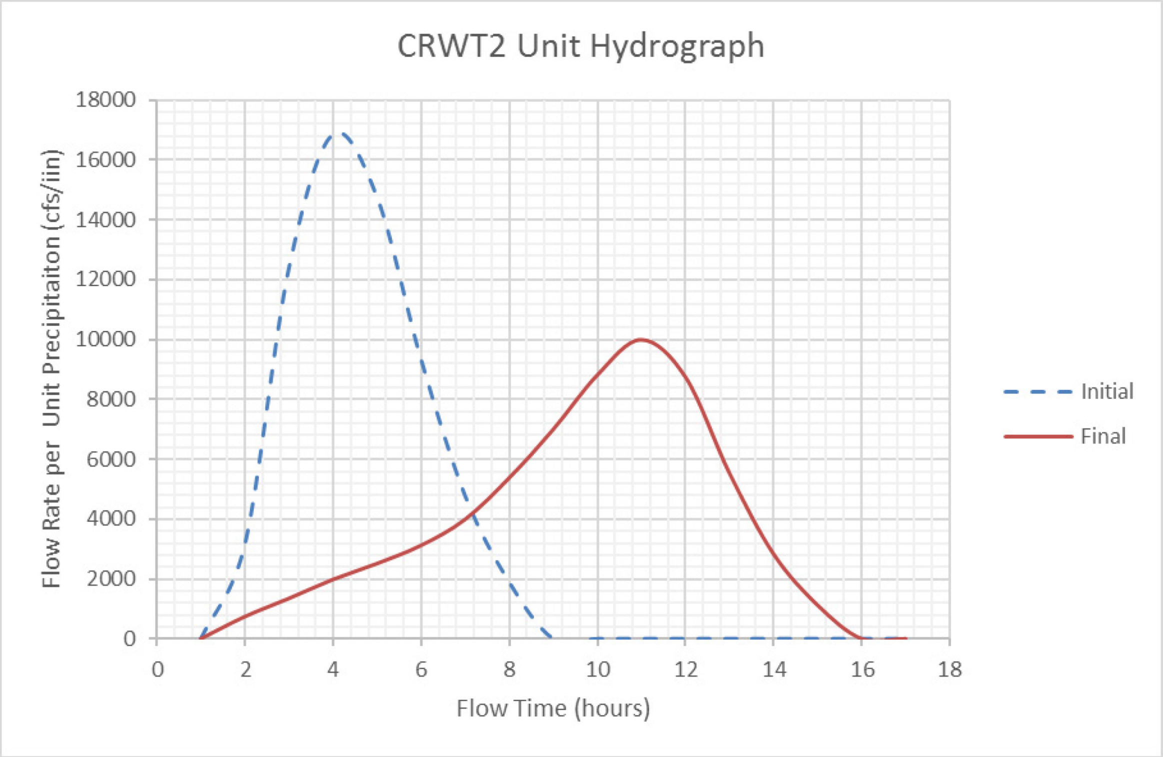
Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZK and UZFWM (which together influence the timing and magnitude of the mid-sized to large events) and LZFSM (which controls the magnitude of the primary baseflow component). Accordingly, emphasis was placed on refining these parameters. To model the net gains mentioned above, a CHANLOSS operation (with a constant inflow rate that is varied monthly) was utilized. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 47.

Table 47. Original Versus Calibrated SAC-SMA Parameters for CRWT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	20	20	0.45	0.01	0.05	0.005	130	2.30	100	25	70	0.150	0.003	0.30	0.3	0.00	3.96
Calib.	1.000	1.000	30	60	0.40	0.01	0.10	0.010	150	2.30	150	50	200	0.130	0.010	0.30	0.3	0.00	8.50

Due to the short available period of record, there were not enough events of sufficient quality to manually derive a UNIT-HG model with a reasonable degree of confidence; therefore, the initial UNIT-HG ordinates were estimated using GIS processes, as described in Appendix B. During the calibration analysis, it was observed that this initial UNIT-HG model consistently resulted in flood peaks that were over-simulated and peaked too quickly. Therefore, the UNIT-HG ordinates were adjusted manually during calibration as shown in Figure 28.

Figure 28. CRWT2 Initial and Final Calibrated UNIT HG



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 48 and 49, respectively. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 48. CRWT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

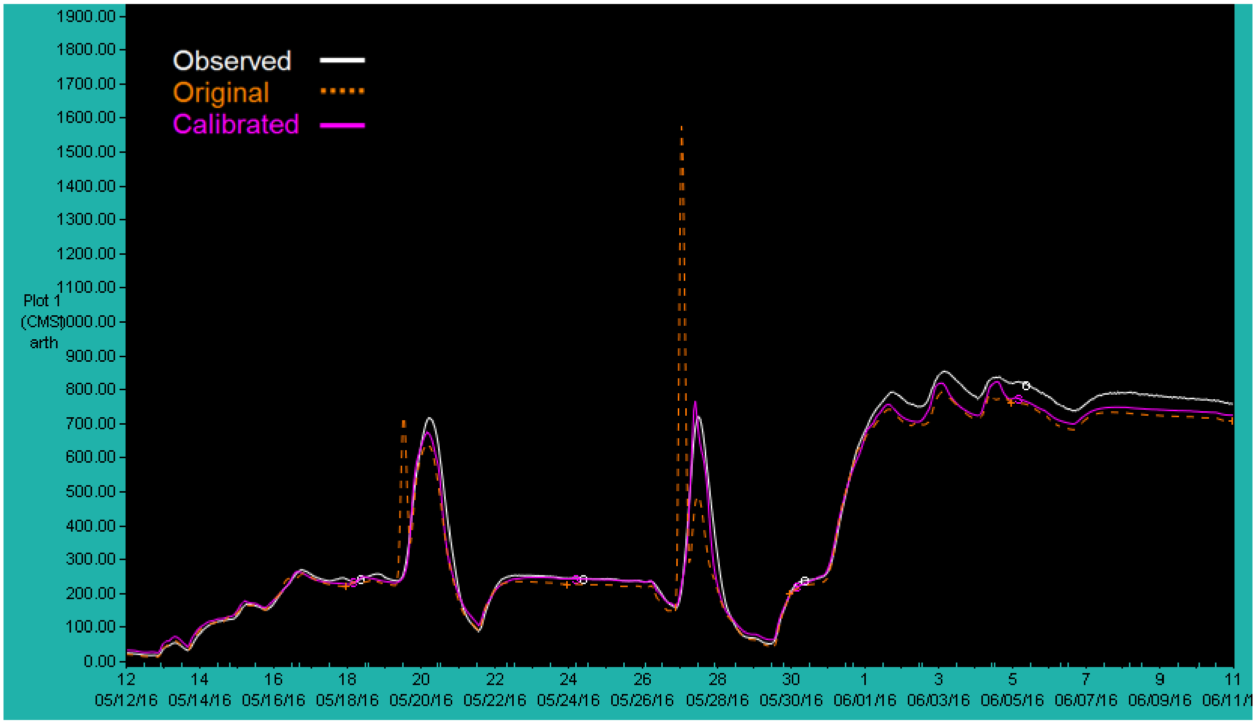
Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean CMS	Obs. std CMS	Sim. std CMS	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
Orig.	-94.3	97.3	76.7	4.4	149.3	34.2	1.9	7.9	217.6	166.9	0.083	-0.2	0.0	75.10	0.36
Calib.	-95.2	95.2	76.7	3.7	149.3	10.2	1.9	2.8	213.4	163.7	0.310	-0.2	0.0	60.00	4.52

Table 49. CRWT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	-8.4	14.0	76.7	70.3	149.3	143.1	1.9	2.0	45.9	35.2	0.973	0.9	0.9	5.35	1.02
Calib.	-1.8	7.3	76.7	75.3	149.3	142.1	1.9	1.9	15.4	11.8	0.998	1.0	1.0	-2.29	1.05

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 29. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 29. Sample Plot Comparing the Original Versus Final Calibration Simulations for CRWT2



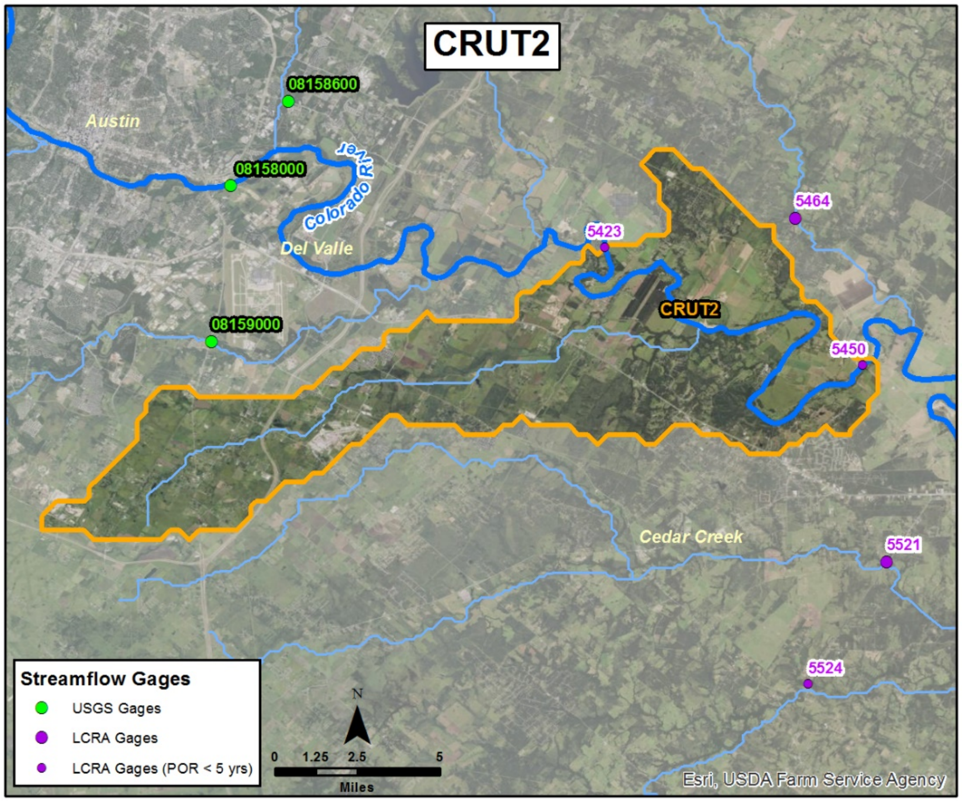
4.4.6 *CRUT2: Colorado River near Utley, TX*

CRUT2 is a rural local sub-basin located about 10 miles southeast of Austin in Travis and Bastrop counties that drains approximately 89 mi^2 locally and 37,199 mi^2 total. Residential/commercial development is light to moderate, with some development south of Austin-Bergstrom Airport. The dominant hydrologic soil groups are types B and D. Type B soils have a moderate, variable infiltration rate with average runoff potential. Type D soils have a low infiltration rate with high runoff potential. Table 50 summarizes the basin characteristics followed by Figure 30 which presents an aerial map of CRUT2.

Table 50. Basin Characteristics for CRUT2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
89 / 37199	699 / 482 / 348	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Clay: 58% Loam: 11% Minor classes: 31%	A: 2%; B: 26%; C: 11%; D: 61%; W: 0%	Shrub/Scrub: 30% Pasture/Hay: 19% Deciduous Forest: 10% Grassland/Herbaceous: 10% Other: 31%

Figure 30. CRUT2 Sub-basin Map



Observed streamflow data are available for LCRA gage 5450 (Colorado River near Utley) from March through December 2016. The average observed streamflow over this period is 3,544 cfs. The typical event peaks within 12 to 24 hours, and takes approximately 1 to 1.5 days to recede back to baseflow levels. The highest instantaneous flow recorded at the gage within the available period is 31,925 cfs in May 2016.

Flow at the outlet is largely influenced by upstream areas due to the large total basin area (37,199 mi^2) relative to the local area (89 mi^2). Although there are possible diversions in the basin there is a consistent baseflow of 300+ cfs. During periods of no precipitation there are frequent small oscillations, presumably from a combination of delayed hydrologic responses from remote portions of its basin area and reservoir releases or return flows upstream. The period of record is very short at only 10 months so it is possible that there are long-term hydrologic trends that were not obvious based on the available data.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream basin CRWT2. Table 51 compares the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 51. Lag/Q and K/Q Pairs for Routing Reach CRWT2 to CRUT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	Lag1	Q1	Lag2	Q2	Lag3	Q3	Lag4	Q4	Lag5	Q5	Lag6	Q6
	Orig.	10	0	8	1400	6	3500	4	100000	9	500297	3	1000594
Lag	Calib.	7	1060	5	1800	2	20000	-	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
	Orig.	6	0	6	3500	6	500297	-	-	-	-	-	-
K	Calib.	2	1060	5	1800	8	20000	12	30000	-	-	-	-

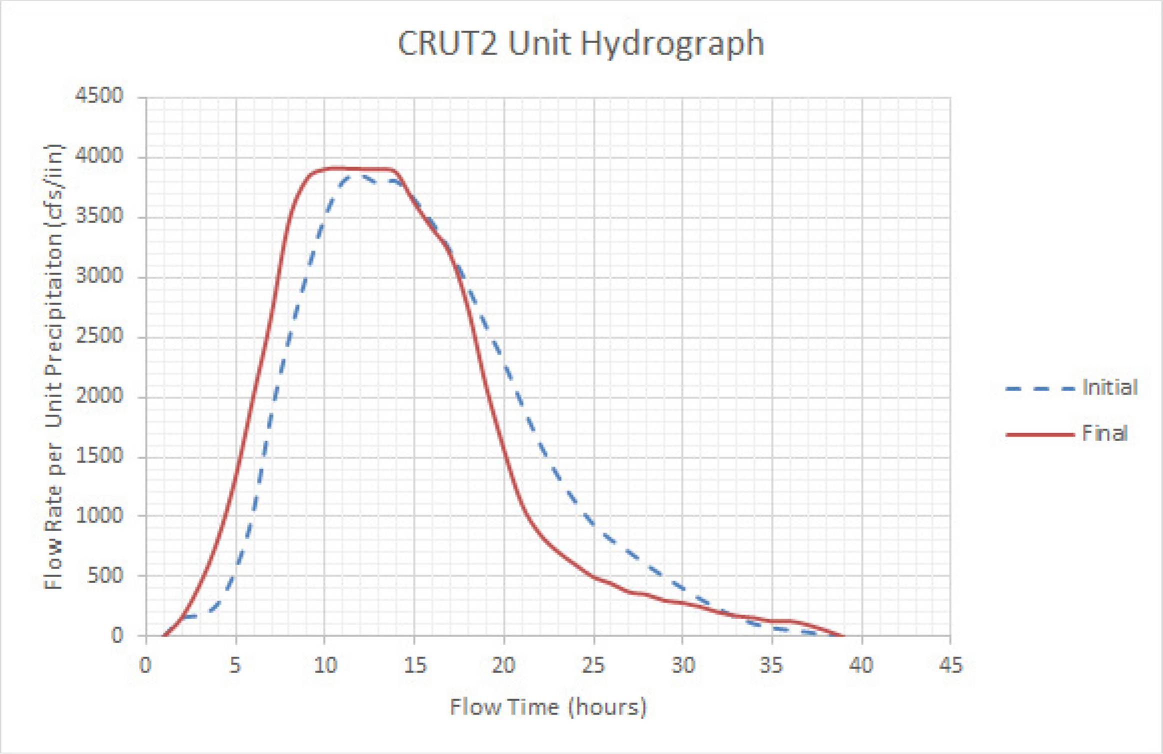
Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to slightly over-simulate total flow peaks, which occurred late compared to the observed. When comparing local flows, the models tended to over-simulate baseflow and medium-sized events while under-simulating the important larger local events. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be those controlling the upper zone of soil, namely UZTWM, UZFWM, and UZK. Accordingly, emphasis was placed on refining these parameters. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 52.

Table 52. Original Versus Calibrated SAC-SMA Parameters for CRUT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	20	20	0.45	0.01	0.05	0.005	130	2.30	100	25	70	0.150	0.003	0.30	0.3	0.00	3.96
Calib.	1.000	1.000	90	45	0.30	0.015	0.10	0.010	100	2.50	150	20	150	0.060	0.002	0.10	0.3	0.00	1.50

The UNIT-HG model was derived manually from two (2) events during the observed period, as described in Appendix B, and performed well during the initial calibration runs. The model was adjusted slightly to peak earlier and recede more quickly based on calibration analysis results. The initial and final UNIT-HG model ordinates are shown in Figure 31.

Figure 31. CRUT2 Initial and Final Calibrated UNIT HG



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 53 and 54, respectively. These results reflect the small local flow contribution and the importance of the routing modeling. Within the local flow STAT-Q results, there is a large negative volume bias, which is largely due to one period (June 1-11, 2016) where the observed upstream routed flow is higher than the total flow observed at the CRUT2 outlet. The short observed period of record did not allow for a more detailed hydrologic analysis of gains/losses within this reach; however, a review of external references and data available from the LCRA was conducted. This review did not yield any information which warranted accounting for losses within the final CRUT2 models.

Table 53. **CRUT2 Original versus calibrated simulation statistics for local flow (reported from STAT-Q)**

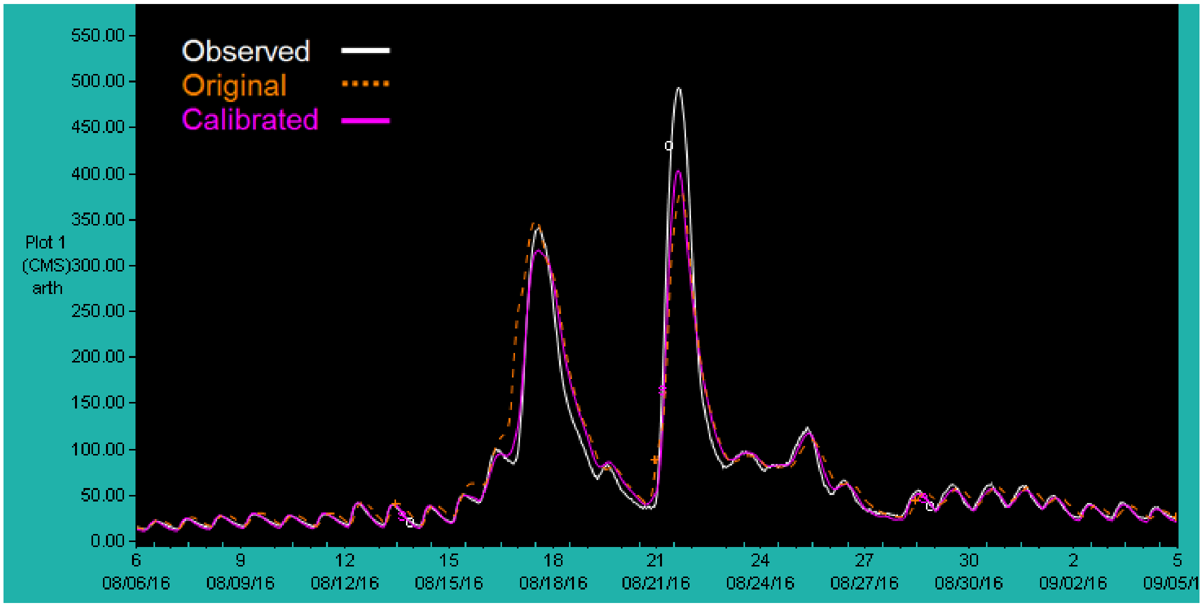
Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean CMS	Obs. std CMS	Sim. std CMS	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
Orig.	-94.3	94.4	94.6	5.4	156.5	27.2	1.7	5.0	185	175.1	0.298	-0.3	0.1	85.40	1.72
Calib.	-95.7	95.7	94.6	4.1	156.5	20.9	1.7	5.1	186.1	176.1	0.325	-0.3	0.0	84.60	2.44

Table 54. **CRUT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)**

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	-1.9	12.7	95	92.8	156.5	162.9	1.7	1.8	30	29	0.985	1.0	0.9	6.8	1.0
Calib.	3.6	8.2	95	98.1	156.5	168.6	1.7	1.7	21	20	0.995	1.0	0.9	4.0	0.9

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 32. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 32. **Sample Plot Comparing the Original Versus Final Calibration Simulations for CRUT2**



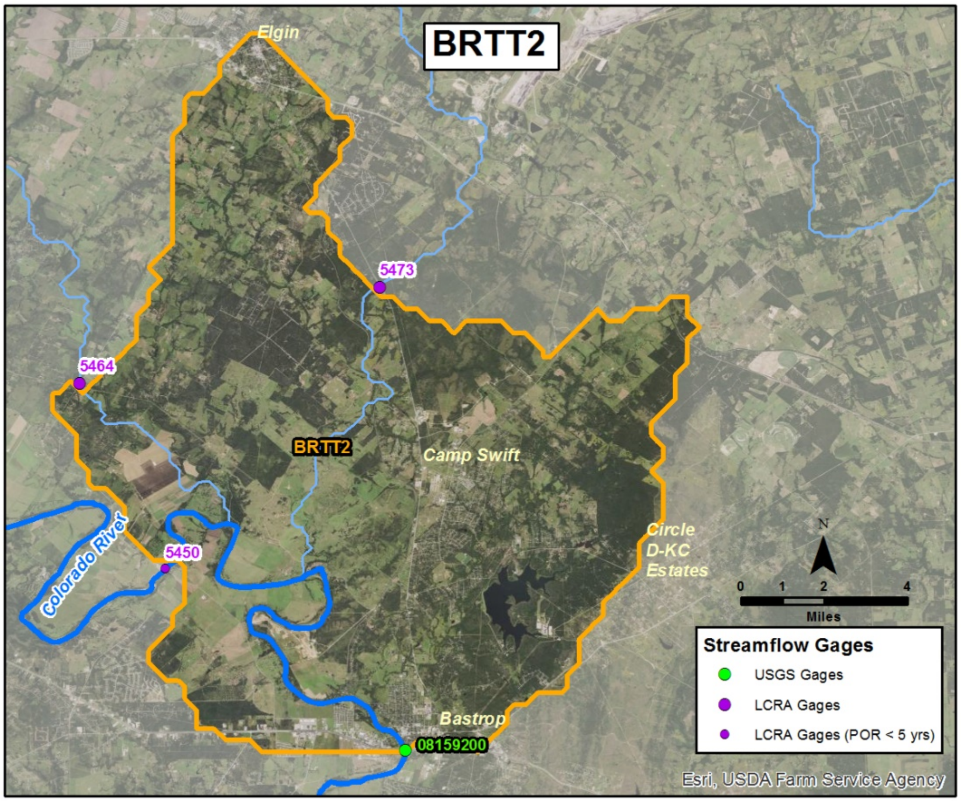
4.4.7 BRTT2: Colorado River at Bastrop, TX

BRTT2 is a rural local sub-basin located about 25 miles east of Austin in Bastrop County that drains approximately 126 mi^2 locally and 37,551 mi^2 total. Residential/commercial development is light, with the primary land use being pasture/hay. All or portions of the towns of Bastrop (population 7,218), Camp Swift (population 6,383), and Elgin (population 8,135) are contained within the sub-basin boundary. Lake Bastrop is also contained within BRTT2. The LCRA, which owns and operates the lake, is permitted to pump from the Colorado River at a rate no greater than 33.33 cfs according to the certificate of adjudication dated March 4th, 1963. The dominant hydrologic soil groups are types B and D. Type B soils have a moderate, variable infiltration rate with average runoff potential. Type D soils have a low infiltration rate with high runoff potential. Table 55 summarizes the basin characteristics followed by Figure 33 which presents an aerial map of BRTT2.

Table 55. Basin Characteristics for BRTT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
126 / 37551	643 / 454 / 341	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Sandy Clay Loam: 28% Clay Loam: 28% Minor classes: 44%	A: 8%; B: 33%; C: 9%; D: 51%; W: 0%	Pasture/Hay: 25% Shrub/Scrub: 17% Deciduous Forest: 13% Evergreen Forest: 13% Other: 32%

Figure 33. BRTT2 Sub-basin Map



Observed streamflow data are available for USGS gage 08159200 (Colorado River at Bastrop, TX) from January 2000 through December 2016. The average observed streamflow over this period is 1,711 cfs. The typical event peaks within 12 to 36 hours, and takes approximately 2 to 3 days to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 79,600 cfs, which occurred in October 1960. With just 0.3% of its total area comprised by the local area, flow is primarily influenced by upstream contributions.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream basins CRUT2, EGYT2, and EGZT2. Tables 56 through 58 compare the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 56. Lag/Q and K/Q Pairs for Routing Reach CRUT2 to BRTT2(All Lag and K in Hours and All Q in cfs)

	Sim.	Lag 1	Q1	Lag 2	Q2	Lag 3	Q3	Lag 4	Q4	Lag 5	Q5	Lag 6	Q6
	Orig.	10	0	8	1400	6	3500	4	100000	9	500297	3	1000594
Lag	Calib.	2	-	-	-	-	-	-	-	-	-	-	-

	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
	Orig.	6	0	6	3500	6	500297	-	-	-	-	-	-
K	Calib.	3	12400	8	20000	12	30000	-	-	-	-	-	-

Table 57. Lag/Q and K/Q Pairs for Routing Reach EGYT2 to BRTT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**	**Lag4**	**Q4**
	Orig.	9	10	5	25	5	250	14	350
Lag	Calib.	0	-	-	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**
	Orig.	12	25	8	50	10	200	-	-
K	Calib.	9.0	5000	18.00	10000	-	-	-	-

Table 58. Lag/Q and K/Q Pairs for Routing Reach EGZT2 to BRTT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**
	Orig.	6	20	9	30	12	100
Lag	Calib.	0	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
	Orig.	5	10	8	25	-	-
K	Calib.	4.0	900	6.00	2650	8	10600

Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to over-simulate low flows, while under-simulating high flows. Therefore, the focus of calibration effort was aimed at correcting these weaknesses while maintaining the overall water balance. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be LZSK (which controls the recession rate of the secondary baseflow component) and UZFWM (which influences the timing and magnitude of the largest surface runoff events). Accordingly, emphasis was placed on refining these parameters.

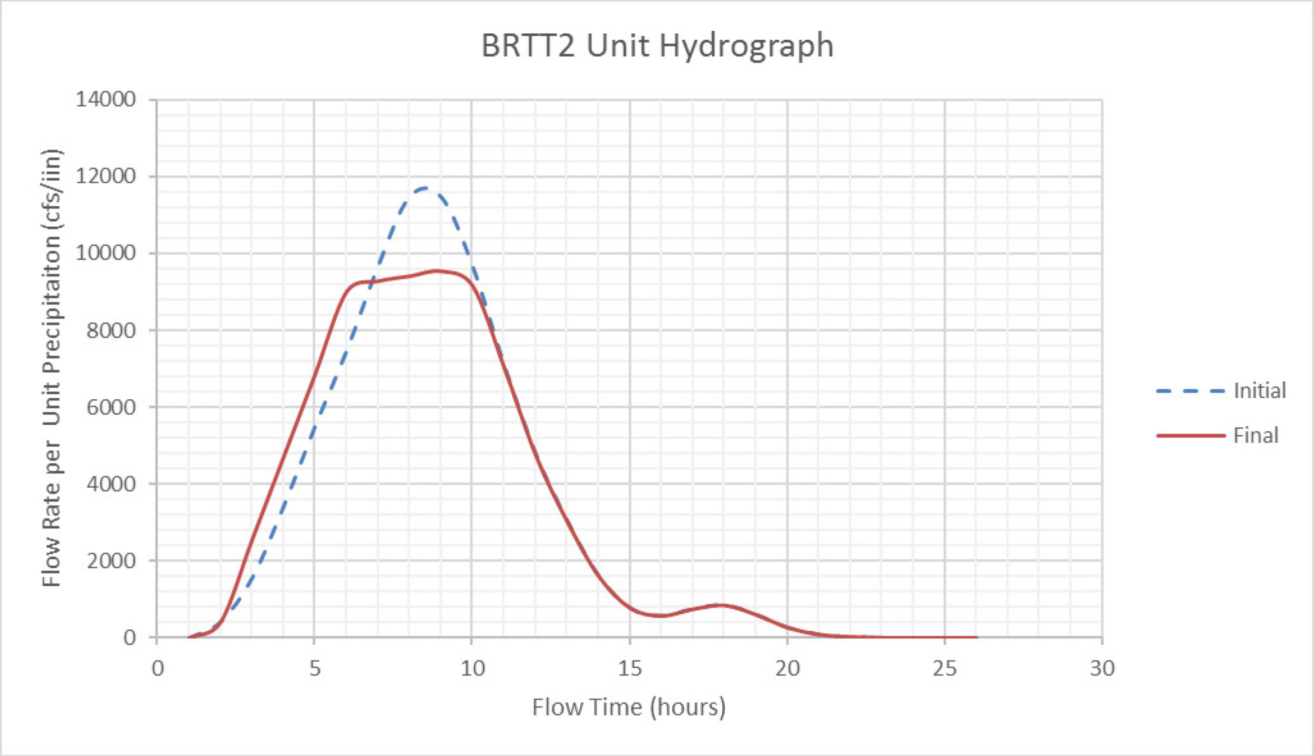
Overall calibration was challenging due to the short period of record. In addition, diversions to Lake Bastrop and, possibly other irrigation diversions, are likely influencing the total streamflow. Therefore, a CHANLOSS operation (with a constant rate that is varied monthly) was incorporated into the final hydrologic models. The rates specified within this operation should be reevaluated once a longer historical streamflow period of record becomes available for analysis. A SIDE value of 1.0 was also specified within the SAC-SMA operation to account for losses from the local area runoff. These local losses may be related to karst influences or due to agricultural activities within the area. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 59.

Table 59. Original Versus Calibrated SAC-SMA Parameters for BRTT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	20	20	0.45	0.010	0.05	0.005	130	2.30	100	25	70	0.150	0.003	0.30	0.3	0.00	3.96
Calib.	1.000	1.000	75	75	0.50	0.01	0.05	0.010	100	2.50	175	40	175	0.080	0.011	0.05	0.3	1.00	5.13

Due to the short available period of record, there were not enough events of sufficient quality to manually derive a UNIT-HG model with a reasonable degree of confidence; therefore, the initial UNIT-HG ordinates were estimated using GIS processes, as described in Appendix B. During the calibration analysis, the UNIT-HG ordinates were revised to reduce the peak magnitude and increase the slope of the rising limb slightly, as seen in Figure 34.

Figure 34. BRTT2 Initial and Final Calibrated UNIT HG



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system.

A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 60 and 61, respectively.

Table 60. BRTT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

Sim.	**% Bias**	**Abs. % Bias**	**Obs. Qmean CMS**	**Sim. Qmean 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**
Orig.	-91.9	95.5	35.3	2.9	93.5	24.3	2.7	8.5	272.6	96.2	0.249	-0.1	0.1	32.50	0.96
Calib.	-95.6	95.7	35.3	1.6	93.5	12.0	2.7	7.7	269.3	95.0	0.443	0.0	0.1	29.90	3.45

Table 61. BRTT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	**% Bias**	**Abs. % Bias**	**Obs. Qmean CMS**	**Sim. Qmean 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**
Orig.	7.2	29.1	35.3	37.8	93.5	112.2	2.7	3.0	112.1	39.6	0.942	0.8	0.8	5.57	0.79
Calib.	0.2	15.3	35.3	35.3	93.5	100.1	2.7	2.8	49.3	17.4	0.986	1.0	0.9	2.73	0.92

In addition to considering the STAT-Q output, the PEAKFLOW operation was used during the calibration analysis to evaluate model performance for the recent large flood events, as shown in Table 62. As seen in the table, these flood events are simulated well by the calibrated models, although there is timing error during the 1/26/2012 event. Timing errors such as this are sometimes due to the observed peak occurring near midnight, which can trigger an error despite the simulated peak actually being predicted relatively close to the actual observed time.

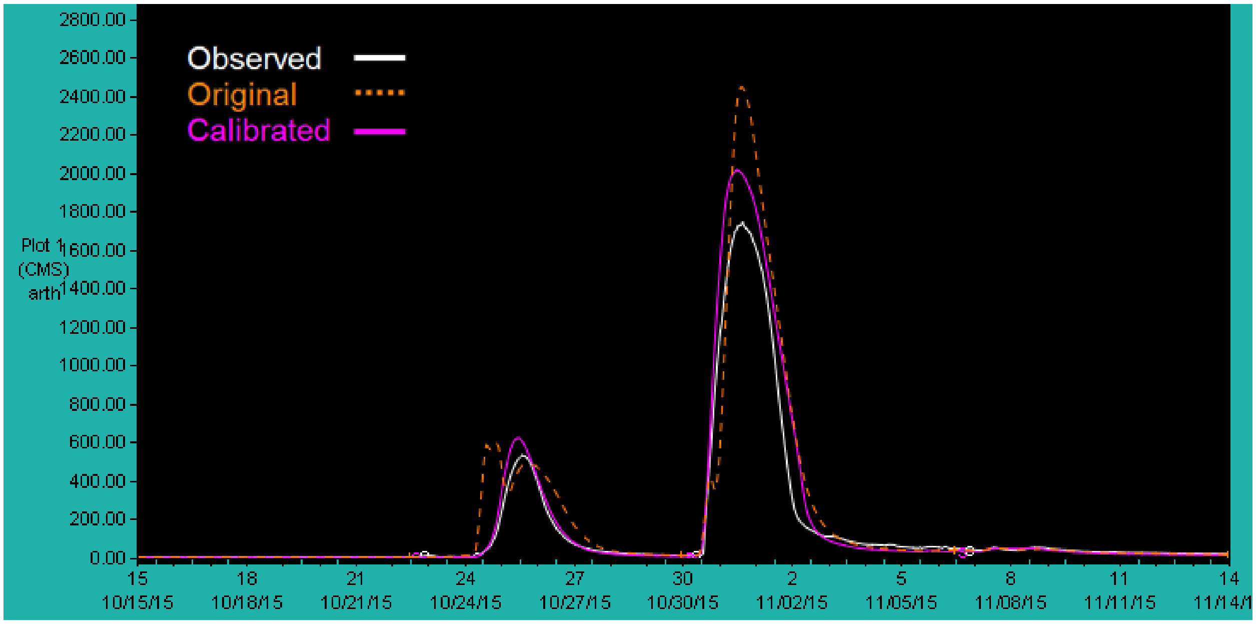
Table 62. BRTT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		**Simulated Peak**		**Timing Error (Days)**	**Discharge Error (CMS)**	**Discharge Ratio (Sim/Obs)**
Q (CMS)	**Date**	**Q (CMS)**	**Date**			
118.0	5/13/2011	120.0	5/13/2011	0	2.0	1.02
813.0	1/26/2012	677.0	1/26/2012	1	-136.0	0.83
223.0	9/30/2013	204.0	9/30/2013	0	-19.0	0.92

1190.0	11/1/2013	1220.0	11/1/2013	0	30.0	1.03
1370.0	5/26/2015	1200.0	5/26/2015	0	-170.0	0.88
1740.0	10/31/2015	2020.0	10/31/2015	0	280.0	1.16

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 35. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 35. Sample Plot Comparing the Original Versus Final Calibration Simulations for BRTT2



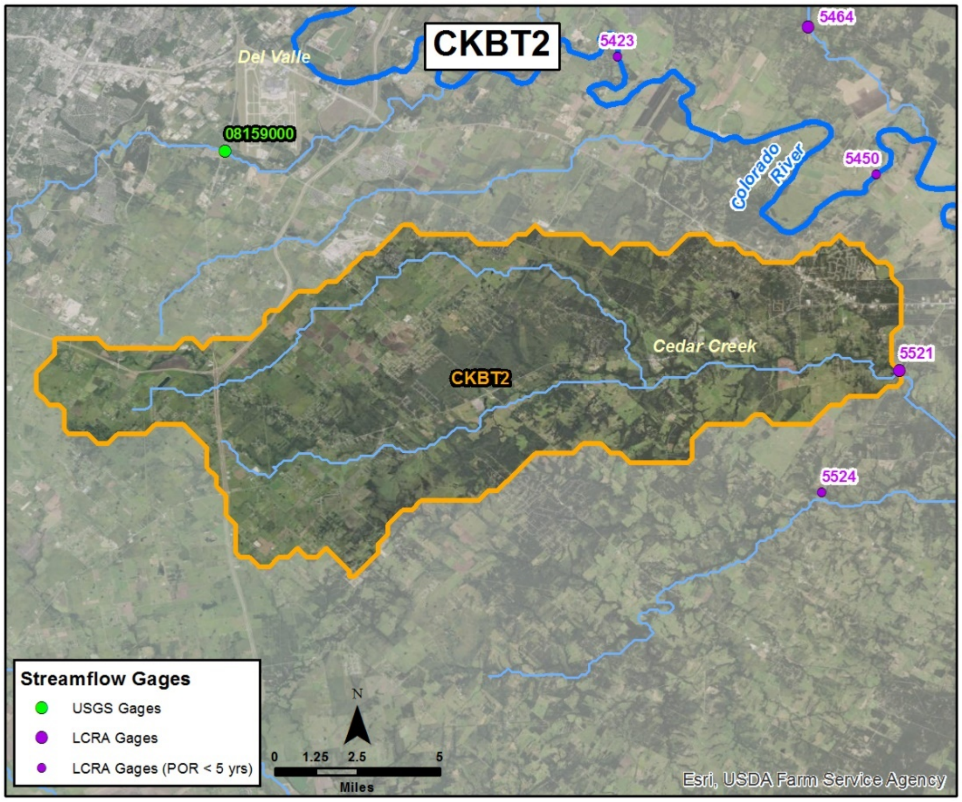
4.4.8 CKBT2: Cedar Creek near Bastrop, TX

CKBT2 is a primarily rural headwater sub-basin located 15 miles southeast of Austin in Travis, Bastrop, and Caldwell counties that drains approximately 131 mi^2. Residential/commercial development is relatively light, with the western portion of Bastrop and a few small, unincorporated towns contained within the sub-basin boundary. Geologically, CKBT2 lies at the edge of the Balcones Fault Zone, and therefore may be influenced to a degree by karst formations. The dominant hydrologic soil group within the local drainage area is type D, which indicates very low infiltration rates and very high runoff potential. Table 63 summarizes the basin characteristics followed by Figure 36 which presents an aerial map of CKBT2.

Table 63. Basin Characteristics for CKBT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
131 / 131	748 / 524 / 361	Texas Blackland Prairie, Northern Part	Clay: 59% Other: 19% Clay Loam: 15% Minor classes: 7%	A: 0%; B: 6%; C: 4%; D: 90%; W: 0%	Shrub/Scrub: 30% Deciduous Forest: 15% Pasture/Hay: 12% Grassland/Herbaceous: 11% Other: 32%

Figure 36. CKBT2 Sub-basin Map



Observed streamflow data are available for LCRA gage 5521 (Cedar Creek near Bastrop) from January 2009 through December 2016. The average observed streamflow over this period is 55 cfs. The typical event peaks within a day, and takes approximately 1-2 additional days to recede back to baseflow levels from peak flow. The highest instantaneous flow recorded at the gage during the period of record is 30,573 cfs, which occurred in October 2015.

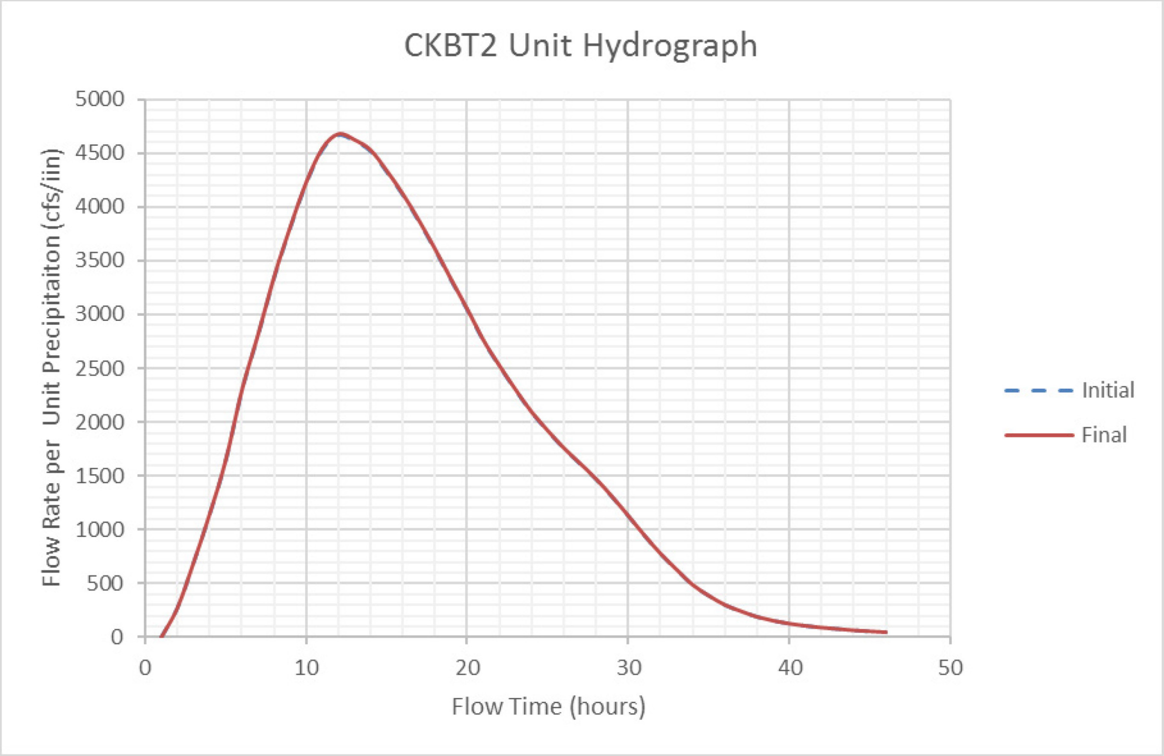
Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to over-predict the frequency of runoff events and the magnitudes of the streamflow peaks. The simulated responses were also typically delayed relative to the observed. Therefore, the focus of calibration effort was aimed at increasing infiltration rates and producing quicker yet smaller responses. Over the course of the calibration analysis, the most sensitive SAC-SMA parameters were found to be UZTWM (which can control the timing of the model response) and UZFWM (which influences the timing and magnitude of the largest surface runoff events). Accordingly, emphasis was placed on refining these parameters. In addition, during calibration the initial PET estimates were lowered slightly in response to simulated volume bias over the calibration period from 2011 to 2016. A SIDE value of 1.0 was specified to account for local runoff losses, possibly related to karst formations. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 64.

Table 64. Original Versus Calibrated SAC-SMA Parameters for CKBT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	25	30	0.50	0.002	0.05	0.007	150	2.50	100	15	30	0.150	0.003	0.05	0.3	0.00	2.34
Calib.	1.000	1.000	60	15	0.50	0	0.05	0.040	150	2.50	250	15	40	0.100	0.001	0.05	0.3	1.00	1.54

The ordinates for the initial UNIT HG were based on six (6) events in the period of record, as described in Appendix B. Figure 37 shows the initial UNIT-HG ordinates, which performed well and were not altered during the calibration analysis.

Figure 37. CKBT2 Initial and Final Calibrated UNIT HG



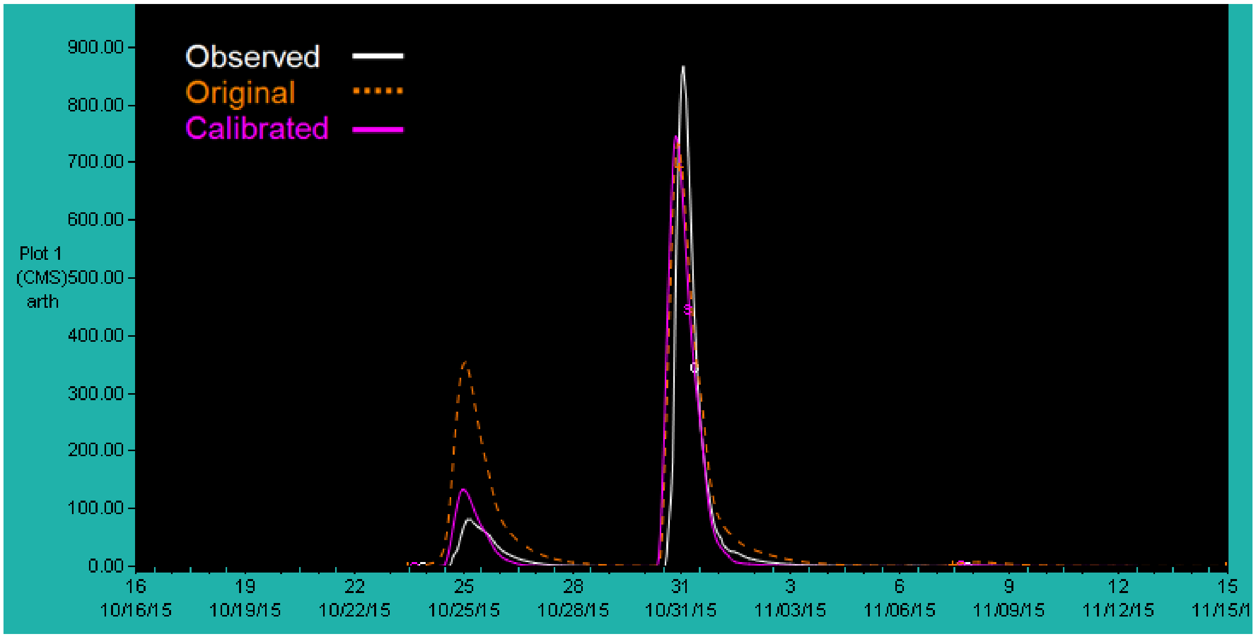
The final calibrated parameter set produces an improved simulation when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models is presented in Table 65. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 65. CKBT2 Original Versus Calibrated Simulation Statistics (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	98.5	120.6	1.9	3.8	23.3	26.4	12.2	7.0	637.7	12.2	0.890	0.7	0.8	-1.07	0.79
Calib.	2.5	51.5	1.9	2.0	23.3	23.8	12.2	12.2	518.9	9.9	0.912	0.8	0.9	0.16	0.89

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 38. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 38. Sample Plot Comparing the Original Versus Final Calibration Simulations for CKBT2



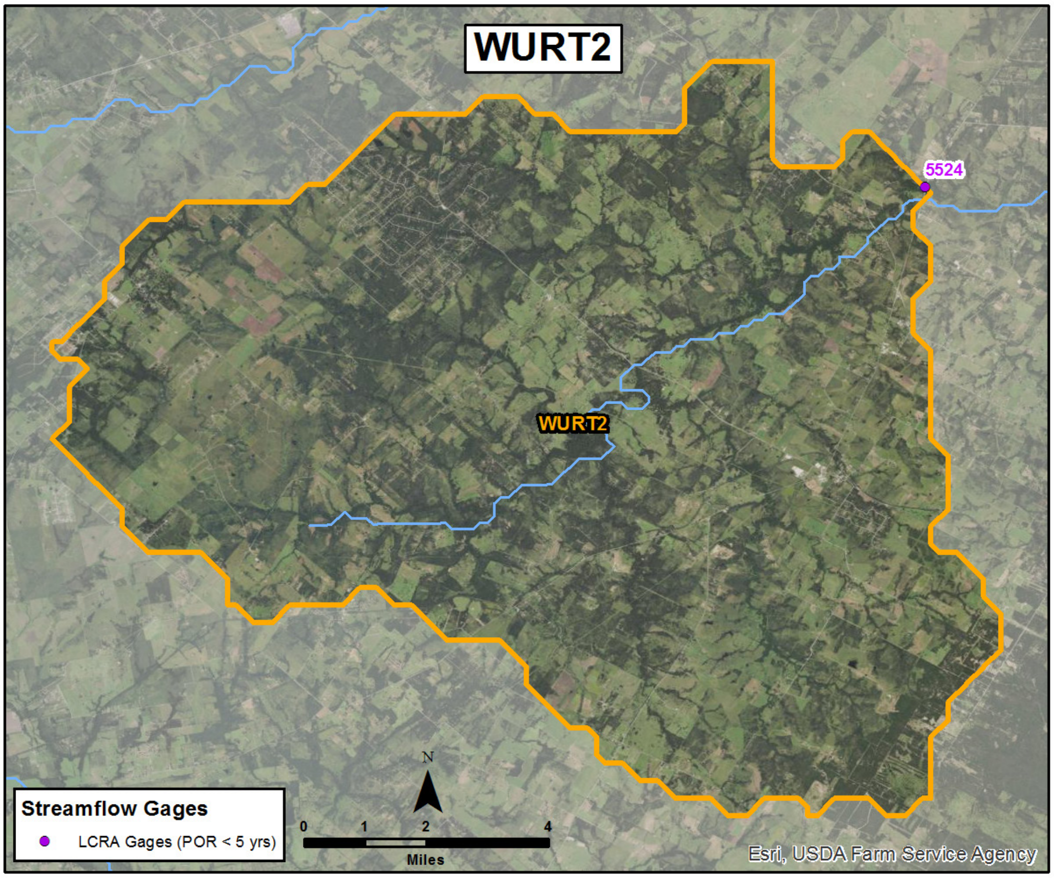
4.4.9 WURT2: Walnut Creek near Rockne, TX

WURT2 is a rural headwater sub-basin located in the Colorado River basin approximately 10 miles southwest of Bastrop that drains approximately 107.2 mi^2. Residential/commercial development is very light, with the towns of Red Rock and Dale (population of less than 300) contained within the sub-basin boundary. Geologically, WURT2 lies near the edge of the Balcones Fault Zone, and therefore may be influenced to a degree by karst formations. The dominant hydrologic soil group within the local drainage area is type D, which indicates very low infiltration rates and very high runoff potential. Table 66 summarizes the basin characteristics followed by Figure 39 which presents an aerial map of WURT2.

Table 66. Basin Characteristics for WURT2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
107 / 107	663 / 490 / 351	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Clay: 56% Other: 24% Minor classes: 20%	A: 2%; B: 9%; C: 0%; D: 89%; W: 0%	Shrub/Scrub: 26% Deciduous Forest: 21% Pasture/Hay: 16% Developed, Open Space: 10% Other: 27%

Figure 39. WURT2 Sub-basin Map



Observed streamflow data are available for LCRA gage 5524 (Walnut Creek near Rockne) from February through December 2016. The average observed streamflow over this period is 126.29 cfs. The typical event peaks within 15 hours, and takes approximately a day to recede back to baseflow levels (about 1 cfs). The highest instantaneous flow recorded within the period of record at the gage is 22,803 cfs, which occurred in May 2016.

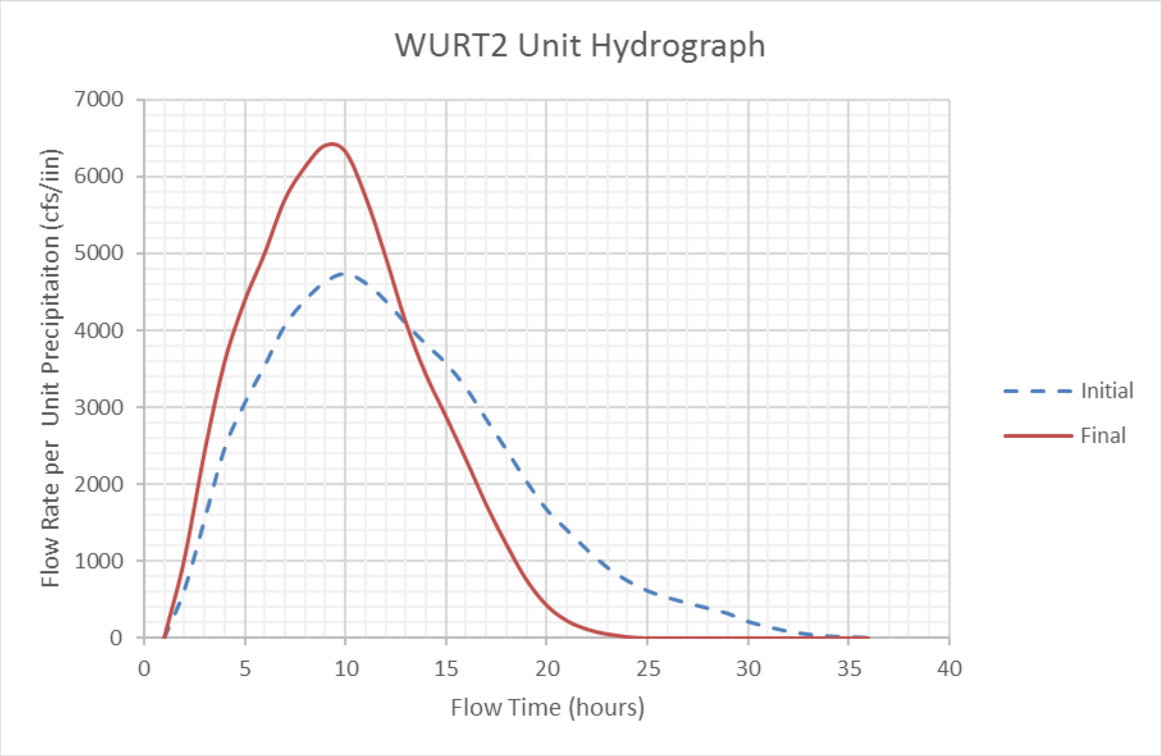
Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tend to under-simulate peak flows and over-simulate baseflow. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZFWM (which influences the timing and magnitude of the largest surface runoff events) and SIDE (a local runoff loss parameter that primarily impacts baseflow contribution). Accordingly, emphasis was placed on refining these parameters. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 67. A SIDE value of 1.0 was specified to account for local runoff losses, possibly related to karst formations.

Table 67. Original Versus Calibrated SAC-SMA Parameters for WURT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	25	30	0.50	0.002	0.05	0.007	150	2.50	100	15	30	0.150	0.003	0.05	0.3	0.00	2.34
Calib.	1.000	1.000	40	15	0.50	0	0.05	0.000	250	2.10	150	15	30	0.150	0.001	0.02	0.3	1.00	2.28

The ordinates for the initial UNIT-HG model were based on four (4) historical events, as described in Appendix B. The initial model, however, was modified during the calibration analysis based on shape and timing of the simulated response. The hydrograph ordinates were adjusted to peak slightly earlier and higher as shown in Figure 40, which improved the simulation.

Figure 40. WURT2 Initial and Final Calibrated UNIT HG



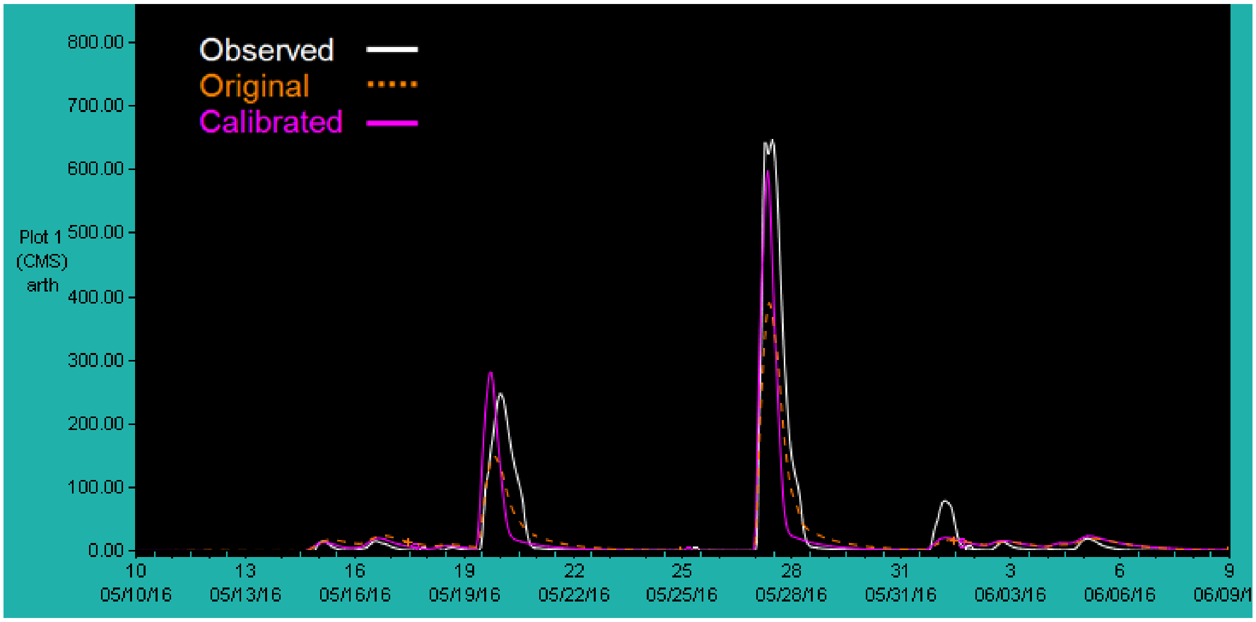
The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for the total flows are presented in Table 68. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 68. WURT2 Original Versus Calibrated Simulation Statistics (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	40.6	103.4	3.6	5.0	29.9	20.7	8.3	4.1	424.2	15.2	0.883	0.7	0.6	-2.83	1.27
Calib.	-1.9	69.3	3.6	3.5	29.9	24.8	8.3	7.1	430.1	15.4	0.858	0.7	0.7	-0.05	1.03

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 41. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 41. Sample Plot Comparing the Original Versus Final Calibration Simulations for WURT2



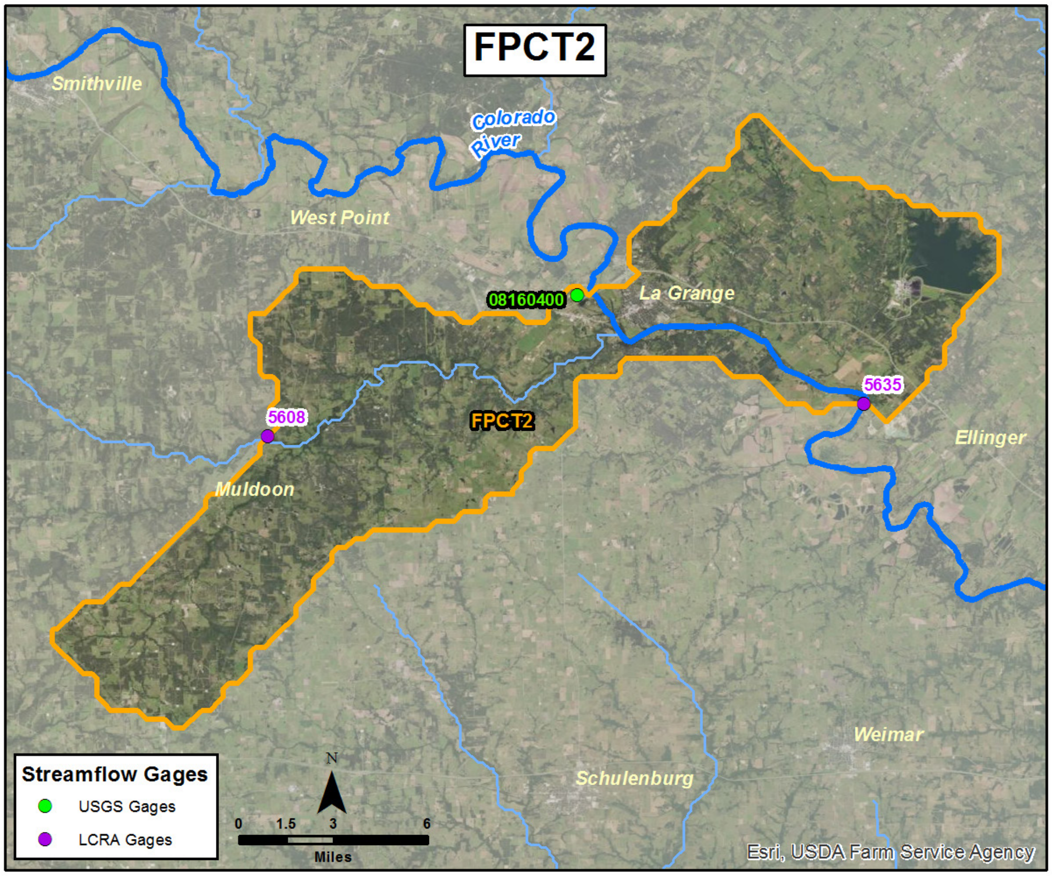
4.4.10 FPCT2: Colorado River at FPP River Plant, TX

FPCT2 is a rural local sub-basin located 50 miles southeast of Austin near the town of La Grange in Fayette County that drains approximately 156 mi^2 locally and 38,692 mi^2 total. Residential/commercial development is light, with only portions of the town of La Grange contained within the sub-basin boundary. There are also several small incorporated communities including Muldoon, Rutersville, Halsted, O'Quinn, and Hostyn. Lake Fayette is located within the sub-basin boundaries. This lake is used as storage for cooling water at a nearby power plant. Diversions to the lake from a pumping station along the river and return flows from Cedar Creek are visible from aerial imagery. The dominant hydrologic soil group within the local drainage area is type D, which indicates very low infiltration rates and very high runoff potential. Table 69 summarizes the basin characteristics followed by Figure 42 which presents an aerial map of FPCT2.

Table 69. Basin Characteristics for FPCT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
156 / 38692	545 / 347 / 213	Texas Blackland Prairie, Southern Part; Texas Claypan Area, Southern Part	Clay: 53% Other: 24% Minor classes: 23%	A: 0%; B: 17%; C: 17%; D: 66%; W: 0%	Pasture/Hay: 35% Shrub/Scrub: 20% Deciduous Forest: 16% Other: 29%

Figure 42. FPCT2 Sub-basin Map



Observed streamflow data are available for LCRA gage 5635 from July 2010 through December 2016. The average observed streamflow over this period is 1,405 cfs. The typical event peaks within 12-36 hours, and takes approximately 1-2 days to recede back to baseflow levels. The highest instantaneous flow recorded at the gage within the period of record is 94,180 cfs, which occurred in May 2016. As with the nearby local area sub-basins on the Colorado River, the flow at the outlet of FPCT2 is mainly influenced by upstream contributions; just 0.4% of its drainage area is local. Water is pumped from the Colorado River to Lake Fayette for power plant cooling consistently throughout the year, some of which is returned via Cedar Creek. Local hydrologic response to precipitation is relatively delayed, taking 1.5-2 days to peak after a rain event. This may be related to the shape and slope of the local drainage area.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream basins LGRT2 and MLDT2. Tables 70 and 71 compare the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 70. Lag/Q and K/Q Pairs for Routing Reach LGRT2 to FPCT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag 1**	**Q1**	**Lag2**	**Q2**	**Lag 3**	**Q3**	**Lag 4**	**Q4**	**Lag5**	**Q5**	**Lag 6**	**Q6**
	Orig.	3	0	8	1000	6	5000	6	20000	8	100000	10	999999
Lag	Calib.	1	-	-	-	-	-	-	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
	Orig.	4	0	6	50000	9	85000	12	999999	-	-	-	-
K	Calib.	7.0	3500	3.00	10000	-	-	-	-	-	-	-	-

Table 71. Lag/Q and K/Q Pairs for Routing Reach MLDT2 to FPCT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**
	Orig.	6	20	9	50	12	269
Lag	Calib.	2	700	4	1800	6	7000
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
	Orig.	25	50	22	250	18	400
K	Calib.	2.0	700	4.00	1800	0	-

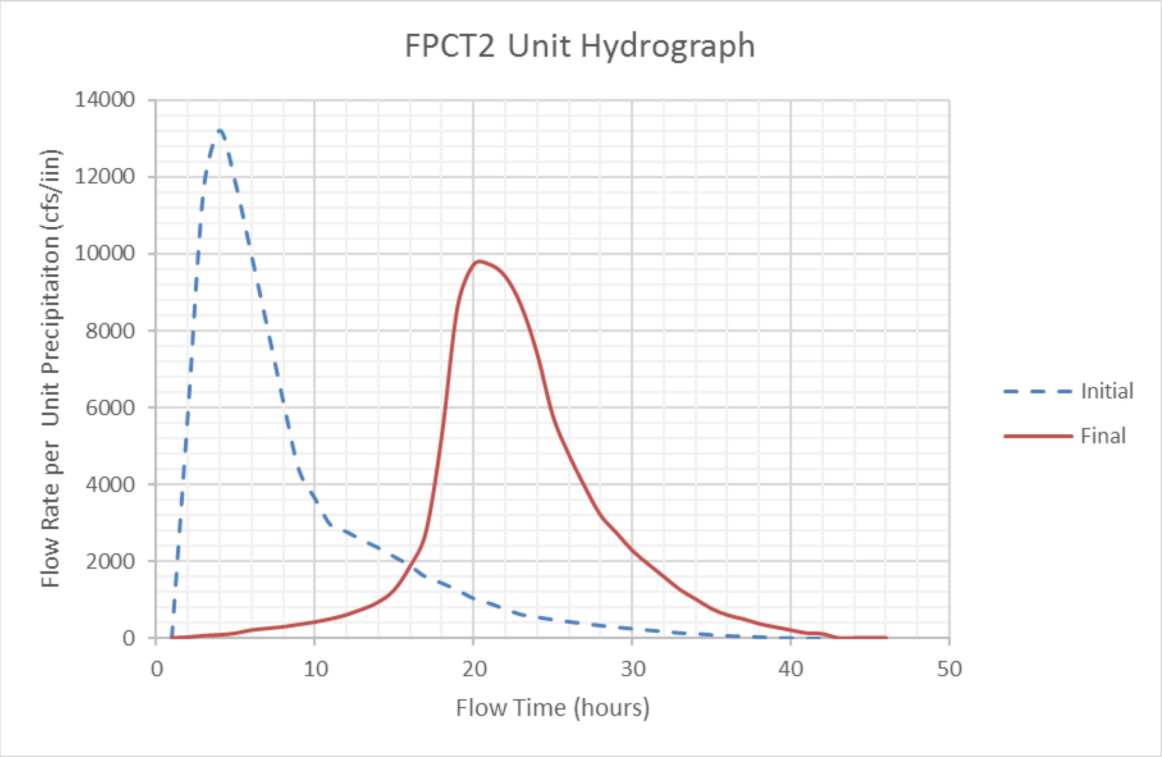
Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to under-simulate runoff events, and that the simulated peak occurred too early. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZFWM (which influences the timing and magnitude of the largest surface runoff events) and LZFSM (which specifies the magnitude of the secondary baseflow component and can influence timing of simulated runoff). Accordingly, emphasis was placed on refining these parameters. A CHANLOSS operation was incorporated to model the net diversions into Lake Fayette. The CHANLOSS was parameterized with a constant rate of 176 cfs. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 72.

Table 72. Original Versus Calibrated SAC-SMA Parameters for FPCT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	25	25	0.50	0.000	0.00	0.005	110	2.30	115	20	60	0.150	0.002	0.05	0.3	0.00	3.12
Calib.	1.000	1.000	50	40	0.50	0.005	0.03	0.020	200	2.50	275	20	150	0.060	0.002	0.05	0.3	0.00	1.50

The ordinates for the initial UNIT-HG model were manually derived based on four (4) historical events, as described in Appendix B. The initial model, however, was modified during the calibration analysis based on shape and timing of the simulated response. A large delay in the UNIT-HG peak response was specified during the calibration analysis and found to perform well. It may be that the initial events selected for the manual analysis are not representative of the hydrologic response during large, surface runoff events. The final adjustments to the UNIT-HG model are shown in Figure 43.

Figure 43. FPCT2 Initial and Final Calibrated UNIT HG



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 73 and 74, respectively. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 73. FPCT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

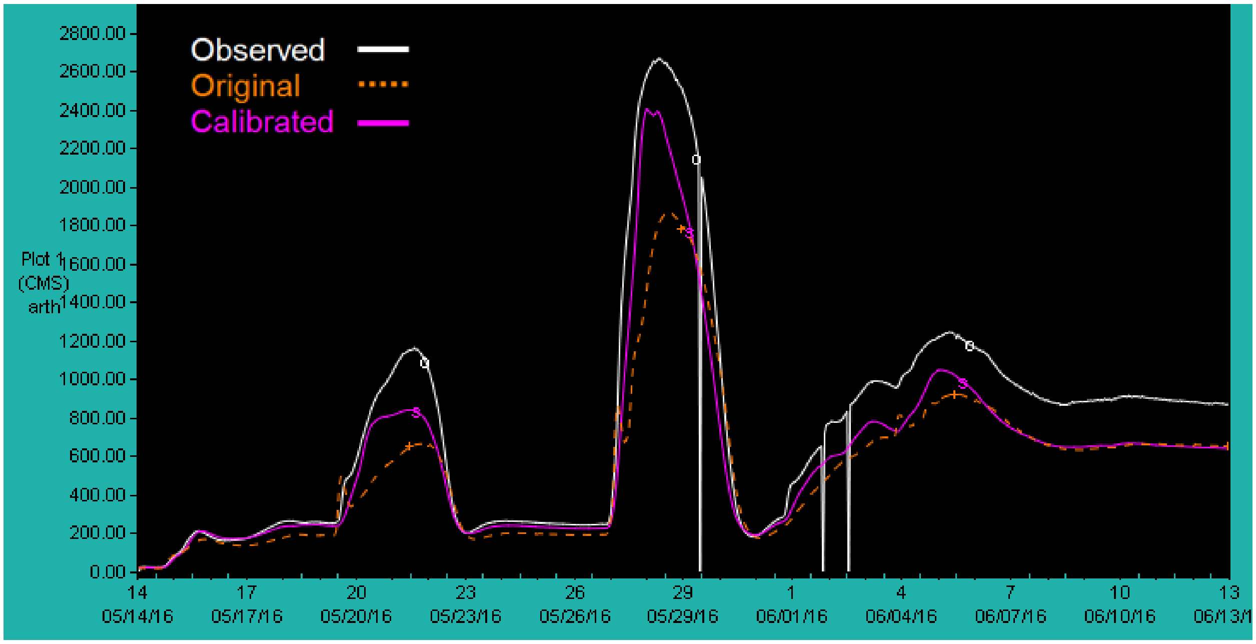
Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean CMS	Obs. std CMS	Sim. std CMS	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
Orig.	-91.9	95.8	38.4	3.1	134.6	24.4	3.5	7.9	348	133.7	0.316	0.0	0.1	33.00	1.74
Calib.	-96.0	96.1	38.4	1.5	134.6	11.8	3.5	7.6	347.1	133.4	0.577	0.0	0.1	28.20	6.59

Table 74. FPCT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	-22.3	33.1	38.4	29.9	134.6	97.3	3.5	3.3	144.0	55.4	0.939	0.8	0.7	-0.36	1.30
Calib.	-12.6	25.2	38.4	33.6	134.6	111.4	3.5	3.3	99.2	38.1	0.970	0.9	0.8	-0.97	1.17

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 44. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 44. Sample Plot Comparing the Original Versus Final Calibration Simulations for FPCT2



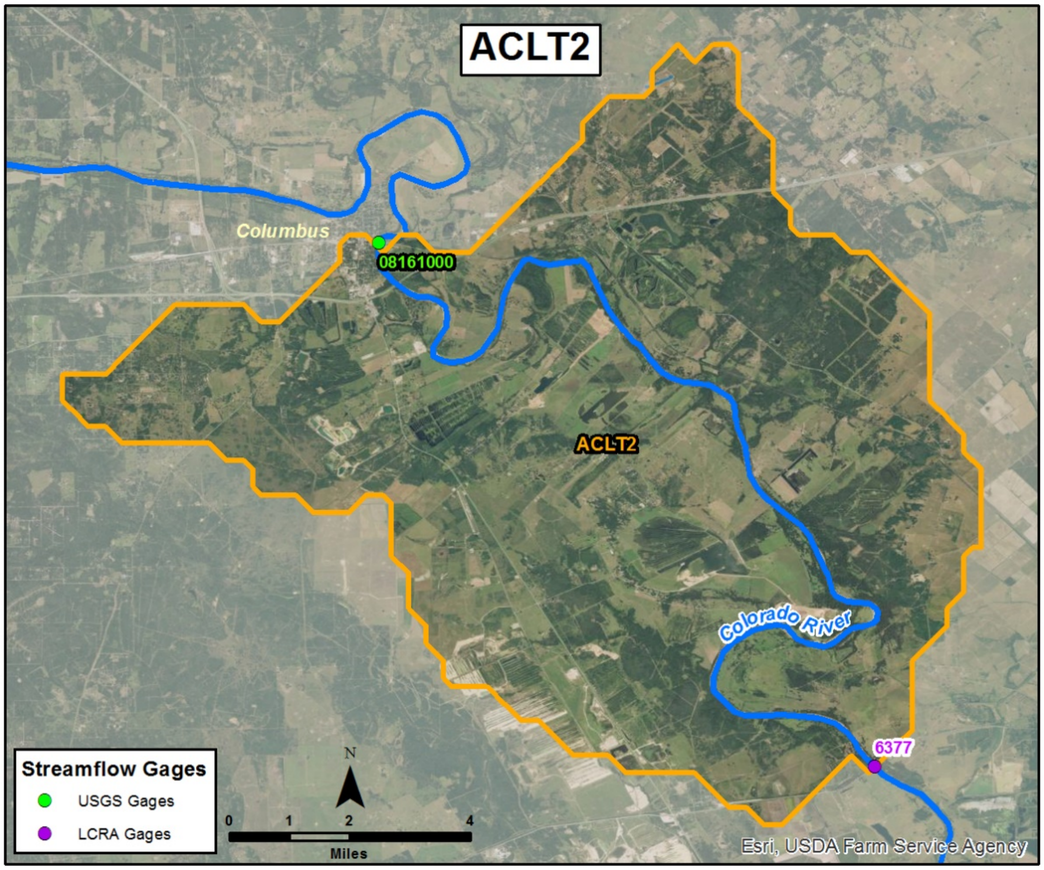
4.4.11 ACLT2: Colorado River near Altair, TX

ACLT2 is a rural local sub-basin located in the Colorado River basin immediately south of Columbus that drains approximately 87 mi^2 locally and 39,292 mi^2 total. Residential/commercial development is light, with the towns of Alleyton (population 1,301) and some parts of Columbus (population 3,655) contained within the sub-basin boundary. This region is heavily agricultural, with large irrigation diversions to support rice farming and other crops. The dominant hydrologic soil group within the local drainage area is type D, which indicates very low infiltration rates and very high runoff potential. Table 75 summarizes the basin characteristics followed by Figure 45 which presents an aerial map of ACLT2.

Table 75. Basin Characteristics for ACLT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
87 / 39292	299 / 205 / 151	Gulf Coast Prairies; Texas Claypan Area, Southern Part	Clay: 50% Sandy Clay Loam: 15% Sandy Loam: 12% Clay Loam: 10% Minor classes: 13%	A: 0%; B: 9%; C: 11%; D: 80%; W: 0%	Pasture/Hay: 43% Deciduous Forest: 16% Evergreen Forest: 10% Other: 31%

Figure 45. ACLT2 Sub-basin Map



Observed streamflow data are available for LCRA gage 6377 (Colorado River near Altair) from November 2003 through January 2017. The average observed streamflow over this period is 2,184 cfs. The typical event peaks within 1.5-3 days, and takes approximately 2-4 days to recede back to baseflow levels. The highest instantaneous flow recorded at the gage within the period of record is 76,231 cfs in November 2004.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream basin CBST2. Table 76 compares the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 76. Lag/Q and K/Q Pairs for Routing Reach CBST2 to ACLT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**	**Lag4**	**Q4**	**Lag5**	**Q5**	**Lag6**	**Q6**
	Orig.	3	0	3	50000	6	100000	9	500000	6	999999	-	-
Lag	Calib.	3.5	10600	1	35000	0	106000	-	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
	Orig.	3	0	3	15000	12	40000	18	70000	24	100000	18	999999
K	Calib.	4	10600	8	35000	30	106000	-	-	-	-	-	-

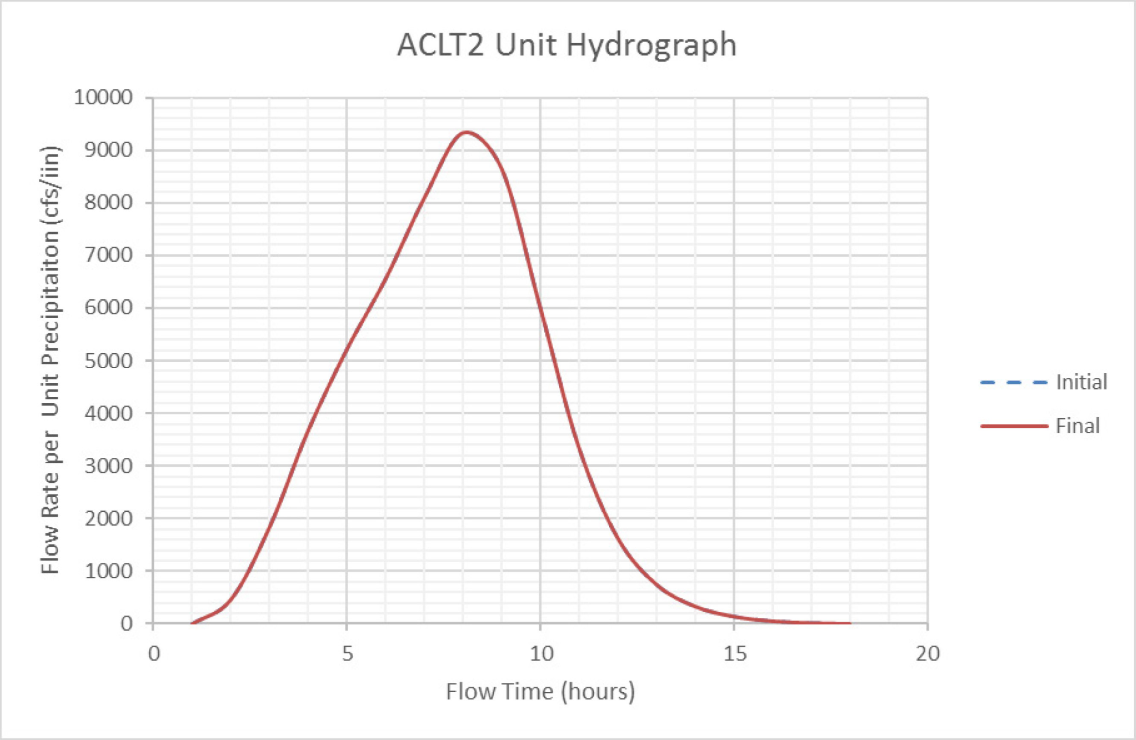
Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to over-simulate peak flows significantly. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZTWM, UZFWM, ZPERC, REXP, and LZTWM. Accordingly, emphasis was placed on refining these parameters. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 77. As noted above, there are large irrigation diversions within this region. Just downstream of the ACLT2 gage, the LCRA operates the Lakeside and Garwood pumping stations, which divert water directly from the Colorado River to service two large irrigation projects. Based on the water balance at ACLT2, it appears that total flows at ACLT2 are significantly impacted. Therefore, a LOOKUP operation was incorporated into the final hydrologic models.

Table 77. Original Versus Calibrated SAC-SMA Parameters for ACLT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	0.953	67	35	0.28	0.000	0.03	0.085	57	2.05	330	10	110	0.125	0.017	0.30	0.3	0.00	3.12
Calib.	1.000	1.000	50	75	0.50	0.005	0.03	0.020	250	3.00	120	20	150	0.060	0.002	0.05	0.3	0.00	1.50

Although a long period of record exists for ACLT2, attempts to manually derive a UNIT-HG model from historical events were unsuccessful due to noise in the hydrograph calculated from the routed and total flow observations. The UNIT-HG ordinates (see Figure 46) were, therefore, estimated using GIS processes, as described in Appendix B. The initially derived UNIT-HG model performed well during the calibration analysis and were not modified.

Figure 46. ACLT2 Initial and Final Calibrated UNIT HG



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 78 and 79, respectively. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 78. ACLT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

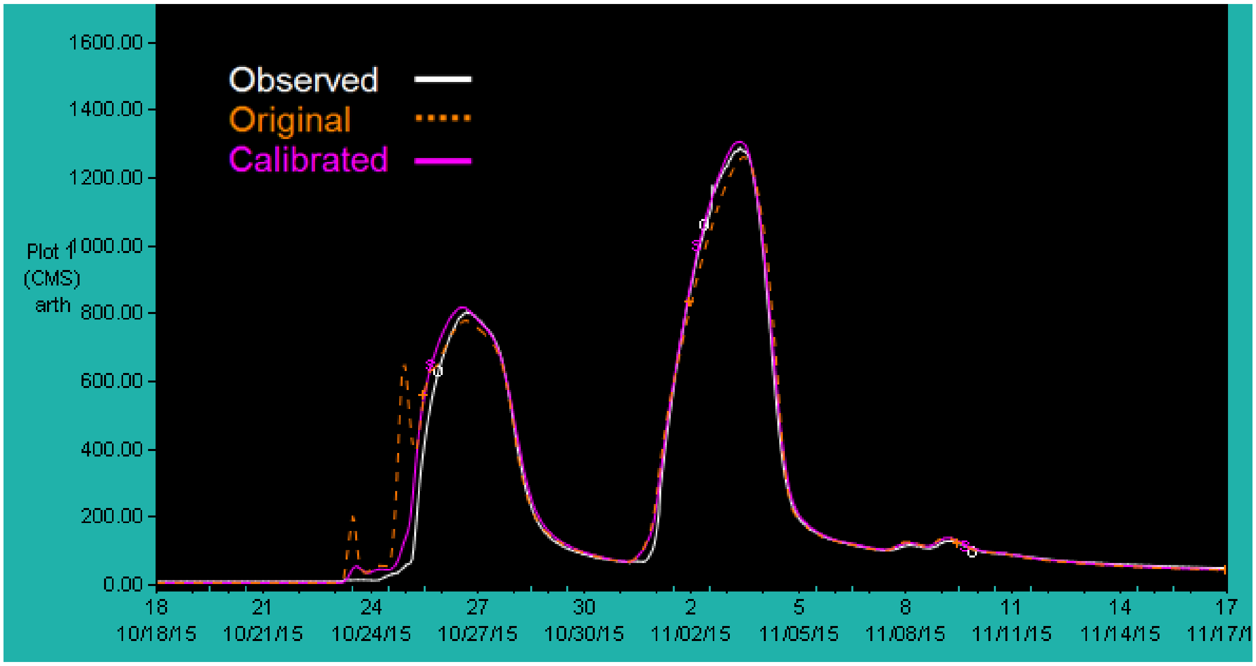
Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean CMS	Obs. std CMS	Sim. std CMS	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
Orig.	-93.2	95.1	61.4	4.2	142.0	18.6	2.3	4.4	244.9	150.4	0.218	-0.1	0.0	54.40	1.67
Calib.	-98.0	98.0	61.4	1.3	142.0	6.7	2.3	5.3	247.1	151.8	0.411	-0.1	0.0	50.50	8.67

Table 79. ACLT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	2.6	13.9	61.4	63.0	142.0	145.0	2.3	2.3	40.0	24.5	0.986	1.0	1.0	0.58	0.97
Calib.	3.5	11.8	61.4	63.6	142.0	142.5	2.3	2.2	24.4	15.0	0.995	1.0	1.0	-1.60	0.99

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 47. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 47. Sample Plot Comparing the Original Versus Final Calibration Simulations for ACLT2



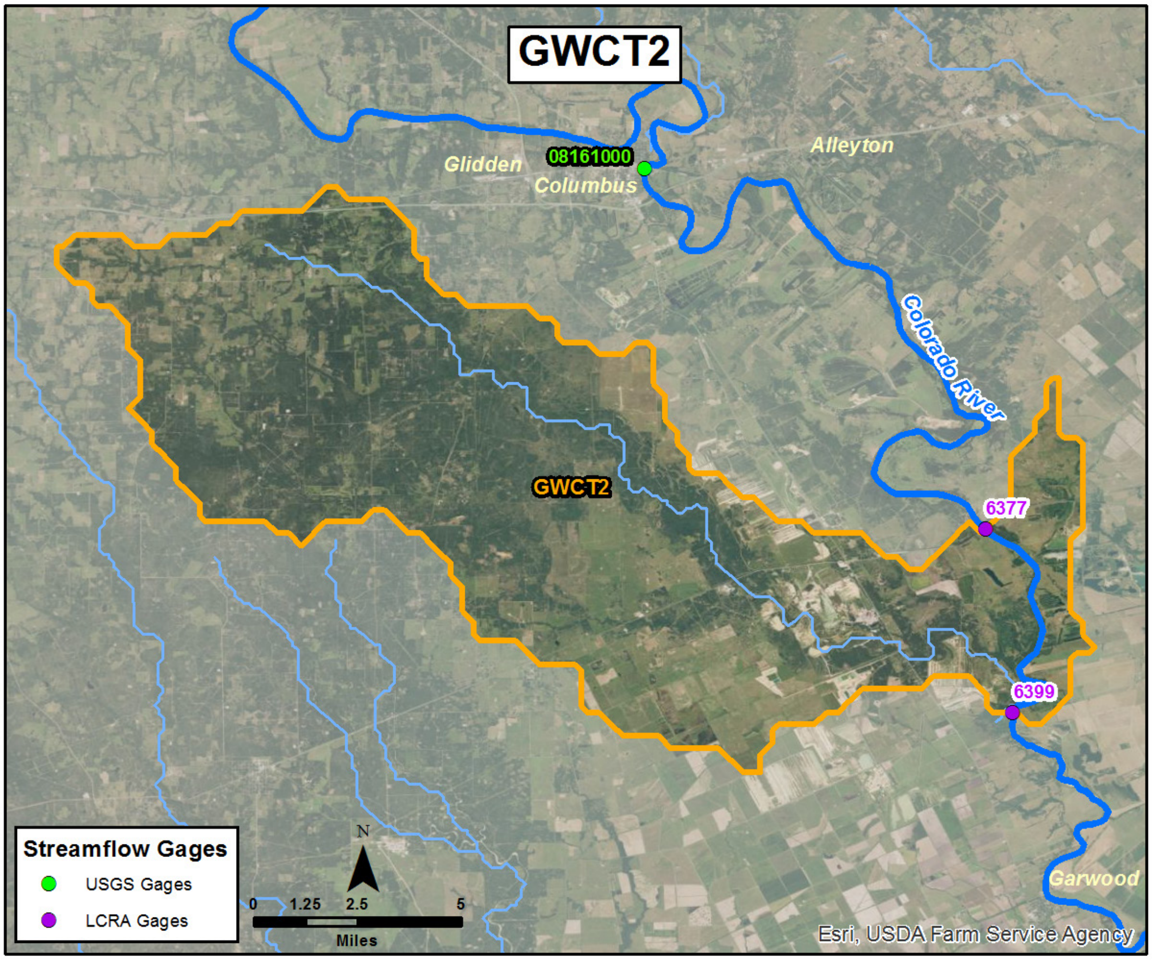
4.4.12 GWCT2: Colorado River near Garwood, TX

GWCT2 is a rural local sub-basin located in the Colorado River basin just west of Eagle Lake that drains approximately 131 mi^2 locally and 39,423 mi^2 total. Residential/commercial development is light, with only the town of Altair (population 110) contained within the sub-basin boundary. This region is heavily agricultural, with large irrigation diversions to support rice farming and other crops. The dominant hydrologic soil group within the local drainage area is type D, which indicates very low infiltration rates and very high runoff potential. Table 80 summarizes the basin characteristics followed by Figure 48 which presents an aerial map of GWCT2.

Table 80. Basin Characteristics for GWCT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
131 / 39423	404 / 248 / 131	Gulf Coast Prairies; Texas Blackland Prairie, Southern Part; Texas Claypan Area, Southern Part	Clay: 41% Clay Loam: 20% Sandy Clay Loam: 16% Sandy Loam: 14% Minor classes: 9%	A: 0%; B: 5%; C: 39%; D: 55%; W: 0%	Pasture/Hay: 27% Deciduous Forest: 17% Evergreen Forest: 16% Shrub/Scrub: 14% Other: 26%

Figure 48. GWCT2 Sub-basin Map



Limited observed streamflow data are available for LCRA gage 6399, despite having a period of record from September 2002 through January 2017, the data are missing from October 2003 through February 2014. The average observed streamflow for the available data is 506 cfs. The typical event peaks within 2-4 days, and takes approximately 3-6 days to recede back to baseflow levels. The highest instantaneous flow recorded at the gage within the available data is 71,607 cfs in April 2016.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream basin ACLT2. Table 81 compares the pre-existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 81. Lag/Q and K/Q Pairs for Routing Reach ACLT2 to GWCT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**	**Lag4**	**Q4**	**Lag5**	**Q5**	**Lag6**	**Q6**
Lag	Orig.	2	0	2	50000	4	100000	6	500000	4	999999	-	-
	Calib.	2	-	-	-	-	-	-	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
K	Orig.	3	0	3	15000	6	40000	12	70000	12	100000	9	999999
	Calib.	0	-	-	-	-	-	-	-	-	-	-	-

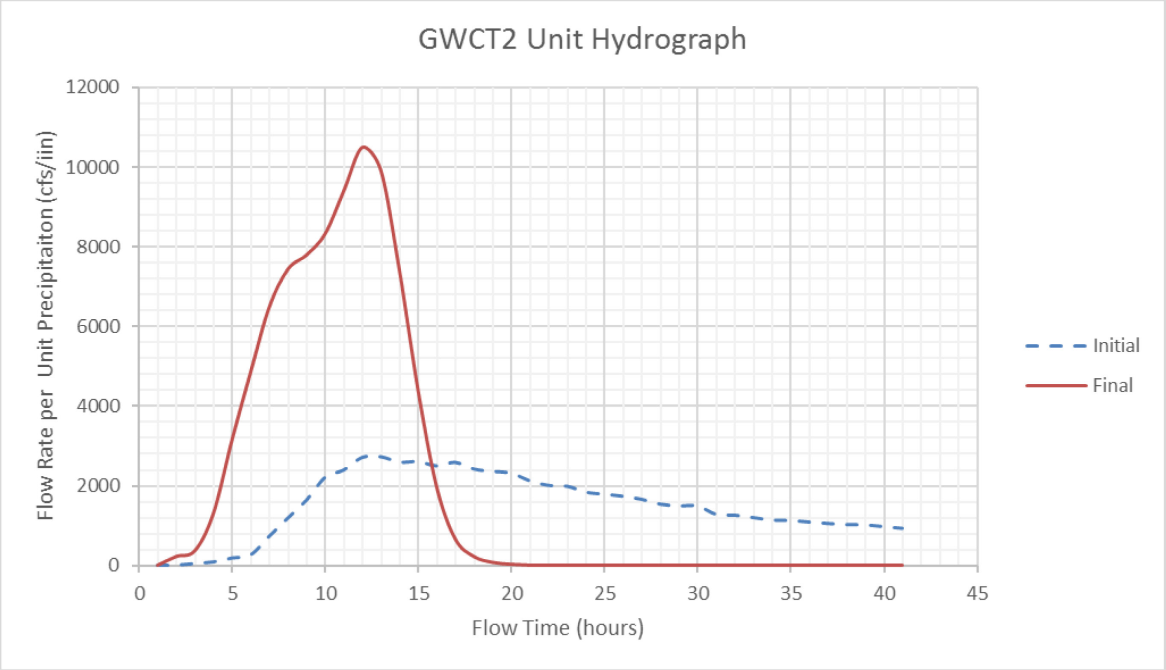
Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to over-simulate peak flows significantly. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZTWM, UZFWM, ZPERC, REXP and LZTWM. Accordingly, emphasis was placed on refining these parameters. A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 82. As noted above, there are large irrigation diversions within this region. Within GWCT2, the LCRA operates the Lakeside and Garwood pumping stations, which divert water directly from the Colorado River to service two large irrigation projects. Based on the water balance at CWCT2, however, it appears that there are large gains between the ACLT2 and GWCT2 gages. These gains are likely related to irrigation return flows. Therefore, a CHANLOSS operation (with a variable percentage gain rate ranging from 0 – 30% applied to the routed flow) was incorporated into the final hydrologic models.

Table 82. Original Versus Calibrated SAC-SMA Parameters for GWCT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	0.953	67	35	0.28	0.000	0.03	0.085	57	2.05	330	10	110	0.125	0.017	0.30	0.3	0.00	3.12
Calib.	1.000	1.000	50	75	0.50	0.005	0.03	0.020	225	2.80	200	25	125	0.050	0.002	0.05	0.3	0.00	1.50

The original manually estimated UNIT-HG model for GWCT2 was derived from a small number of historical events, of which the actual local contribution to flow was difficult to estimate. This initial UNIT-HG was tested during the calibration analysis but did not perform well. The final UNIT-HG ordinates were, therefore, estimated using GIS processes, as described in Appendix B. The new ordinates proved to perform satisfactorily. The initial and final UNIT-HG model ordinates are shown in Figure 49.

Figure 49. GWCT2 Initial and Final Calibrated UNIT HG (Plotted to 40 Ordinates for Clarity/Scale)



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 83 and 84, respectively. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 83. GWCT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

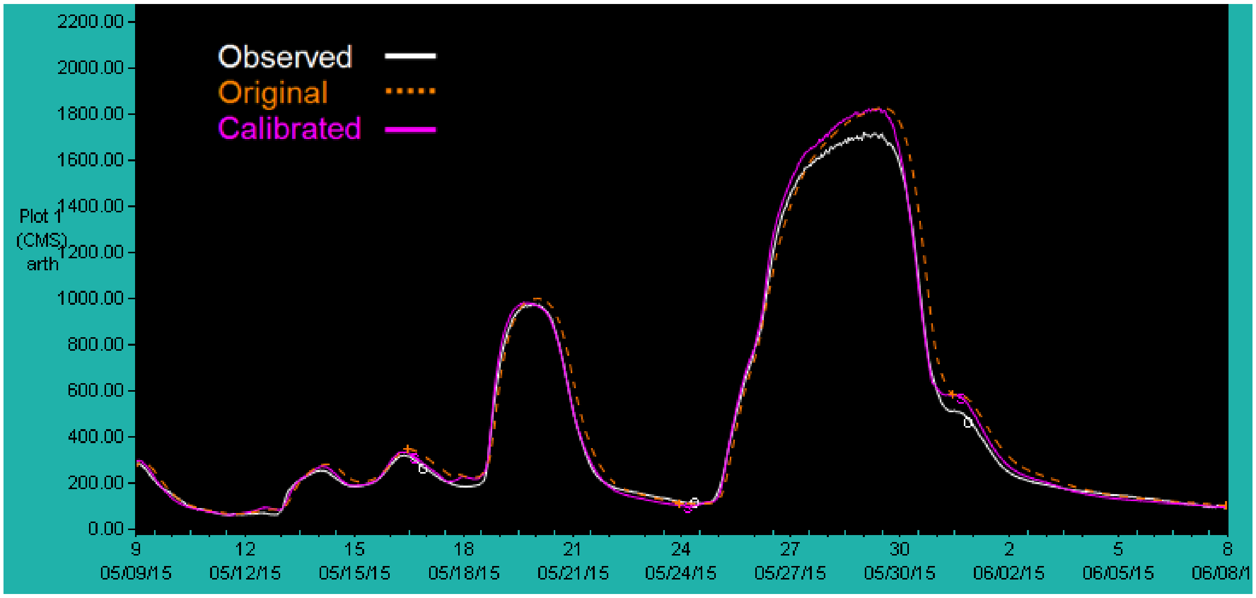
Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean CMS	Obs. std CMS	Sim. std CMS	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
Orig.	-90.7	91.4	108.3	10.0	248.6	22.7	2.3	2.3	237.1	256.7	0.538	-0.1	0.0	49.20	5.89
Calib.	-96.5	96.7	108.3	3.8	248.6	14.6	2.3	3.9	243.7	263.9	0.456	-0.1	0.0	78.90	7.77

Table 84. GWCT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	6.0	12.0	108.3	114.8	248.6	257.8	2.3	2.2	28.2	30.5	0.994	1.0	1.0	-1.72	0.96
Calib.	0.3	9.4	108.3	108.6	248.6	254.3	2.3	2.3	20.1	21.7	0.997	1.0	1.0	2.53	0.97

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 50. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 50. Sample Plot Comparing the Original Versus Final Calibration Simulations for GWCT2



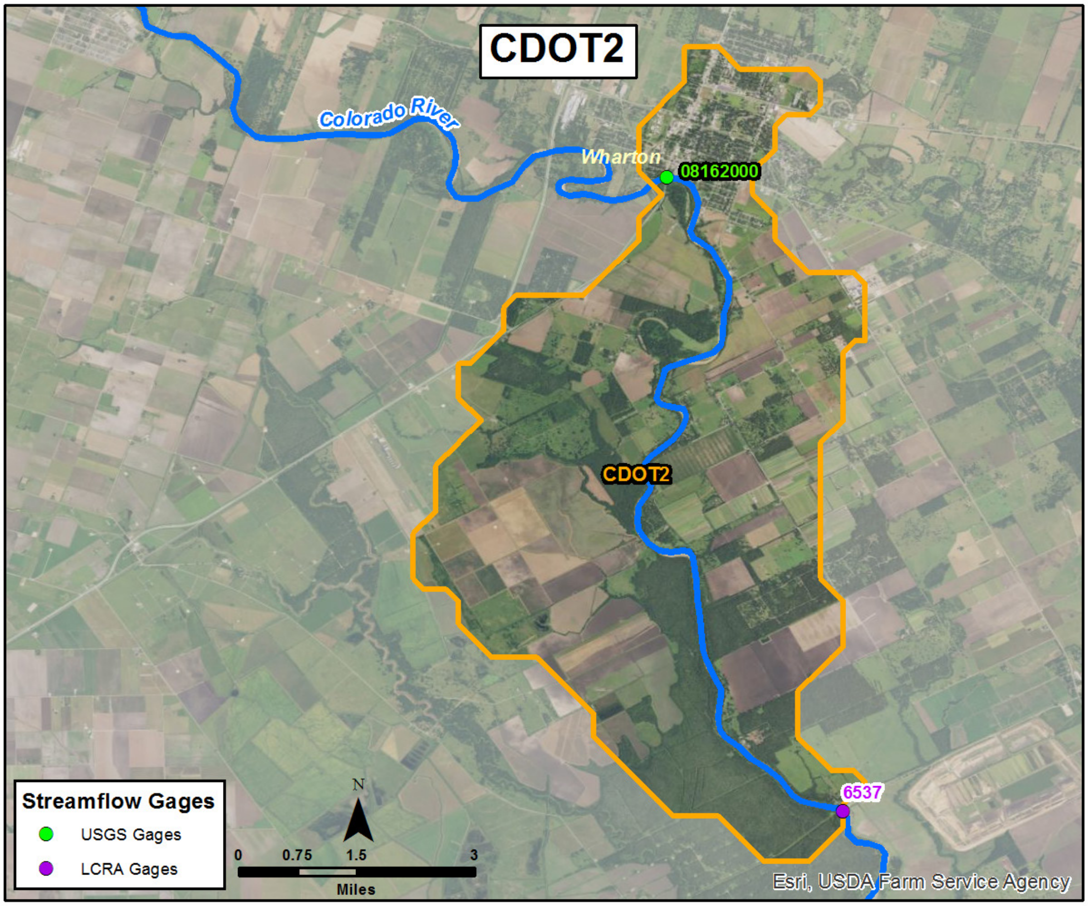
4.4.13 CDOT2: Colorado River near Lane City, TX

CDOT2 is a rural local sub-basin located in the Colorado River basin immediately south of Wharton that drains approximately 30 mi^2 locally and 39,635 mi^2 total. Residential/commercial development is light, with only portions of the town of Wharton (population 8,659) contained within the sub-basin boundary. This region is heavily agricultural, with large irrigation diversions to support rice farming and other crops. The dominant hydrologic soil group within the local drainage area is type D, which indicates very low infiltration rates and very high runoff potential. Table 85 summarizes the basin characteristics followed by Figure 51 which presents an aerial map of CDOT2.

Table 85. Basin Characteristics for CDOT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
30 / 39635	102 / 90 / 72	Gulf Coast Prairies	Clay: 96% Minor classes: 4%	A: 0%; B: 6%; C: 0%; D: 93%; W: 0%	Cultivated Crops: 34% Pasture/Hay: 24% Deciduous Forest: 10% Other: 32%

Figure 51. CDOT2 Sub-basin Map



Observed streamflow data are available for LCRA gage 6537 (Colorado River near Lane City) from June 2000 through January 2017. The average observed streamflow over this period is 2,226 cfs. The typical event peaks within 2-4 days, and takes approximately 2-4 days to recede back to baseflow levels. The highest instantaneous flow recorded at the gage during the period of record is 72,541 cfs in November 2004.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing model calibration was performed for flows from the upstream basin WHAT2. Table 86 compares the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 86. Lag/Q and K/Q Pairs for Routing Reach WHAT2 to CDOT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	Lag1	Q1	Lag2	Q2	Lag3	Q3	Lag4	Q4	Lag5	Q5	Lag6	Q6
	Orig.	2	0	4	50000	6	100000	9	500000	6	999999	-	-
Lag	Calib.	2.0	20000	3	100000	-	-	-	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
	Orig.	6	0	9	15000	18	40000	42	70000	48	100000	42	999999
K	Calib.	2	0	3	15900	5	100000	-	-	-	-	-	-

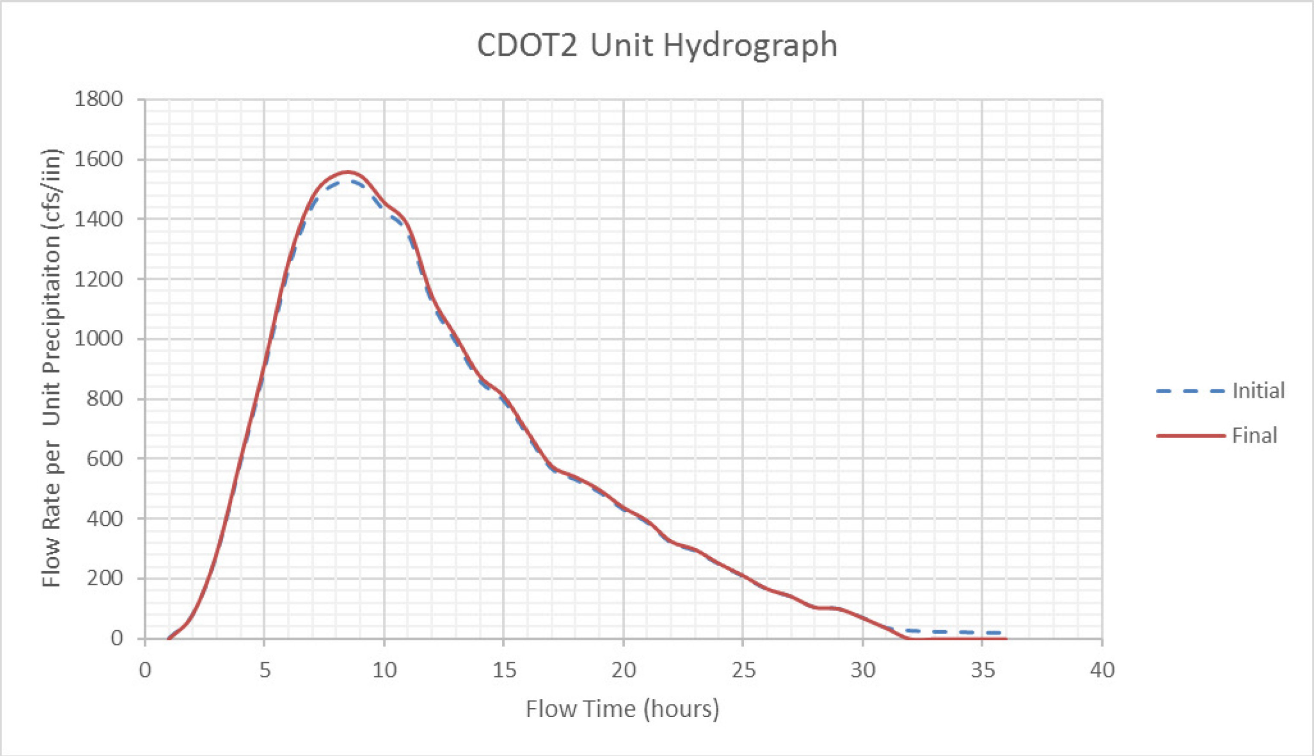
Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to over-simulate peak flows. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZTWM, UZFWM and LZFPM. Accordingly, emphasis was placed on refining these parameters. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 87. As noted above, there are large irrigation diversions within this region. Just upstream of the CDOT2 gage, the LCRA operates the first of three large pumping stations, which divert water directly from the Colorado River for the Gulf Coast irrigation project. Based on the water balance at CDOT2, it appears that total flows at the gage are impacted by this diversion. Therefore, a CHANLOSS operation (with a constant loss rate of 35 cfs applied to the routed flow) was incorporated into the final hydrologic models.

Table 87. Original Versus Calibrated SAC-SMA Parameters for CDOT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	0.935	67	35	0.28	0.000	0.03	0.085	57	2.05	330	10	110	0.125	0.017	0.30	0.3	0.00	3.12
Calib.	1.000	1.000	45	75	0.50	0.01	0.05	0.020	300	3.50	200	30	100	0.100	0.010	0.10	0.3	0.00	4.00

The UNIT-HG model, shown in Figure 52 was derived manually using five (5) historical events, as described in Appendix B. Despite difficulties in estimating local flows in the lower Colorado River, the resulting UNIT-HG performed well, and was only slightly modified during the calibration analysis.

Figure 52. CDOT2 Initial and Final Calibrated UNIT HG



The final calibrated models improve the simulation performance significantly when compared to using the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models for local and total flows are presented in Tables 88 and 89, respectively. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 88. CDOT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

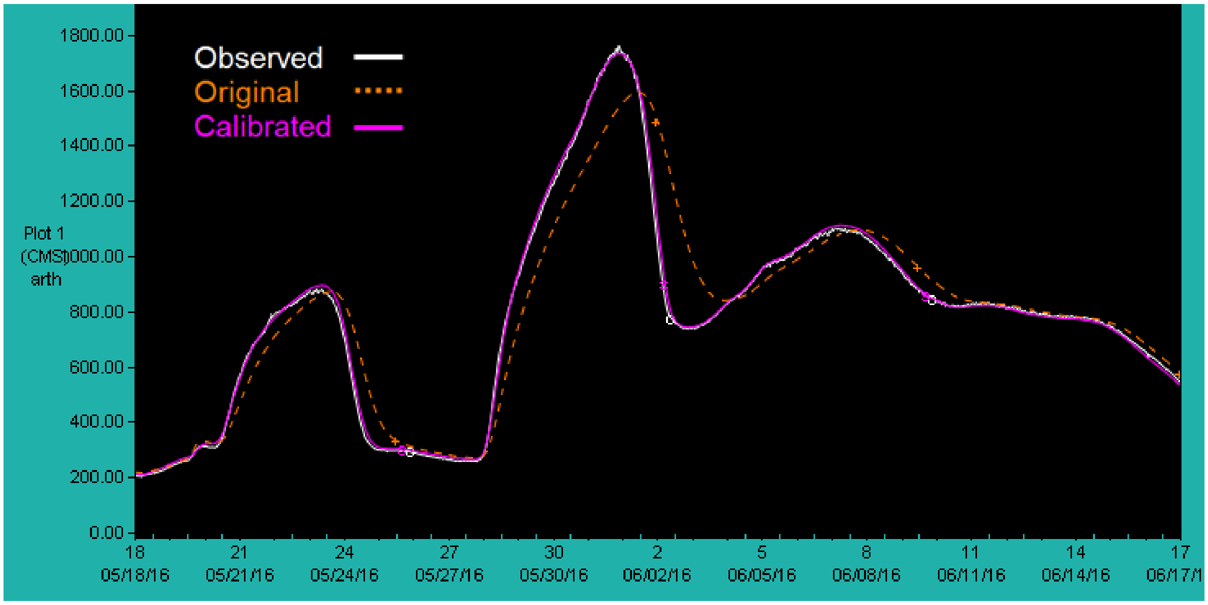
Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean CMS	Obs. std CMS	Sim. std CMS	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
Orig.	-97.3	97.5	57.2	1.6	156.9	5.5	2.7	3.5	289.3	165.4	0.217	-0.1	0.0	47.50	6.18
Calib.	-99.1	99.1	57.2	0.5	156.9	2.4	2.7	4.9	290.6	166.2	0.297	-0.1	0.0	47.70	19.30

Table 89. CDOT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	3.9	13.5	57.2	59.4	156.9	156.4	2.7	2.6	51.3	29.3	0.983	1.0	1.0	-1.39	0.99
Calib.	0.3	6.3	57.2	57.4	156.9	159.2	2.7	2.8	13.3	7.6	0.999	1.0	1.0	0.73	0.98

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 53. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 53. Sample Plot Comparing the Original Versus Final Calibration Simulations for CDOT2



4.5 Calibration Results for the Guadalupe River Basin

The sub-basins within the Guadalupe River basin that were included in this study are highlighted in Figure 54. A summary of the calibrated parameters from the LAG/K and SAC-SMA operations are provided in Tables 90 – 92. A summary of the hourly simulation statistics produced by the STAT-Q operation are provided in Table 93 (total flow) and Table 94 (local flow).

Figure 54. Calibrated Sub-basins in the Guadalupe River Basin

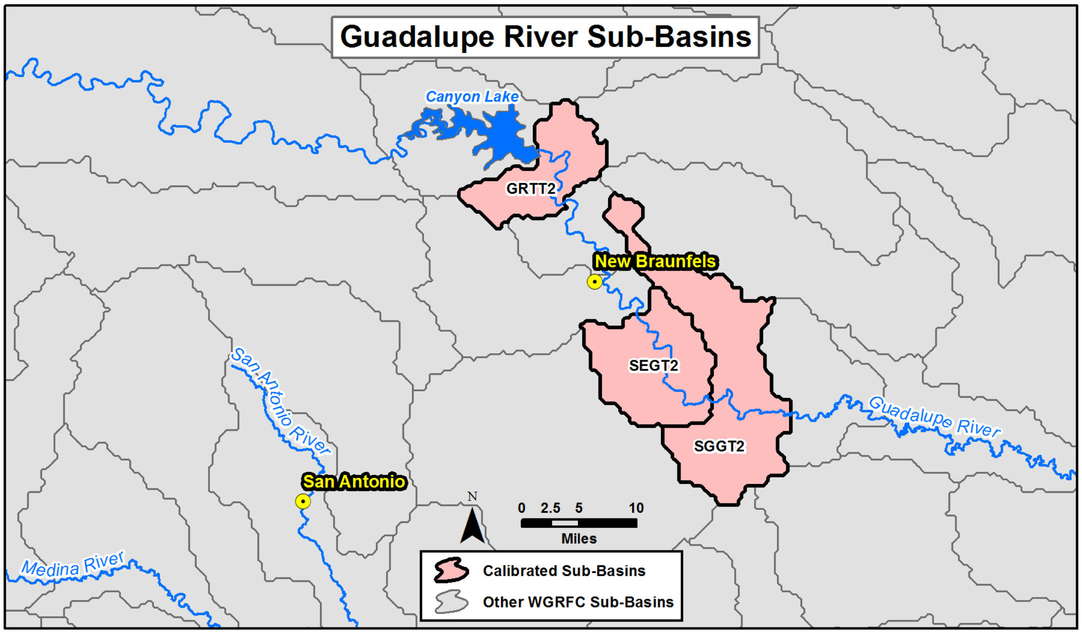


Table 90. Summary of Lag/Q Pairs for Modeled Reaches in the Guadalupe River Basin

Routing to	Routing from	Lag Parameters			
		Lag1 (hr)	Q1 (cfs)	Lag2 (hr)	Q2 (cfs)
GRTT2	SMCT2	3	500	2	30000
SGGT2	GBCT2	2	17500		
SGGT2	SEGT2	3	22000	1	42300

Table 91. Summary of K/Q Pairs for Modeled Reaches in the Guadalupe River Basin

Routing to	Routing from	K Parameters			
		K1 (hr)	Q1 (cfs)	K2 (hr)	Q2 (cfs)
GRTT2	SMCT2	0.5			
SGGT2	GBCT2	1	17500		
SGGT2	SEGT2	0.5	22000	6	42300

Table 92. Calibrated SAC-SMA Parameters for Modeled Sub-basins in the Guadalupe River Basin

NWS Basin ID	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
GRTT2	1.0	1.0	35	70	0.50	0.000	0.03	0.08	250	2.40	150	30	100	0.200	0.015	0.45	0.3	0.00	7.50
SEGT2	1.0	1.0	30	30	0.30	0.000	0.01	0.00	50	1.50	40	30	130	0.115	0.010	0.30	0.3	0.00	4.75
SGGT2	1.0	1.0	25	75	0.50	0.010	0.18	0.02	155	2.20	150	60	80	0.030	0.015	0.05	0.3	0.00	3.00

Table 93 Total Flow Simulation Statistics for Modeled Sub-basins in the Guadalupe River Basin

NWS Basin ID	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
GRTT2	-0.31	16.97	9.28	9.25	22.48	22.26	2.42	2.41	54.34	5.04	0.975	0.95	0.97	0.17	0.98
SEGT2	2.73	16.78	23.31	23.94	11.68	9.52	0.50	0.40	30.05	7.00	0.802	0.64	0.65	-0.27	0.99
SGGT2	0.41	28.89	17.18	17.25	30.88	27.66	1.80	1.60	53.08	9.12	0.957	0.91	0.86	-1.26	1.07

Table 94. Local Flow Simulation Statistics for Modeled Sub-basins in the Guadalupe River Basin

NWS Basin ID	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
GRTT2	-90.69	91.84	9.28	0.86	22.48	6.18	2.42	7.16	254.50	23.61	0.205	-0.10	0.06	8.63	0.75
SEGT2	-94.97	95.10	23.31	1.17	11.68	5.35	0.50	4.56	101.40	23.64	0.768	-3.10	0.35	21.30	1.68
SGGT2	-94.79	95.06	17.18	0.89	30.88	5.68	1.80	6.35	190.90	32.80	0.499	-0.13	0.09	14.80	2.71

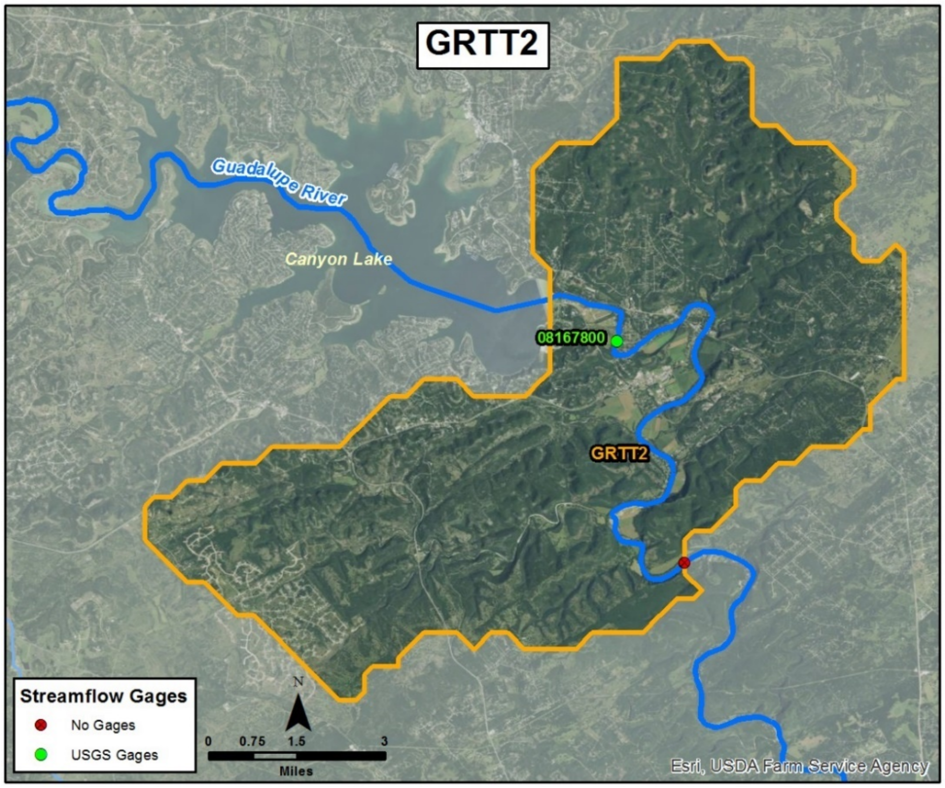
4.5.1 GRTT2: Guadalupe River at Third Crossing, TX

GRTT2 is a primarily rural local sub-basin located 30 miles northeast of San Antonio in Comal County that drains approximately 57 mi^2 locally and 1,508 mi^2 total. Residential/commercial development is minimal, with minor portions of Canyon Lake (a census-designated area with several unincorporated communities) including Sattler contained within the sub-basin boundary. The sub-basin receives the outflow from Canyon Lake and groundwater inflow is well documented and may provide additional streamflow. Table 95 summarizes the basin characteristics followed by Figure 55 which presents an aerial map of GRTT2.

Table 95. Basin Characteristics for GRTT2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
57 / 1508	1332 / 1006 / 722	Edwards Plateau, Eastern Part	Clay Loam: 37% Loam: 24% Clay: 20% Silty Clay: 17% Minor classes: 2%	A: 1%; B: 8%; C: 40%; D: 51%; W: 1%	Evergreen Forest: 60% Shrub/Scrub: 12% Other: 28%

Figure 55. GRTT2 Sub-basin Map



Observed streamflow data are not available for the outlet of this basin. Estimates were derived from USGS gage 08168500 (Guadalupe River above Comal River at New Braunfels, TX) by scaling measured streamflow based on relative basin areas. For these estimates, data is available from January 2000 through December 2016. The average observed (scaled) streamflow over this period is 310 cfs. The typical event peaks within 12 hours, and takes approximately 2 days to recede back to baseflow levels. The highest (scaled) instantaneous flow on record is 39,967 cfs. GRTT2 receives flow directly from Canyon Lake, which is closely monitored and controlled by the US Army Corps of Engineers. During dry periods the flow in the Guadalupe River for GRTT2 is almost entirely from Canyon Lake, while local runoff comprises the majority of river flow for short periods following sufficient precipitation.

USGS gage 08168500 at the outlet of NBRT2 (one basin downstream, about 10 river miles), was used to supplement the absence of a gage for GRTT2. Since releases from Canyon Lake almost solely determine flow rates in the river during dry periods, USGS gage 08168500 is typically an adequate representation of flow at the outlet of GRTT2 but with a delay of just a few hours. However, during periods of significant precipitation, this assumption no longer holds true as local hydrologic responses contribute appreciably to the overall flow rate. Therefore, to obtain an estimate for flows at GRTT2, the following steps were taken:

- A 24-hour running average flow was determined.
- If the running average changed by more than 2% and there was precipitation in the previous 24 hours, the change in flow rate was attributed to a runoff event. The average flow calculated before the 2% change occurred was used as the estimated release from Canyon Lake before runoff began.
- Flows in excess of this approximate reservoir release were scaled down based on relative drainage areas between GRTT2 and NBRT2. Only areas downstream of Canyon Lake were considered:
  - GRTT2 local area: 57.4 mi^2
  - NBRT2 local area: 47.7 mi^2
  - NBRT2 total area downstream of Canyon Lake: 57.4 + 47.7 = 105.1 mi^2
  - Scale factor for flow attributed to local runoff = 57.4/105.1 = 0.546

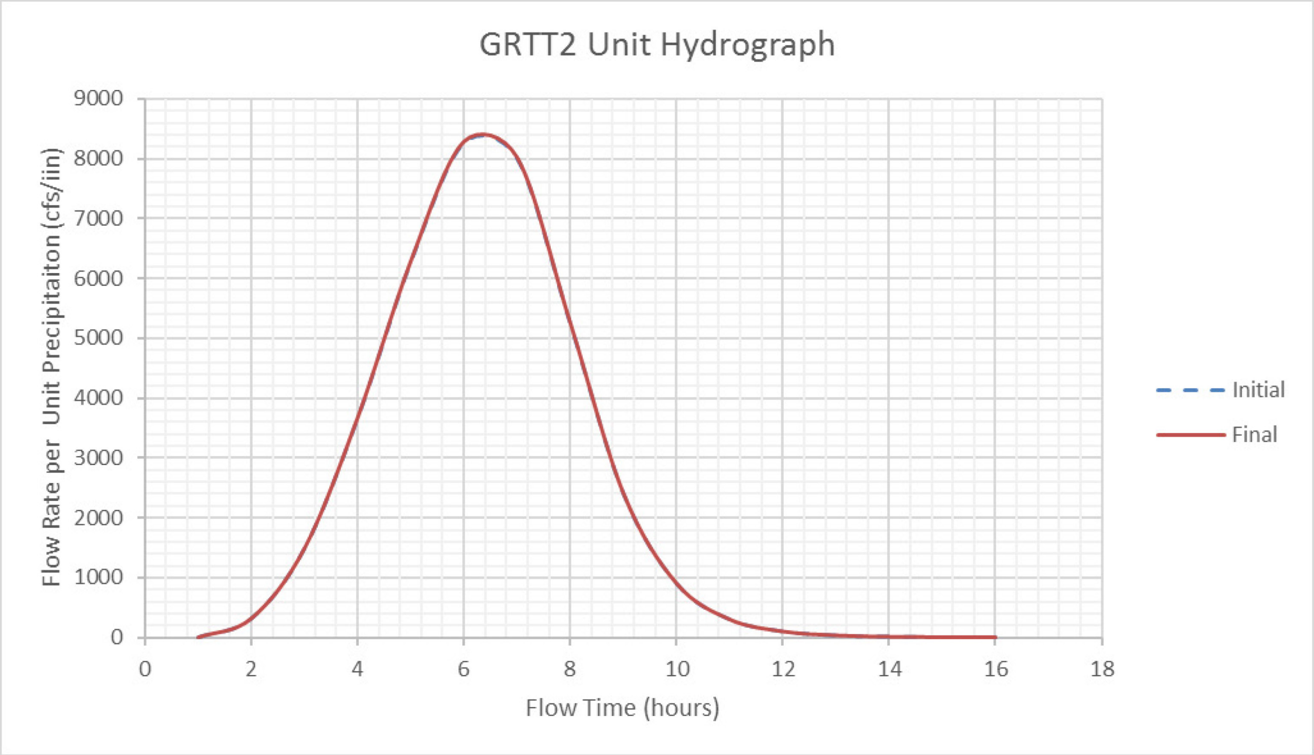
While this approach often works well, there are additional issues with data quality. During larger events the gage at NBRT2 either stops taking measurements or behaves unreliably (i.e. it captures some of the rising and receding limbs but oscillates erratically in between). Measurements where data were clearly erroneous were set to missing.

Furthermore, substantial portions of the period of record show larger flow rates at NBRT2 than at the outlet of Canyon Lake during extended dry periods. Assuming accurate gage readings, this suggests local basin inflow from sources other than Canyon Lake or precipitation. Springs and other groundwater activity have been historically noted within GRTT2 and in the general vicinity, which likely accounts for the increase between the two gages during dry periods. A CHANLOSS operation with a negative constant rate (to produce a positive gain) was utilized to capture this additional inflow.

Elevated baseflows following an event may be a result of the calculated/scaled local flow time series based on the gage for NBRT2 experiencing back water impacts from the inline dam at the next downstream gage, GBCT2. This appears to be an issue for the recessions of the medium-sized events but impacts may be less prominent for the recessions of the larger events such as late October 2013 and 2015.

Finally, without a gage to analyze historical response to rainfall, the UNIT-HG model (see Figure 56) was derived using GIS processes, as described in Appendix B. The resulting unit hydrograph performed well, so no changes were made to the ordinates or their timing during calibration with the SAC-SMA model.

Figure 56. GRTT2 Initial and Final Calibrated UNIT HG



Before investigating the SAC-SMA and UNIT-HG model parameters, Lag/K routing was performed for upstream basin SMCT2. Due to the missing gage at GRTT2, a direct estimation of Lag/K parameters could not be performed. Rather, SMCT2 was routed past GRTT2 and up to the outflow of NBRT2 (one basin downstream of GRTT2). The results were then scaled back linearly based on the distance along Guadalupe River from (SMCT2 to GRTT2) relative to (SMCT2 to NBRT2):

Distance from SMCT2 to GRTT2: approximately 10.54 miles
Distance from SMCT2 to NBRT2: approximately 21.94 miles
10.54/21.94 = 48.04%

It is assumed that the river retains similar hydraulic characteristics throughout GRTT2 and NBRT2. Table 96 compares the existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 96. Lag/Q and K/Q Pairs for Routing Reach SMCT2 to GRTT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**
	Orig.	2	800	1	5000	3	25000
Lag	Calib.	3.0	500	2	30000	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
	Orig.	0	-	-	-	-	-
K	Calib.	0.5	-	-	-	-	-

Note: The original Lag/K parameters shown are for the legacy sub-basin STLT2, which used to be upstream of GRTT2.

Testing of the existing model parameters from the CHPS configuration provided by the WGRFC revealed that overall the models under-simulated flow, especially the receding limb of the hydrographs. Therefore, the focus of calibration effort was aimed at getting closer to a reasonable water balance and capturing receding hydrograph limbs. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be LZFSM and UZFWM. Accordingly, emphasis was placed on refining these parameters.

While there is uncertainty in the estimated flows against which the models were calibrated, it is often clear when the data is incorrect/inappropriate for calibration (e.g., when the gage produced oscillations instead of peaks during runoff events or when the Canyon Lake releases were significantly smaller than the measurements at NBRT2).

Since the gage failed to capture peak flows for moderate to large runoff events, efforts were focused on capturing the portions of the rising and receding limbs that were physically realistic. A high LZSK value was necessary for GRTT2 compared with other sub-basins in the region. The previously calibrated headwater DRWT2 in the Colorado River basin was helpful in regionalizing the final selection of lower zone parameters LZFPM, LZSK, and LZPK due to similar characteristics between the sub-basins. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 97.

Table 97. Original Versus Calibrated SAC-SMA Parameters for GRTT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	50	30	0.30	0.000	0.01	0.000	50	1.50	100	30	100	0.115	0.010	0.30	0.3	0.00	4.45
Calib.	1.000	1.000	35	70	0.50	0	0.03	0.080	250	2.40	150	30	100	0.200	0.015	0.45	0.3	0.00	7.50

The final calibrated parameter set compares favorably to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations for local and total flows are presented in Tables 98 and 99, respectively. In total flow statistics, these results demonstrate improved simulation of streamflow by every metric, including a near elimination of volume bias and a sizeable decrease in root-mean-square error. Locally, statistics are similar except that the volume bias becomes more negative. While this may appear unfavorable, it is likely an artifact of the additional local inflow not attributable to runoff or upstream reservoir releases (perhaps groundwater) as discussed previously. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 98. GRTT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

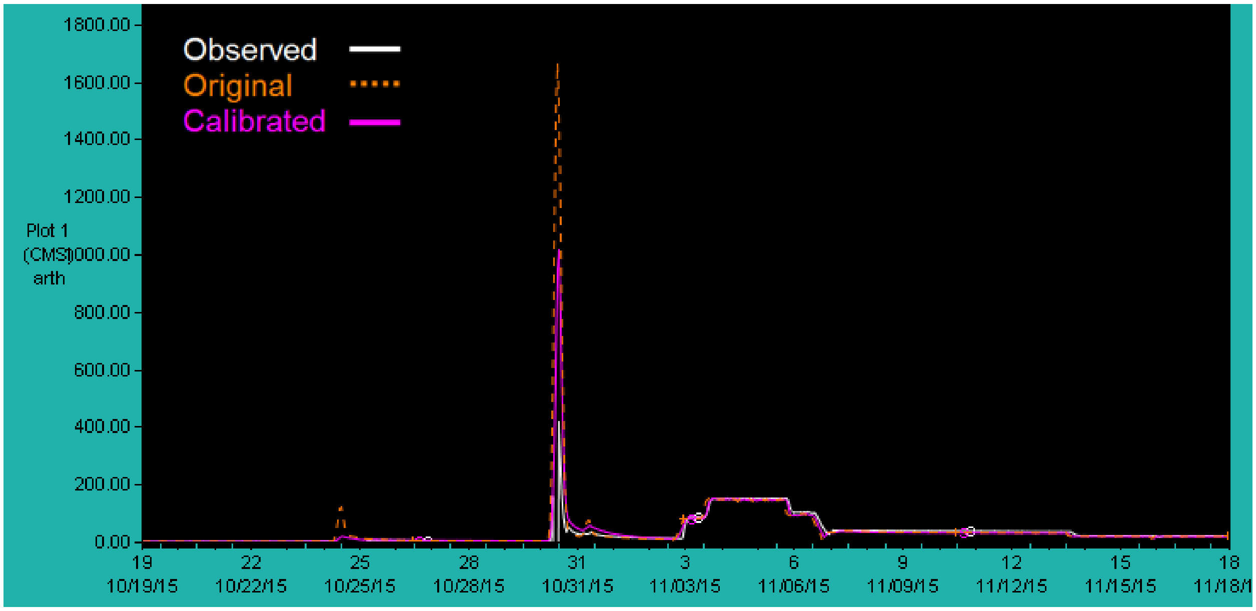
Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean CMS	Obs. std CMS	Sim. std CMS	Obs. Cv	Sim. Cv	% RMS	RMS (CMS)	R	Nash-S. r	Modi. Rm	Best Fit A	Best Fit B
Orig.	-79.4	85.4	9.3	1.9	22.5	10.8	2.4	5.7	259	24.0	0.205	-0.1	0.1	8.46	0.43
Calib.	-90.7	91.8	9.3	0.9	22.5	6.2	2.4	7.2	254.5	23.6	0.205	-0.1	0.1	8.63	0.75

Table 99. GRTT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	**% Bias**	**Abs. % Bias**	**Obs. Qmean CMS**	**Sim. Qmean 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**
Orig.	11.0	21.0	9.3	10.3	22.5	24.3	2.4	2.4	98.2	9.1	0.928	0.8	0.9	0.44	0.86
Calib.	-0.3	17.0	9.3	9.2	22.5	22.3	2.4	2.4	54.3	5.0	0.975	1.0	1.0	0.17	0.98

A sample plot from ICP of the final calibration compared with the original model simulation is provided in Figure 57. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 57. Sample Plot Comparing the Original Versus Final Calibration Simulations for GRTT2



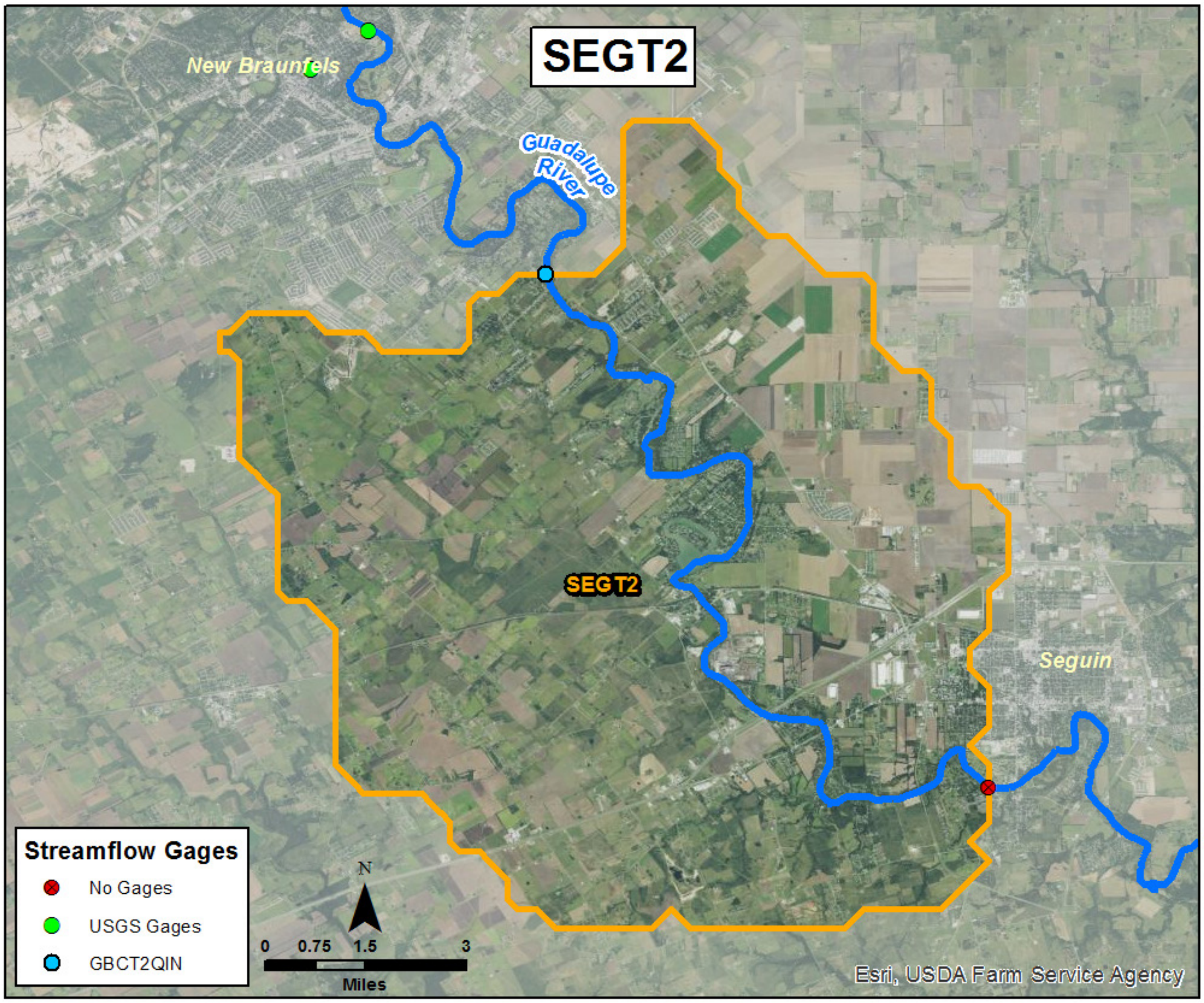
4.5.2 *SEGT2: Guadalupe River at Seguin Water Plant, TX*

SEGT2 is a rural local sub-basin located roughly 25 miles northeast of San Antonio in Guadalupe County that drains approximately 82 mi^2 locally and 1,778 mi^2 total. Outskirts of New Braunfels, the town of McQueeney, and a portion of Seguin are contained within the sub-basin boundary. Two lakes (McQueeney and Placid) are within SEGT2, leading to hydrologic responses downstream that can be more difficult to predict. Table 100 summarizes the basin characteristics followed by Figure 58 which presents an aerial map of SEGT2.

Table 100. Basin Characteristics for SEGT2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
82 / 1778	755 / 589 / 476	Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Clay: 89% Minor classes: 11%	A: 0%; B: 19%; C: 10%; D: 71%; W: 0%	Cultivated Crops: 29% Shrub/Scrub: 22% Pasture/Hay: 15% Developed, Open Space: 12% Grassland/Herbaceous: 10% Other: 12%

Figure 58. SEGT2 Sub-basin Map

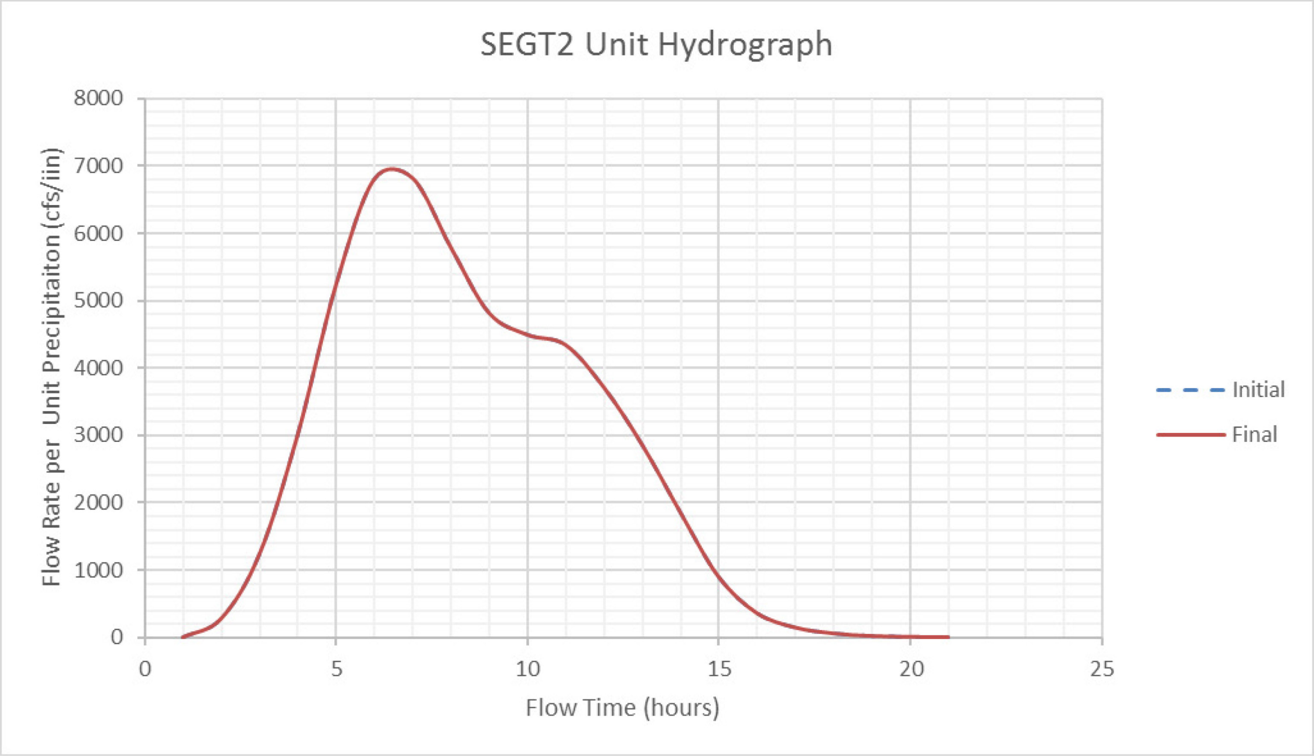


No observed streamflow data is available at the outlet of SEGT2. Hydrologic responses in this basin are thought to be similar to that of downstream SGGT2, with the exception of the reservoirs which likely attenuate upstream flows.

Because no stream gage exists at the outlet of SEGT2, calibration could not be performed directly for this basin. Instead, local flow was simulated, routed in combination with the upstream flow from sub-basin GBCT2, combined with the simulated local flow for SGGT2, and then compared to the stream gage at the outlet of SGGT2. The same set of SAC-SMA parameters for both SEGT2 and SGGT2 were utilized during calibration due to their proximity and similar physical characteristics. These parameters were then checked independently for a 2-month period (mid-October through December of 2016) when stage data were available and resulting streamflow was calculated from a rating curve by the WGRFC. A peak event in early December of that year demonstrated a good simulation with the calculated observed flow. For a detailed explanation and results of the calibration process of the two basins, see the next section on SGGT2.

Although a combined approach for the SAC-SMA runoff modeling in SEGT2 and SGGT2 was used during the calibration analysis, the unit hydrographs were derived separately using GeoTool, as described in Appendix B. In the case of SEGT2 results from GeoTool were found to work satisfactorily and were not altered during calibration (see Figure 59 below).

Figure 59. SEGT2 Initial and Final Calibrated UNIT HG



A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 101. The final calibrated parameter set appears to be an improvement when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations for local and total flows are presented in Tables 102 and 103, respectively. These suggest enhanced simulation performance overall. However, strong caution should be taken when interpreting these statistics as they were computed from just two months of streamflow data calculated from a rating curve and associated stage data by the WGRFC. No instantaneous peak streamflow records were available at this location; therefore, the PEAKFLOW operation was not used to assess model performance.

Table 101. Original Versus Calibrated SAC-SMA Parameters for SEGT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	30	30	0.30	0.000	0.01	0.000	50	1.50	40	30	130	0.115	0.010	0.30	0.3	0.00	4.75
Calib.	1.000	1.000	25	75	0.50	0.010	0.18	0.020	155	2.20	150	60	80	0.030	0.015	0.05	0.3	0.00	3.00

Table 102. SEGT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q Based on Only 2 Months of Streamflow and Precipitation)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	-78.3	86.7	23.3	5.1	11.7	18.3	0.5	3.6	98.08	22.9	0.660	-2.8	0.4	21.20	0.42
Calib.	-95.0	95.1	23.3	1.2	11.7	5.3	0.5	4.6	101.4	23.6	0.768	-3.1	0.4	21.30	1.68

Table 103. SEGT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q Based on Only 2 Months of Streamflow and Precipitation)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	19.4	25.8	23.3	27.8	11.7	22.4	0.5	0.8	75.3	17.5	0.671	-1.3	0.4	13.60	0.35
Calib.	2.7	16.8	23.3	23.9	11.7	9.5	0.5	0.4	30.1	7.0	0.802	0.6	0.7	-0.27	0.99

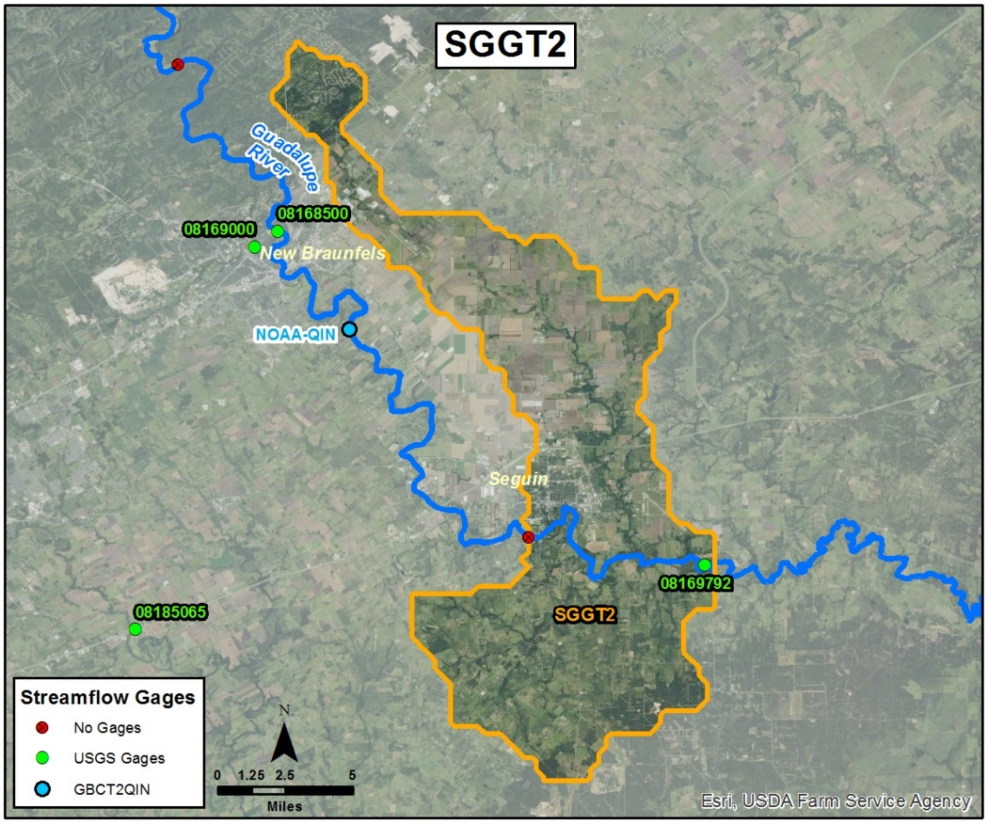
4.5.3 SGGT2: Guadalupe River at FM 1117 near Seguin, TX

SGGT2 is a rural local sub-basin located 25 miles northeast of San Antonio in Guadalupe and Comal Counties that drains approximately 133 mi^2 locally and 1,911 mi^2 total. The towns of Seguin and Geronimo are contained within the sub-basin boundary. SGGT2 has a long "tail" at its upstream end which can lead to a small portion of runoff arriving at the outlet later than the majority of flow. Table 104 summarizes the basin characteristics followed by Figure 60 which presents an aerial map of SGGT2.

Table 104. Basin Characteristics for SGGT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
133 / 1911	1001 / 578 / 443	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part; Texas Claypan Area, Southern Part	Clay: 66% Clay Loam: 10% Clay Loam: 10% Minor classes: 14%	A: 6%; B: 21%; C: 17%; D: 56%; W: 0%	Shrub/Scrub: 22% Cultivated Crops: 20% Pasture/Hay: 19% Developed, Open Space: 10% Other: 29%

Figure 60. SGGT2 Sub-basin Map



Observed streamflow data are available for USGS gage 08169792 (Guadalupe River at Farm-to-Market 1117 near Seguin, TX) from March 2005 through December 2016. The average observed streamflow over this period is 786 cfs. The typical event peaks within 6 hours, and takes 4-5 hours to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 46,300 cfs, which occurred in June 2010.

Streamflow is highly influenced by reservoir releases within SEGT2 and/or SGGT2; Several reservoirs controlled by local authorities are located within these two basins. The flow is typically oscillatory, even without precipitation events, as reservoir releases propagate through the river to the outlet. As a result the local hydrologic response can be difficult to observe as there is a consistent low-flow due to these oscillations. During large events, the local response is more evident but may still be obscured by reservoir releases that prevent flooding upstream of the basin.

Since no streamflow records were available at SEGT2, calibration for SEGT2 was done simultaneously and indirectly by assessing results at SGGT2. Both SEGT2 and SGGT2 were analyzed within the same deck. Due to the unique situation, the following steps were taken for calibration of these two basins:

- In a separate deck, GBCT2 was routed past SEGT2 down to SGGT2 using the Lag/K operation.
- Resulting Lag and K parameters were scaled back linearly based on relative river lengths between the basins. These scaled parameters were used to route GBCT2 to SEGT2, although the quality of results is unknown without flows to compare the routing model to.
- The SAC-SMA model was utilized to predict runoff quantities in the SEGT2 basin.
- The output from the SAC-SMA operation was used as input to the UNIT-HG to predict streamflow at SEGT2's outlet based on the modelled runoff quantities. Unit hydrograph ordinates specified in the UNIT-HG operation were previously estimated using GeoTool.
- Local streamflow (i.e. the output from the UNIT-HG operation) was combined with the routed GBCT2 flow to produce a total simulated flow at SEGT2's outlet.
- Total flow from SEGT2 was routed to SGGT2 using another Lag/K operation with separate parameter values.
- SAC-SMA and UNIT-HG were used in tandem again for SGGT2 to predict local runoff quantities and resulting streamflow at SGGT2's outlet. Although a stream gage and hence a period of record for flow rates exists for SGGT2, the local contribution to the flow rates is unknown without flow rates from SEGT2 upstream to subtract from the total observed flow. Because of this GeoTool was again used to estimate unit hydrograph ordinates.
- Streamflow local to SGGT2 was added to the routed GBCT2/SEGT2 combination to finally obtain a total simulated flow at SGGT2. This total simulated flow was the primary basis to assess both SEGT2 and SGGT2 model performance.

Without streamflow data for SEGT2, a single set of parameters were calibrated for both SEGT2 and SGGT2 since the two basins are directly adjacent and share many similar characteristics.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing was performed for upstream basin SEGT2. Due to the missing gage at SEGT2, a direct estimation of Lag/K parameters could not be performed. Rather, GBCT2 (one basin upstream of SEGT2) was routed past SEGT2 and to the outflow of SGGT2. The results were then scaled back linearly based on the distance along Guadalupe River from GBCT2 to SEGT2 relative to GBCT2 to SGGT2:

Distance from GBCT2 to SEGT2: approximately 15.76 miles
Distance from GBCT2 to SGGT2: approximately 26.35 miles
15.76/26.35 = 59.81%

It is assumed that the river retains similar hydraulic characteristics throughout SEGT2 and SGGT2.

Tables 105 and 106 compare the pre-existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 105. Lag/Q and K/Q Pairs for Routing Reach GBCT2 to SEGT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	Lag1	Q1	Lag2	Q2	Lag3	Q3	Lag4	Q4
	Orig.	4	0	2	5000	3	10000	4	30000
Lag	Calib.	2	-	-	-	-	-	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**
	Orig.	0	0	0	5000	1	10000	1	30000
K	Calib.	1	-	-	-	-	-	-	-

Table 106. Lag/Q and K/Q Pairs for Routing Reach SEGT2 to SGGT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	Lag1	Q1	Lag2	Q2	Lag3	Q3
	Orig.	2	0	2	30000	-	-
Lag	Calib.	3	22000	1	42300	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
	Orig.	0	0	1	10000	1	30000
K	Calib.	0.5	22000	6	42300	-	-

Testing of the existing model parameters from the CHPS configuration provided by the WGRFC revealed that the models performed well. Since the total volume of flow at SGGT2 is mainly influenced by routed flow from GBCT2, a high correlation coefficient and low daily error for total flow is attained regardless of local parameter values. Nonetheless, the SAC-

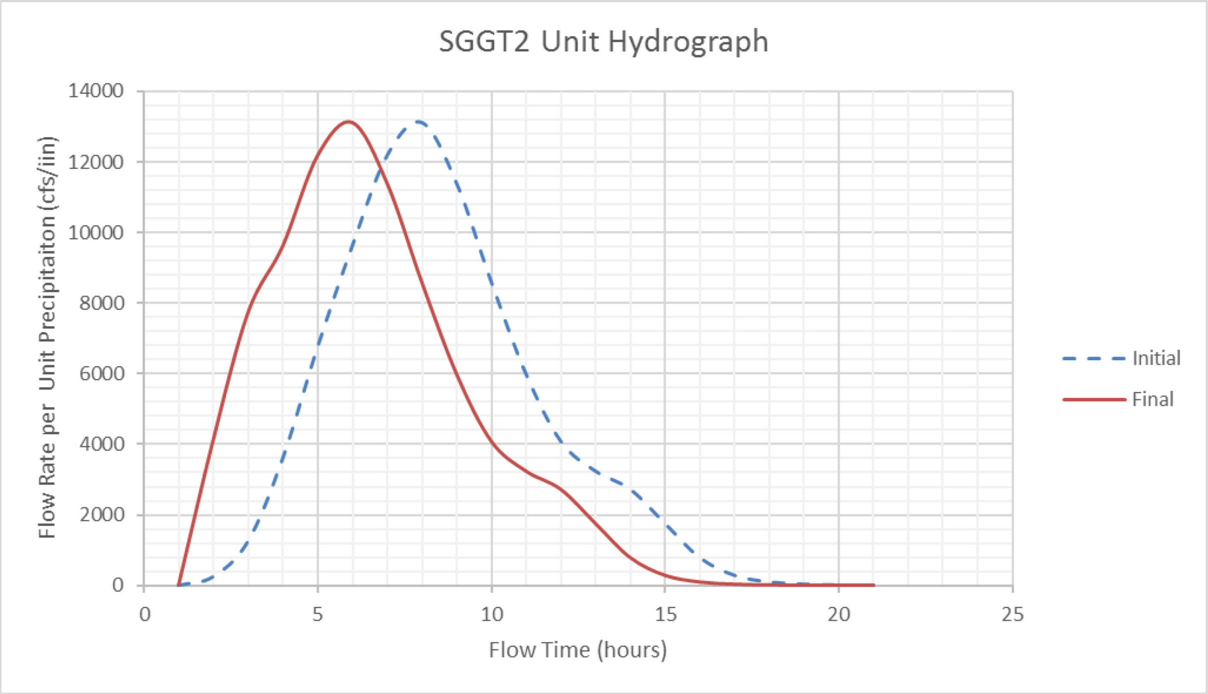
SMA and UNIT-HG operations tended to over-simulate baseflow (likely due to constant artificial low-flows from reservoirs upstream) as well as the magnitude of most runoff events. Therefore, the focus of calibration effort was aimed at lowering baseflow and peak volumes. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZTWM and UZFWM. Accordingly, emphasis was placed on refining these parameters. A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 107.

Table 107. Original Versus Calibrated SAC-SMA Parameters for SGGT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	30	30	0.30	0.000	0.01	0.000	50	1.50	40	30	130	0.115	0.010	0.30	0.3	0.00	4.75
Calib.	1.000	1.000	25	75	0.50	0.010	0.18	0.020	155	2.20	150	60	80	0.030	0.015	0.05	0.3	0.00	3.00

The UNIT-HG model derived from GIS processes, as described in Appendix B, was adjusted manually to peak two hours earlier. Initial and final UNIT-HG ordinates are shown in Figure 61. For some instances the accuracy of low flows was sacrificed to better simulate the larger events. Throughout calibration, it became apparent that peak magnitudes could not be captured consistently. Accordingly, effort was focused on finding a balance between over and under-simulation of peaks.

Figure 61. SGGT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set shows enhanced performance when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations for local and total flows are presented in Tables 108 and 109, respectively. For total statistics these demonstrate an improved volume bias, an appreciable increase in the correlation coefficient, and a decrease in root-mean-square error of more than 50%.

Table 108. SGGT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	-87.2	90.1	17.2	2.2	30.9	14.2	1.8	6.4	188.6	32.4	0.375	-0.1	0.2	15.40	0.82
Calib.	-94.8	95.1	17.2	0.9	30.9	5.7	1.8	6.4	190.9	32.8	0.499	-0.1	0.1	14.80	2.71

Table 109. SGGT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	23.2	39.7	17.2	21.2	30.9	38.3	1.8	1.8	123.1	21.2	0.840	0.5	0.7	2.83	0.68
Calib.	0.4	28.9	17.2	17.3	30.9	27.7	1.8	1.6	53.1	9.1	0.957	0.9	0.9	-1.26	1.07

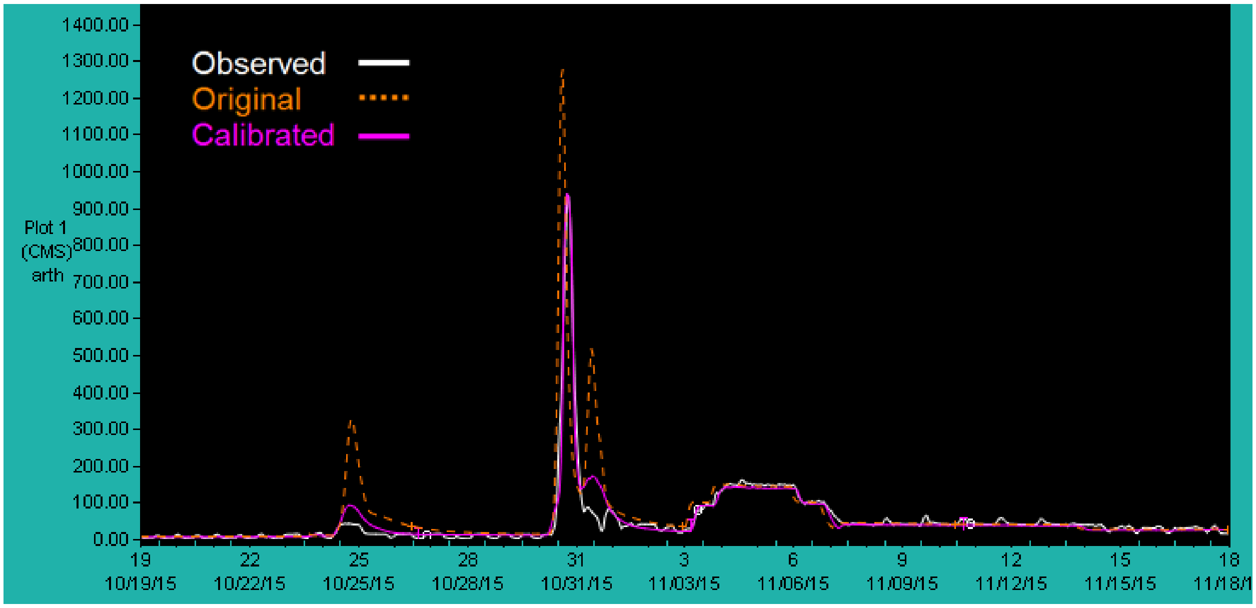
Peakflow data was used to further evaluate calibration results for flood events as shown in Table 110 for several large events throughout the period of record. These statistics are based on the observed USGS instantaneous peakflow values reported. As seen in the table, no timing errors are recorded by the PEAKFLOW operation and peak magnitudes are generally captured well.

Table 110. SGGT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	**Date**	**Q (CMS)**	**Date**			
354.0	1/25/2012	145.0	1/25/2012	0	-209.0	0.41
212.0	9/29/2013	265.0	9/29/2013	0	53.0	1.25
532.0	10/31/2013	499.0	10/31/2013	0	-33.0	0.94
442.0	6/14/2015	342.0	6/14/2015	0	-100.0	0.77
952.0	10/30/2015	940.0	10/30/2015	0	-12.0	0.99

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 62. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 62. Sample Plot Comparing the Original Versus Final Calibration Simulations for SGGT2



4.6 Calibration Results for the San Antonio River Basin

The sub-basins within the San Antonio River basin that were included in this study are highlighted in Figure 63. A summary of the calibrated parameters from the LAG/K and SAC-SMA operations are provided in Tables 111 – 113. A summary of the hourly simulation statistics produced by the STAT-Q operation are provided in Table 114 (total flow) and Table 115 (local flow).

Figure 63. Calibrated Sub-basins in the San Antonio River Basin

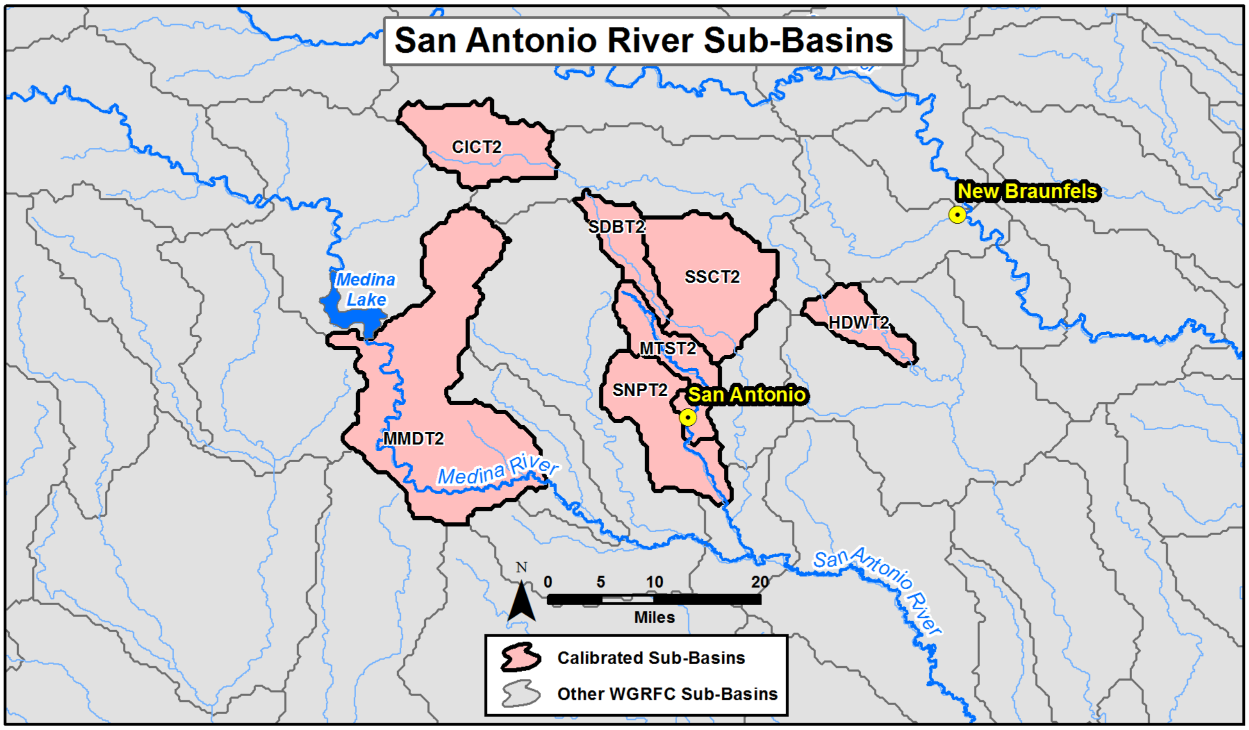


Table 111. Summary of Lag/Q Pairs for Modeled Reaches in the San Antonio River Basin

Routing to	Routing from	Lag Parameters					
		Lag1 (hr)	Q1 (cfs)	Lag2 (hr)	Q2 (cfs)	Lag3 (hr)	Q3 (cfs)
MMDT2	MDLT2	16	530	32	880		
SNPT2	MTST2	1	10	2	200	1	1800
SSCT2	SDBT2	1	35	2	450	0	500
HDWT2	SELT2	6	700	5	8000	3	16000

Table 112. Summary of K/Q Pairs for Modeled Reaches in the San Antonio River Basin

Routing to	Routing from	K Parameters					
		K1 (hr)	Q1 (cfs)	K2 (hr)	Q2 (cfs)	K3 (hr)	Q3 (cfs)
MMDT2	MDLT2	5	175	8	530	12	900
SNPT2	MTST2	6					
SSCT2	SDBT2	0					
HDWT2	SELT2	1	700	5	8000	1	16000

Table 113. Calibrated SAC-SMA Parameters for Modeled Sub-basins in the San Antonio River Basin

NWS Basin ID	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
MMDT2	1.0	1.0	65	55	0.40	0.001	0.15	0.00	210	3.00	110	25	160	0.040	0.010	0.50	0.3	0.00	2.60
MTST2	1.0	1.0	50	30	0.50	0.165	0.05	0.03	295	1.40	200	20	40	0.200	0.040	0.40	0.3	0.00	5.60
SNPT2	1.0	1.0	25	10	0.50	0.150	0.00	0.00	150	3.00	110	40	60	0.030	0.001	0.50	0.3	0.00	1.26
SDBT2	1.0	1.0	40	40	0.50	0.010	0.00	0.08	230	2.00	400	20	40	0.170	0.020	0.00	0.3	0.00	4.20
SSCT2	1.0	1.0	40	40	0.50	0.130	0.02	0.10	300	2.00	150	20	40	0.100	0.020	0.25	0.3	0.00	2.80
CICT2	1.0	1.0	50	50	0.30	0.025	0.05	0.00	60	1.50	75	30	40	0.100	0.015	0.05	0.3	0.00	3.60
HDWT2	1.0	1.0	35	10	0.45	0.050	0.15	0.01	220	2.80	80	40	300	0.080	0.002	0.50	0.3	0.15	3.80

Table 114. Total Flow Simulation Statistics for Modeled Sub-basins in the San Antonio River Basin

NWS Basin ID	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
MMDT2	-3.03	69.52	1.83	1.77	7.64	7.14	4.19	4.04	258.2	4.71	0.799	0.62	0.75	0.31	0.85
MTST2	-2.99	81.58	1.20	1.16	7.04	7.10	5.88	6.12	390.0	4.66	0.782	0.56	0.78	0.30	0.78
SNPT2	15.46	47.94	3.10	3.58	27.42	25.78	8.85	7.20	336.9	10.44	0.925	0.86	0.87	-0.42	0.98
SDBT2	174.4	241.6	0.02	0.05	0.49	0.64	23.36	12.11	2751.0	0.58	0.503	-0.39	0.39	0.00	0.39
SSCT2	9.97	89.60	1.08	1.19	6.54	7.21	6.05	6.06	478.5	5.17	0.721	0.37	0.65	0.30	0.65
CICT2	4.08	62.85	0.91	0.94	9.39	9.57	10.34	10.13	379.3	3.44	0.934	0.87	0.92	0.04	0.92
HDWT2	3.23	47.69	0.97	1.00	6.86	9.38	7.08	9.37	487.3	4.73	0.876	0.53	0.64	0.33	0.64

Table 115. Local Flow Simulation Statistics for Modeled Sub-basins in the San Antonio River Basin

NWS Basin ID	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
MMDT2	-3.03	69.52	1.83	1.77	7.64	7.14	4.19	4.04	258.20	4.71	0.799	0.62	0.75	0.31	0.85
SNPT2	-25.97	55.73	3.10	2.30	27.42	23.08	8.85	10.06	342.80	10.62	0.926	0.85	0.78	0.58	1.10
SSCT2	363.3	377.8	0.55	2.57	4.71	11.73	8.50	4.57	1632.0	9.04	0.743	-2.68	0.30	-0.21	0.30
HDWT2	-50.95	71.96	0.97	0.48	6.86	2.06	7.08	4.34	632.60	6.14	0.492	0.20	0.15	0.19	1.64

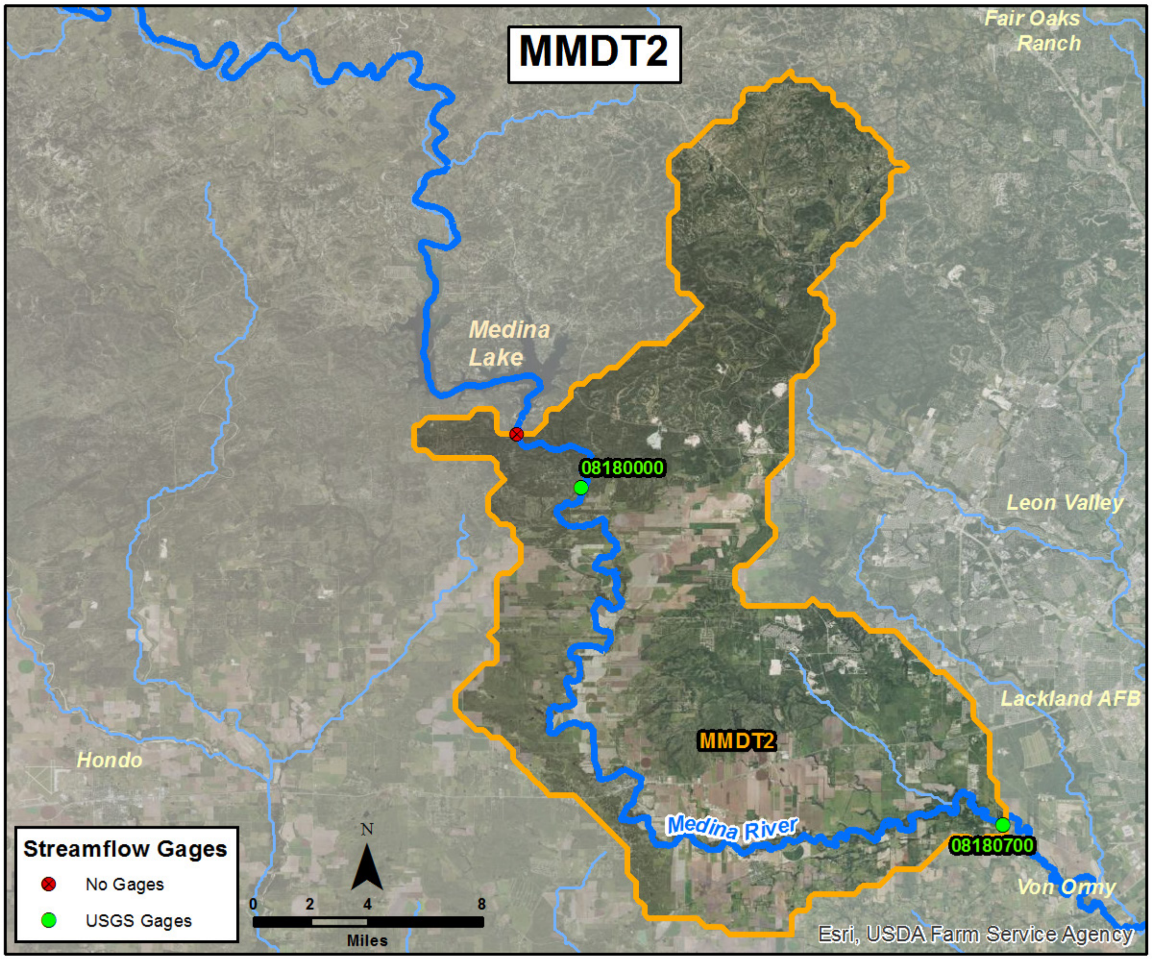
4.6.1 MMDT2: Medina River near Macdona, TX

MMDT2 is a rural local sub-basin located 20 miles west of San Antonio in Bexar, Medina, and Bandera counties that drains approximately 253 mi^2 locally and 894 mi^2 total. According to the National Land Cover Database (NLCD), the area is comprised of approximately 36% forest, 34% grassland and shrubs, and 15% crops. The remaining 15% includes a small amount of residential/commercial development, with the towns of Lacoste, Castroville and Rio Medina contained within the sub-basin boundary. It is a relatively large basin. MMDT2 drains the Medina River (Rio Medina), which is very sinuous and flat. Its upstream boundary is at Medina Lake from which it receives flow. There is a diversion about 3.5 miles northwest of the town of Rio Medina which appears to be used for agricultural purposes. Many springs have been noted historically throughout the basin, but it is likely that some or all of them have dried up at least in part due to groundwater pumping. Soils within MMDT2 are primarily Hydrologic Soil Group D with smaller portions of B and C. Table 116 summarizes the basin characteristics followed by Figure 64 which presents an aerial map of MMDT2.

Table 116. Basin Characteristics for MMDT2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
253 / 894	1837 / 1000 / 604	Edwards Plateau, Eastern Part; Northern Rio Grande Plain; Texas Blackland Prairie, Northern Part	Clay: 55% Other: 20% Loam: 16% Minor classes: 9%	A: 0%; B: 19%; C: 17%; D: 64%; W: 0%	Evergreen Forest: 26% Shrub/Scrub: 22% Cultivated Crops: 15% Grassland/Herbaceous: 12% Deciduous Forest: 10% Other: 15%

Figure 64. MMDT2 Sub-basin Map



Observed streamflow data are available from January 2000 through January 2017 at USGS gage 08180700, Medina River near Macdona, TX. The average observed streamflow over this period is 181 cfs. The typical event peaks within half a day, and takes approximately two days to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 55,200 cfs in July 2002.

Unlike many sub-basins in the area, MMDT2 seems to maintain a consistent baseflow. This may be due to releases from the upstream Medina Lake. Despite hydrologically remote areas in the basin and lack of urbanization, runoff response tends to be relatively quick, often peaking within six hours. The poorly infiltrating, claylike soils in the basin are likely responsible for this. During and after large events, the basin appears to be receive significant releases from Medina Lake, presumably to attenuate flow and prevent dam overtopping, causing larger flow rates than expected. Unfortunately, no gage exists at Medina Lake's outlet to confirm this.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing was performed for upstream basin MDLT2. Table 117 compares the pre-existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 117. Lag/Q and K/Q Pairs for Routing Reach MDLT2 to MMDT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**
	Orig.	0	-	-	-	-	-
Lag	Calib.	16	530	32	880	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
	Orig.	6	0	12	1000011	-	-
K	Calib.	5	175	8	530	12	900

Testing of the existing model parameters from the CHPS-FEWS configuration provided by the WGRFC revealed that the models failed to simulate the consistent baseflow and under-simulated most events. Therefore, the focus of calibration effort was aimed at capturing baseflow and predicting larger runoff events. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be those controlling the upper soil zone, namely UZTWM, UZFWM, and UZK. Accordingly, emphasis was placed on refining these parameters. The unit hydrograph derived from the original analysis was slightly tweaked manually by discarding the first two ordinates and adding the lost volume to the next two ordinates, scaled by their relative magnitudes. This appeared to result in better prediction of peak flows. The model performs reasonably well, although MMDT2 occasionally has markedly different responses to similar precipitation events. As a result, the model sometimes predicts a hydrograph that is not observed, even with a decently high UZTWM value. A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 118.

Table 118. Original Versus Calibrated SAC-SMA Parameters for MMDT2

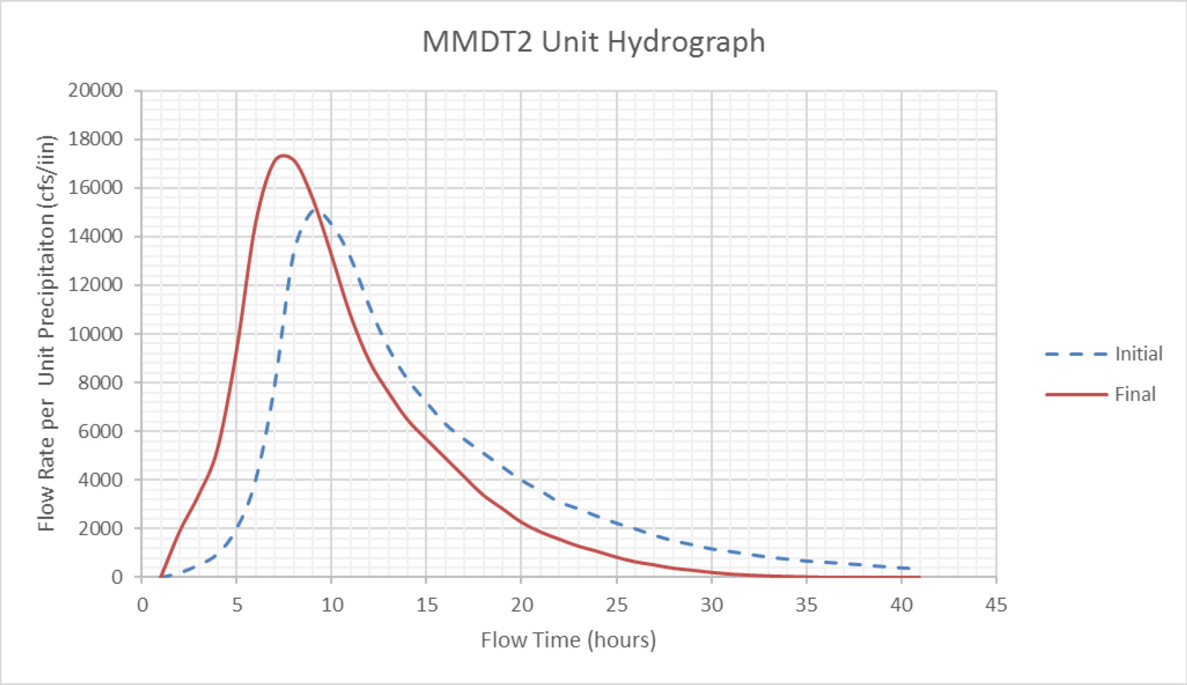
Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	0.892	82	56	0.20	0.000	0.00	0.000	198	3.18	400	34	225	0.122	0.039	0.00	0.3	0.00	12.92
Calib.	1.000	1.000	65	55	0.40	0.001	0.15	0.000	210	3.00	110	25	160	0.040	0.010	0.50	0.3	0.00	2.60

No gage exists at Medina Lake's outlet. Two nearby gages were used to approximate the upstream flow instead, but the period of record for these ended in September 2007 while calibration efforts were focused on 2011 onwards. Based on the flow approximated prior to 2008, releases from the lake typically did not affect the downstream flow aside from "baseflow" (likely low-flow releases in reality) and a few very large events. In case of large events, releases occurred to mitigate flooding which caused atypically large and long receding limbs of the hydrographs. While this creates some additional uncertainty in the calibration, it makes more sense to leave the large error between simulated and observed flows incurred from the Medina Lake releases rather than attempting to simulate flows as if they occurred as a result of local hydrological response. The lack of upstream flow information is likely responsible for the high percent bias in June, in larger events, and in the annual deficit of flow in the model.

All four instances of the largest observed flow interval (>3,030 cfs) occur due to one rainfall event starting on 6/1/2016 which takes the entire month to recede. Considering the magnitude of the event it is possible (or even probable) that the atypically large error between observed and modeled flows arises due to releases from Medina Lake, which are not known due to missing gage data. Of the 25 largest daily errors, 20 of them occur in June 2016.

The ordinates for the initial UNIT HG were based on two historical events, as described in Appendix B. The ordinates were manually adjusted to peak two hours early. This improved overall peak timing and magnitude. Figure 65 demonstrates the final adjustments made to the UNIT HG during calibration.

Figure 65. MMDT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set produces a significantly improved simulation when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations for local and total flows are presented in Table 119 and 120, respectively. These demonstrate a large improvement to the water balance as seen in the reduced percent bias. The correlation coefficient and other statistics also show a significant improvement from the calibration efforts. Since the upstream flow from Medina Lake was assumed to be near-zero over the calibration, the presented local and total statistics are the same for this sub-basin.

Table 119. MMDT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	240.3	287.2	1.8	6.2	7.6	17.2	4.2	2.8	772.9	14.1	0.666	-2.4	0.3	-0.01	0.30
Calib.	-3.0	69.5	1.8	1.8	7.6	7.1	4.2	4.0	258.2	4.7	0.799	0.6	0.7	0.31	0.85

Table 120. MMDT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	240.3	287.2	1.8	6.2	7.6	17.2	4.2	2.8	772.9	14.1	0.666	-2.4	0.3	-0.01	0.30
Calib.	-3.0	69.5	1.8	1.8	7.6	7.1	4.2	4.0	258.2	4.7	0.799	0.6	0.7	0.31	0.85

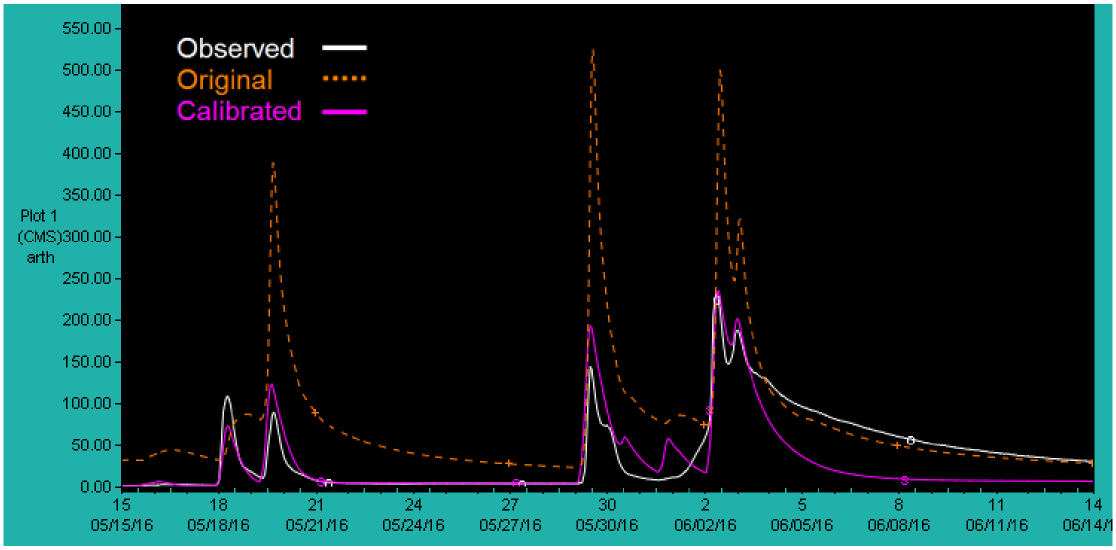
Peakflow data was used to further evaluate calibration results for flood events as shown in Table 121 for the June 2016 event. These statistics are based on the lone observed instantaneous peakflow value reported by the USGS for this basin's gage. As seen in the table, the simulated/observed discharge ratio is close to one indicating good model performance for the most recent event.

Table 121. MMDT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
233.0	6/2/2016	236.0	6/2/2016	0	3.0	1.01

A sample plot from ICP of the final calibration compared with the original model simulation is provided in Figure 66. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 66. Sample Plot Comparing the Original Versus Final Calibration Simulations for MMDT2



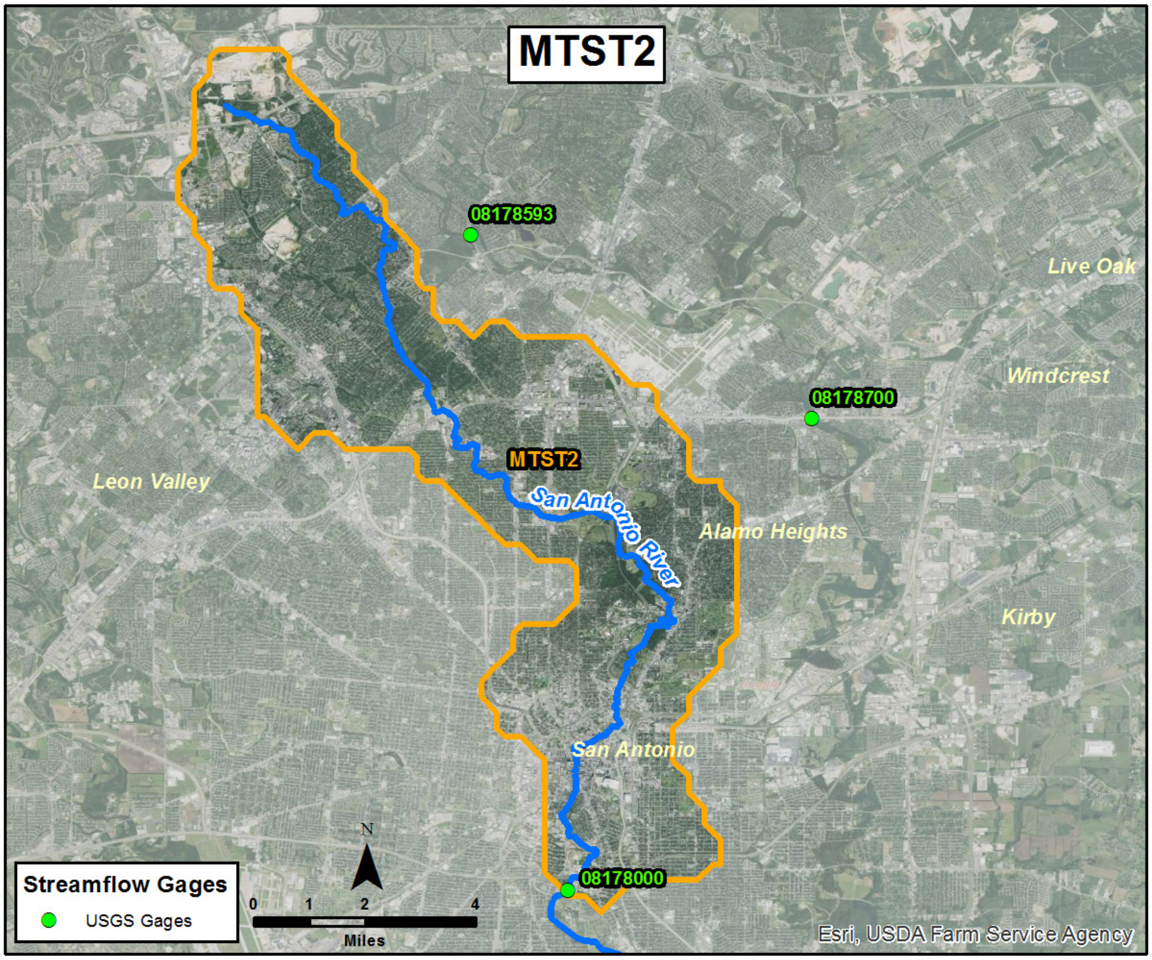
4.6.2 *MTST2: San Antonio River at Mitchell Street, San Antonio, TX*

MTST2 is a densely developed urban headwater sub-basin within the San Antonio River basin that contains the central downtown district of the city of San Antonio. The sub-basin area drains approximately 50 mi^2 and includes multiple flood control structures, as well as natural springs, that impact the hydrologic response to precipitation events. The dominant hydrologic soil group within the local drainage area is type D, which indicates very low infiltration rates and very high runoff potential. Table 122 summarizes the basin characteristics followed by Figure 67 which presents an aerial map of MTST2.

Table 122. Basin Characteristics for MTST2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
50 / 50	1122 / 815 / 610	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 78% Loam: 12% Minor classes: 10%	A: 0%; B: 14%; C: 36%; D: 50%; W: 0%	Developed, Low Intensity: 27% Developed, Open Space: 24% Developed, Medium Intensity: 22% Developed, High Intensity: 19% Other: 8%

Figure 67. MTST2 Sub-basin Map



Observed streamflow data are available for USGS gage 08178050 (San Antonio River at Mitchell Street) from December 1992 through December 2016. The average observed streamflow over this period is 83 cfs. The typical event peaks within 1-2 hours, and takes less than 6 hours to recede back to baseflow levels. The highest instantaneous flow recorded at the gage within the period of record is 22,400 cfs in May 2013. Several hydrologic features within MTST2 impact the recorded streamflow. Within MTST2, there are three major flood control features: (1) the San Antonio flood control tunnel is a 24-ft diameter sub-surface tunnel that diverts high flows near the intersection of highways I-35 and I-37 and moves water under the downtown area to an outlet upstream of the streamflow gage near the intersection of Lone Star Blvd. and Mission Rd.; (2) the Olmos detention dam, which detains flood flows within the normally dry Olmos Reservoir, resides in the northern portion of the sub-basin near the highway 281 and Devine Rd. overpass; and, (3) the San Pedro Creek flood control tunnel, which diverts high flows in San Pedro Creek out of the sub-basin through an inlet located near the Laredo St. and Guadalupe Ybarra St. intersection. In addition, there are a number of natural springs (e.g., Brackenridge Park area) within the sub-basin which contribute to the elevated and relatively constant baseflow.

Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models extremely over-simulate peak flows and under-simulate baseflow. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZFWM (which influences the timing and magnitude of the largest surface runoff events) and PCTIM (which defines the percentage of the sub-basin area where direct runoff occurs due to impervious surfaces). Accordingly, emphasis was placed on refining these parameters. A summary of the original SAC-SMA parameter values and the results of the calibration analysis are provided in Table 123.

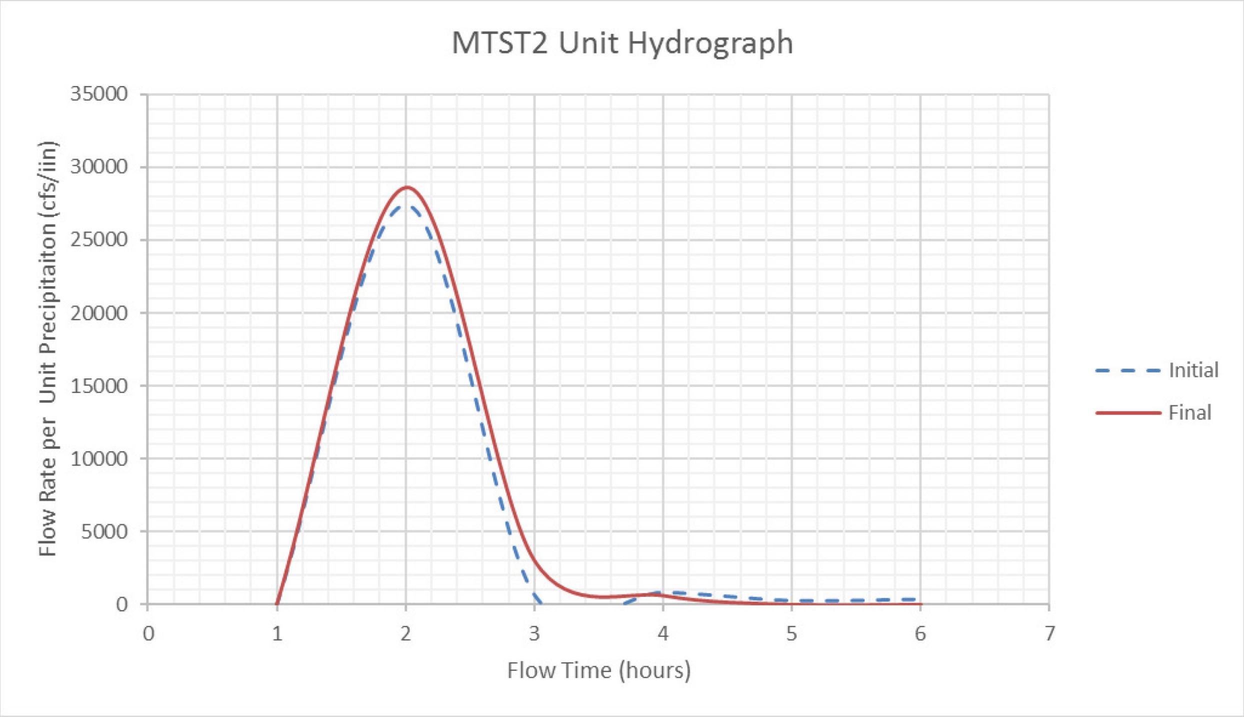
Because the San Antonio flood tunnel discharges back to the river upstream of the sub-basin outlet, diversion modeling was not required to replicate its impacts. After mid-sized to large flood events, however, the observed flow consistently displays a long, drawn out recession period where streamflow is artificially elevated. This may be a result of the San Antonio tunnel emptying. It may also be a result of the Olmos detention dam, or some combination of the two. This recession behavior could not be replicated with the hydrologic models without significantly inhibiting the ability of the models to simulate the largest flood peaks. To account for the San Pedro flood control tunnel, a CHANLOSS operation (with a constant percentage loss rate of 4%, which is equivalent to the proportion of the San Pedro Creek drainage area compared to the total MTST2 drainage area) was incorporated into the final hydrologic models. To account for the presence of the natural springs within the sub-basin, another CHANLOSS operation was applied. This operation was parameterized to add a constant flow of approximately 7 cfs to the baseflow.

Table 123. Original Versus Calibrated SAC-SMA Parameters for MTST2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	0.892	80	15	0.50	0.040	0.00	0.000	20	1.03	204	25	305	0.101	0.007	0.01	0.3	0.00	4.66
Calib.	1.000	1.000	50	30	0.50	0.165	0.05	0.030	295	1.40	200	20	40	0.200	0.040	0.40	0.3	0.00	5.60

The ordinates for the initial UNIT-HG model were based on four (4) historical events, as described in Appendix B. The initial model performed well and was only modified slightly during the calibration analysis. Figure 68 shows the initial and final UNIT-HG models.

Figure 68. MTST2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set produces a significantly improved simulation when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical output from STAT-Q of the original versus calibrated models are presented in Table 124. The table shows a significant improvement in model performance based on the calibration analysis.

Table 124. MTST2 Original Versus Calibrated Simulation Statistics (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	87.7	136.2	1.2	2.2	7.0	23.5	5.9	10.5	1572.0	18.8	0.753	-6.1	0.2	0.69	0.23
Calib.	-3.0	81.6	1.2	1.2	7.0	7.1	5.9	6.1	390.0	4.7	0.782	0.6	0.8	0.30	0.78

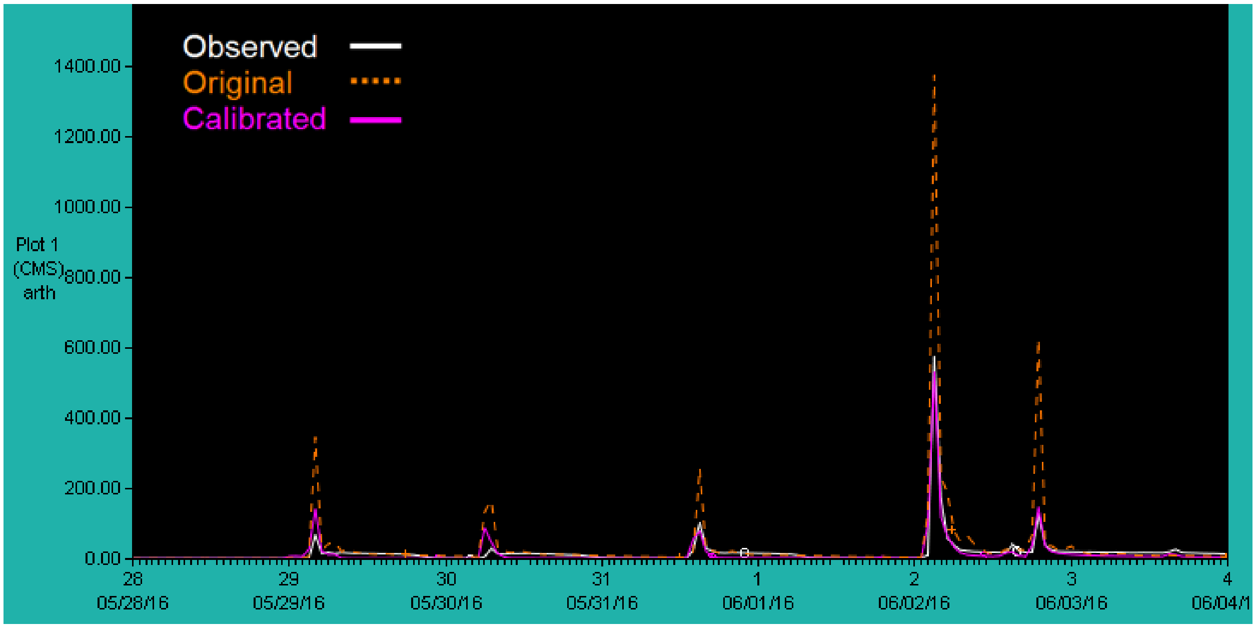
In addition to considering the STAT-Q output, the PEAKFLOW operation was used during the calibration analysis to evaluate model performance for the recent large flood events, as shown in Table 125 for several large events in the period of record. These statistics are based on the observed USGS instantaneous peakflow values reported. As seen in the table, the two largest flood events in the available record are simulated within 9% of the observed flow reported by USGS.

Table 125. MTST2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	**Date**	**Q (CMS)**	**Date**			
112.0	5/12/2011	61.0	5/12/2011	0	-51.0	0.55
331.0	8/19/2012	121.0	8/19/2012	0	-210.0	0.37
634.0	5/25/2013	602.0	5/25/2013	0	-32.0	0.95
261.0	7/18/2014	142.0	7/18/2014	0	-119.0	0.54
274.0	5/23/2015	148.0	5/23/2015	0	-126.0	0.54
586.0	6/2/2016	532.0	6/2/2016	0	-54.0	0.91

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 69. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 69. Sample Plot Comparing the Original Versus Final Calibration Simulations for MTST2



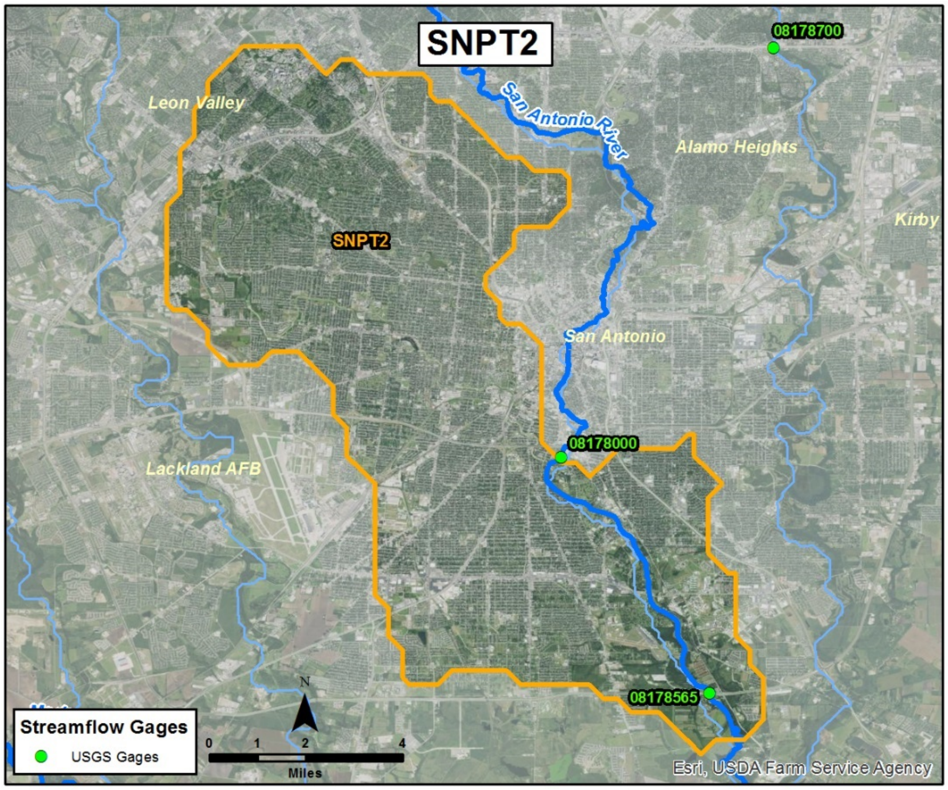
4.6.3 *SNPT2: San Antonio River at Loop 410, San Antonio, TX*

SNPT2 is an urban local sub-basin located at San Antonio River basin that drains approximately 75 locally and 125 mi^2 total. Residential/commercial development is heavy, with major portions of city of San Antonio (population 1.437 Million) and Balcones Heights (population 1,898) contained within the sub-basin boundary. Table 126 summarizes the basin characteristics followed by Figure 70 which presents an aerial map of SNPT2.

Table 126. Basin Characteristics for SNPT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
75 / 125	1014 / 693 / 505	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 85% Loam: 12% Minor classes: 3%	A: 0%; B: 32%; C: 15%; D: 53%; W: 0%	Developed, Low Intensity: 33% Developed, Open Space: 24% Developed, Medium Intensity: 22% Developed, High Intensity: 13% Other: 8%

Figure 70. SNPT2 Sub-basin Map



Observed streamflow data are available from USGS gage 08178565 (San Antonio River at Loop 410, San Antonio, TX) from October 1986 through January 2017. The average observed streamflow over this period is 129 cfs. The typical event peaks within 2.5-3.5 hours, and takes approximately 5-6 hours to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 81,400 cfs, which occurred in May 2013.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing was performed for upstream basin MTST2. Table 127 compares the pre-existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 127. Lag/Q and K/Q Pairs for Routing Reach MTST2 to SNPT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**
Lag	Orig.	3	800	1	5000	1	25000
	Calib.	1.0	10	2	200	1	1800
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
K	Orig.	0	-	-	-	-	-
	Calib.	6.0	-	-	-	-	-

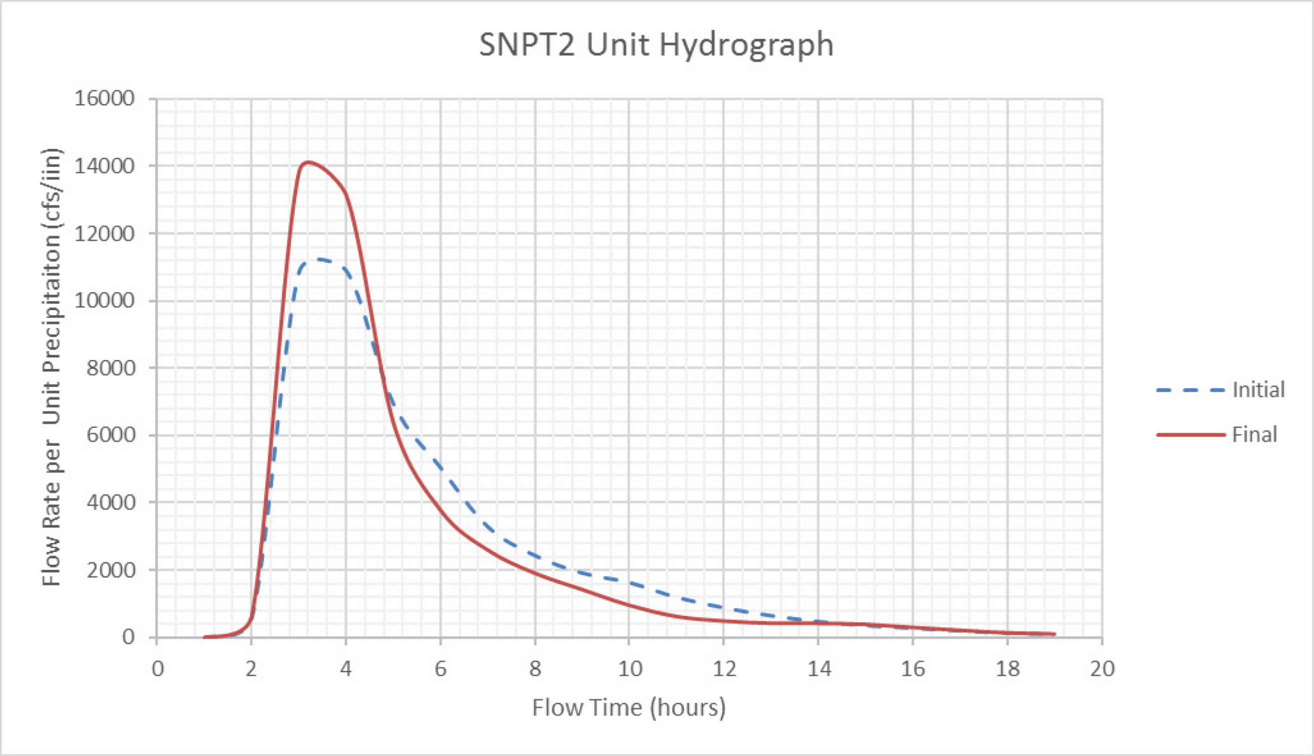
Testing of the existing model parameters from the CHPS-FEWS configuration provided by the WGRFC revealed that the models extremely under simulate peak and base flows. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZTWM, ZPERC, REXP, LZSK and LZPK. Accordingly, emphasis was placed on refining these parameters. The biggest event in May 2013 is significantly under-simulated. However, as in the case of other nearby basins in the San Antonio area, this appears to be a result of a poor MAPX estimation as several rain gages in the area recorded much higher precipitation depths over the 48 hours that the storm occurred. Therefore focus was placed on capturing the largest peaks in later years of the period of record. A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 128.

Table 128. Original Versus Calibrated SAC-SMA Parameters for SNPT2

Sim.	**PXADJ**	**PEADJ**	**UZTWM**	**UZFWM**	**UZK**	**PCTIM**	**ADIMP**	**RIVA**	**ZPERC**	**REXP**	**LZTWM**	**LZFSM**	**LZFPM**	**LZSK**	**LZPK**	**PFREE**	**RSERV**	**SIDE**	**PBASE**
Orig.	1.000	0.892	80	15	0.50	0.040	0.00	0.000	20	1.03	204	25	305	0.101	0.007	0.01	0.3	0.00	4.66
Calib.	1.000	1.000	25	10	0.50	0.15	0.00	0.000	150	3.00	110	40	60	0.030	0.001	0.50	0.3	0.00	1.26

The initial unit hydrograph ordinates were derived from three historical events described in Appendix B and placed into the UNIT-HG operation. Manual adjustments were made to better capture the peak magnitudes and a faster recession as depicted in Figure 71.

Figure 71. SNPT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set provides better-quality simulations when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations for local and total flows are presented in Tables 129 and 130, respectively. These demonstrate an improvement for almost every statistic in the tables.

Table 129. SNPT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	1.4	61.2	3.1	3.1	27.4	23.7	8.8	7.5	393	12.2	0.897	0.8	0.8	-0.16	1.04
Calib.	-26.0	55.7	3.1	2.3	27.4	23.1	8.8	10.1	342.8	10.6	0.926	0.9	0.8	0.58	1.10

Table 130. SNPT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	41.6	70.8	3.1	4.4	27.4	28.6	8.8	6.5	380.8	11.8	0.913	0.8	0.9	-0.74	0.88
Calib.	15.5	47.9	3.1	3.6	27.4	25.8	8.8	7.2	336.9	10.4	0.925	0.9	0.9	-0.42	0.98

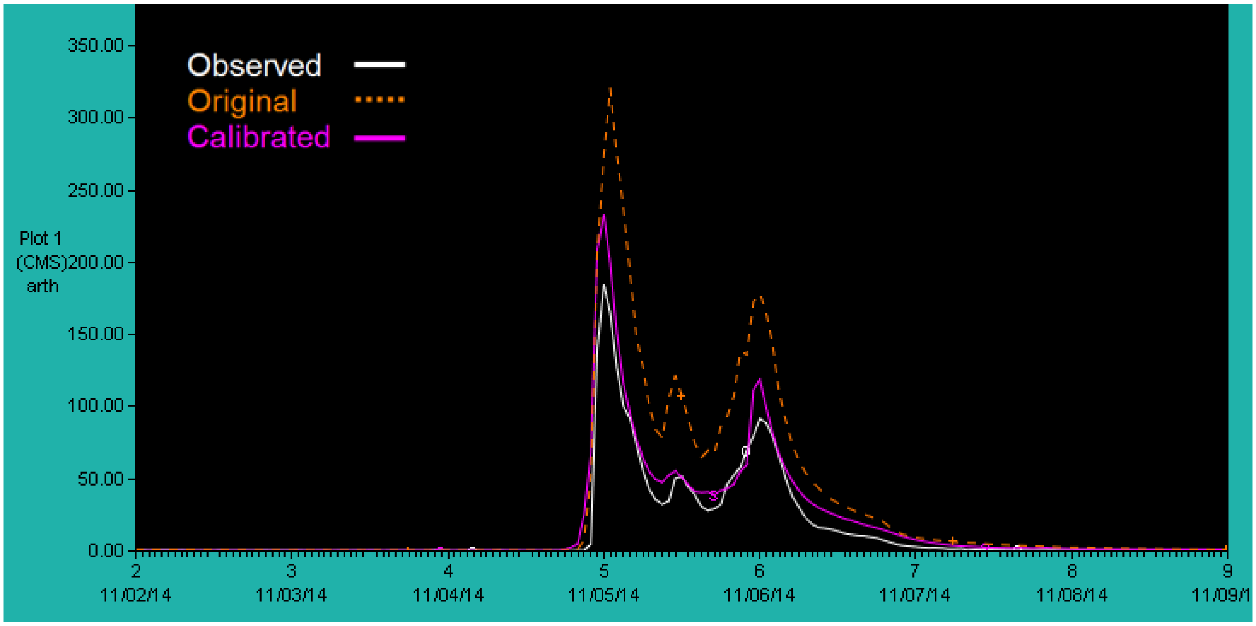
Peakflow data was used to further evaluate calibration results for flood events as shown in Table 131 for several large events in the period of record. These statistics are based on the observed USGS instantaneous peakflow values reported. As seen in the table, peaks are typically simulated within 16% of their magnitudes (the May 2013 was intentionally omitted from the table due to known precipitation errors) while no timing errors are observed.

Table 131. SNPT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
138.0	1/9/2011	119.0	1/9/2011	0	-19.0	0.86
615.0	8/19/2012	582.0	8/19/2012	0	-33.0	0.95
467.0	5/13/2014	544.0	5/13/2014	0	77.0	1.16
1300.0	5/23/2015	797.0	5/23/2015	0	-503.0	0.61
1520.0	9/26/2016	1330.0	9/26/2016	0	-190.0	0.88

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 72. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 72. Sample Plot Comparing the Original Versus Final Calibration Simulations for SNPT2



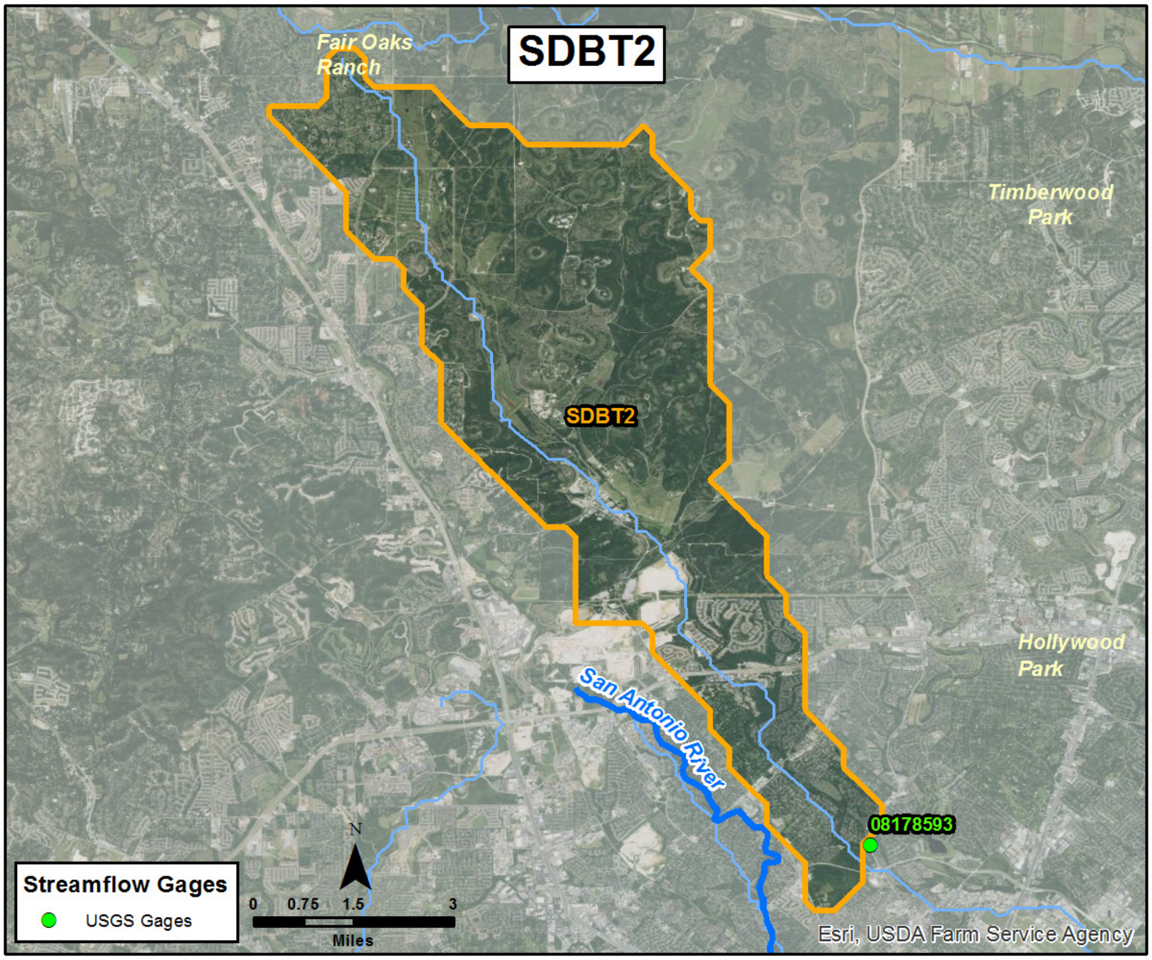
4.6.4 SDBT2: Salado Creek at Blanco Road, San Antonio, TX

SDBT2 is a suburban/rural headwater sub-basin located in the northern greater area of San Antonio within Bexar County that drains approximately 34 mi^2. Several San Antonio suburban communities such as Shavano Park, Inwood, and Castle Hills Forest as well as the U.S Army training base Camp Bullis are contained within the sub-basin boundary. The basin lies within the Balcones Fault Zone near the edge of the Edwards aquifer where karst is known to exist. Table 132 summarizes the basin characteristics followed by Figure 73 which presents an aerial map of SNPT2.

Table 132. Basin Characteristics for SDBT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
34 / 34	1417 / 1168 / 846	Edwards Plateau, Eastern Part	Other: 54% Clay: 45% Minor classes: 1%	A: 0%; B: 0%; C: 14%; D: 86%; W: 0%	Evergreen Forest: 44% Shrub/Scrub: 19% Developed, Open Space: 11% Other: 26%

Figure 73. SDBT2 Sub-basin Map



Observed streamflow data are available for USGS gage 08178593 (Salado Creek at Blanco Road, San Antonio, TX) from October 2009 through December 2016. The average observed streamflow over this period, excluding intermittent missing data points, is 0.94 cfs. The typical event peaks within one day, and takes approximately one additional day after peak flow to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 3,490 cfs, which occurred in May 2013.

There are very few sizeable events and many of these have missing data points. The few high flows on record occur primarily in May, late September, and October and quickly recede back to zero, perhaps in part due to the flashy nature of events associated with urbanized basins.

Testing of the existing model parameters from the CHPS-FEWS configuration provided by the WGRFC revealed that the models overpredicted the number and magnitude of responses to storm events. These responses were also typically delayed. Therefore, the focus of calibration effort was aimed at increasing infiltration rates and producing quicker yet smaller responses. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZK and UZFWM. Accordingly, emphasis was placed on refining these parameters.

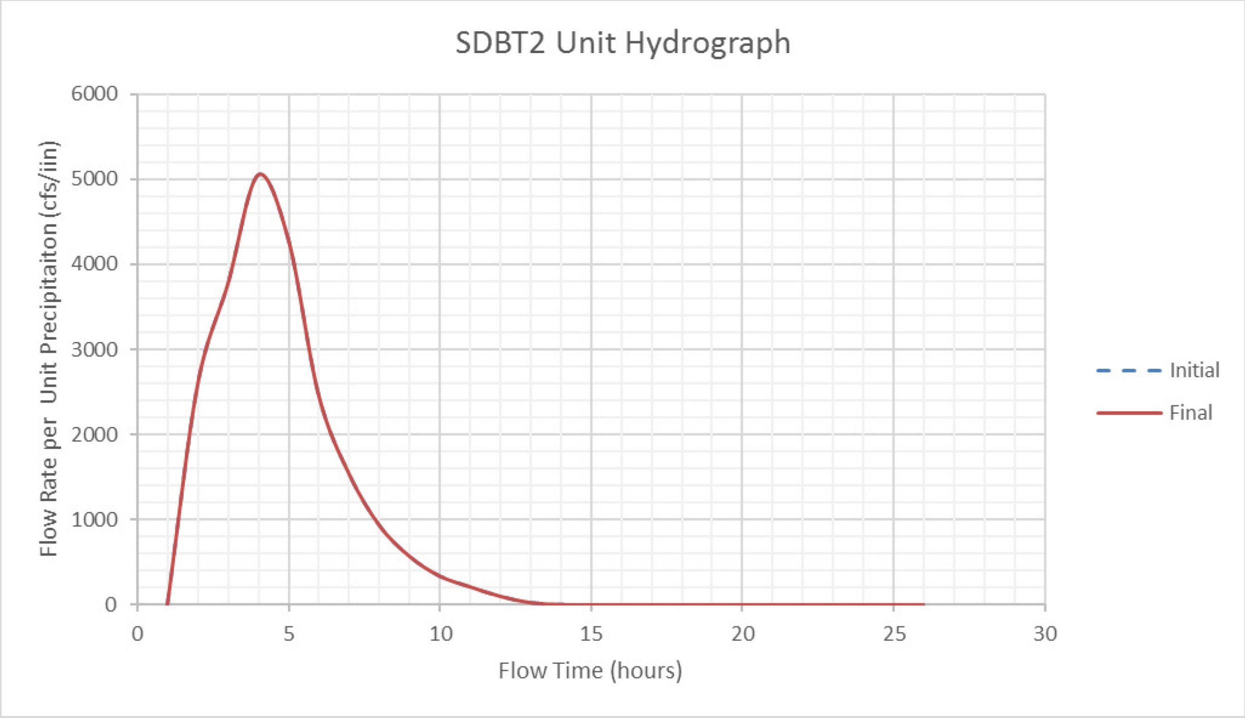
It was observed that the basin outlet experiences virtually no baseflow. To model these losses, which are likely related to karst geology in the region, a CHANLOSS operation (with a constant rate) was utilized. A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 133.

Table 133. Original Versus Calibrated SAC-SMA Parameters for SDBT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	1.000	22	43	0.40	0.010	0.05	0.001	36	1.04	367	23	350	0.100	0.007	0.11	0.3	0.00	4.75
Calib.	1.000	1.000	40	40	0.50	0.010	0.00	0.080	230	2.00	400	20	40	0.170	0.020	0.00	0.3	0.00	4.20

The initial unit hydrograph ordinates were derived from three historical events, as described in Appendix B, and used to paramaterize the UNIT-HG operation. This initial unit hydrograph model (shown in Figure 74) performed well, so no changes were made to the ordinates or their timing during the calibration analysis.

Figure 74. SDBT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set is an improvement by nearly every metric when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations is presented in Table 134. The correlation coefficient is the only statistic to worsen. This is believed to be primarily attributable to the single event on 5/23/2013, where (as is the case with several other basins in the San Antonio vicinity) the MAP underrepresents the precipitation that occurred.

Table 134. SDBT2 Original Versus Calibrated Simulation Statistics (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	5243.2	5244.5	0.0	1.1	0.5	5.7	23.4	5.1	26260.0	5.5	0.633	-125.0	0.1	-0.04	0.05
Calib.	174.4	241.6	0.0	0.1	0.5	0.8	23.4	13.3	2468.0	0.5	0.747	-0.1	0.5	-0.01	0.48

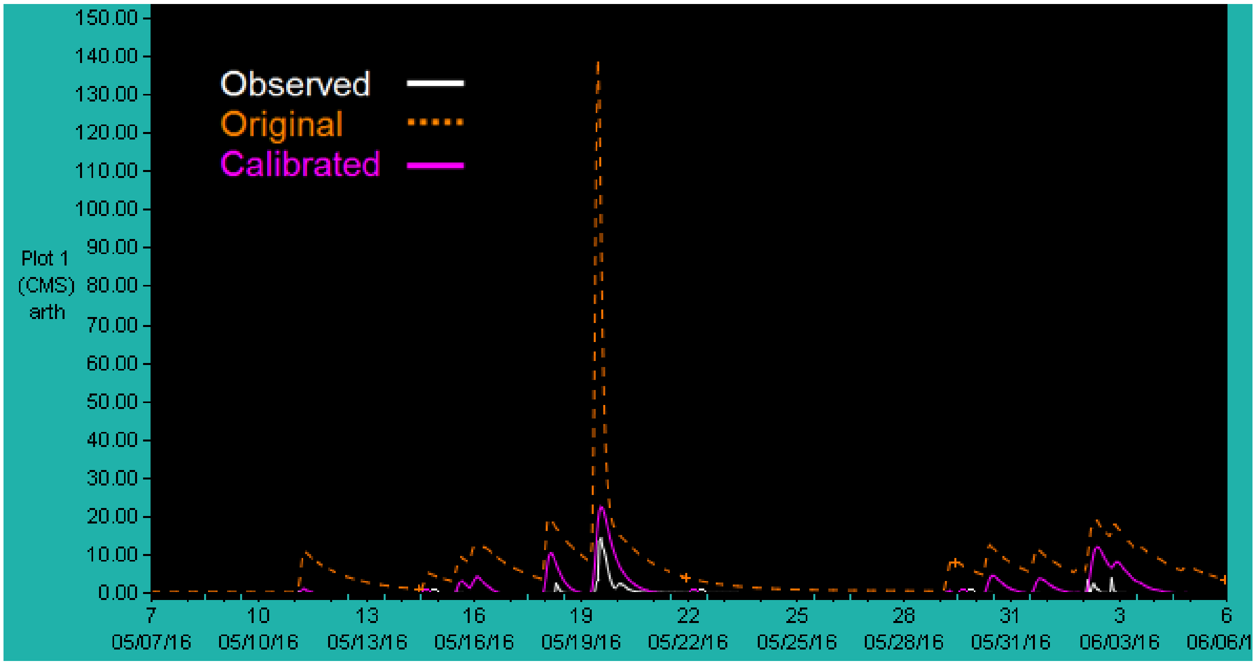
Peakflow data was used to further evaluate calibration results for flood events (see Table 135). These statistics are based on the observed USGS instantaneous peakflow values reported. The table shows only two events, one of which was the previously discussed storm on 5/23/2013 that lacked accurate MAP to produce reasonable simulated streamflow. The other peakflow event in October 2015 has no calculated timing error and only a 2% difference between observed and simulated flows.

Table 135. SDBT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
98.8	5/25/2013	13.4	5/25/2013	0	-85.4	0.14
96.9	10/30/2015	101.0	10/30/2015	0	4.1	1.04

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 75. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 75. Sample plot comparing the original versus final calibration simulations for SDBT2



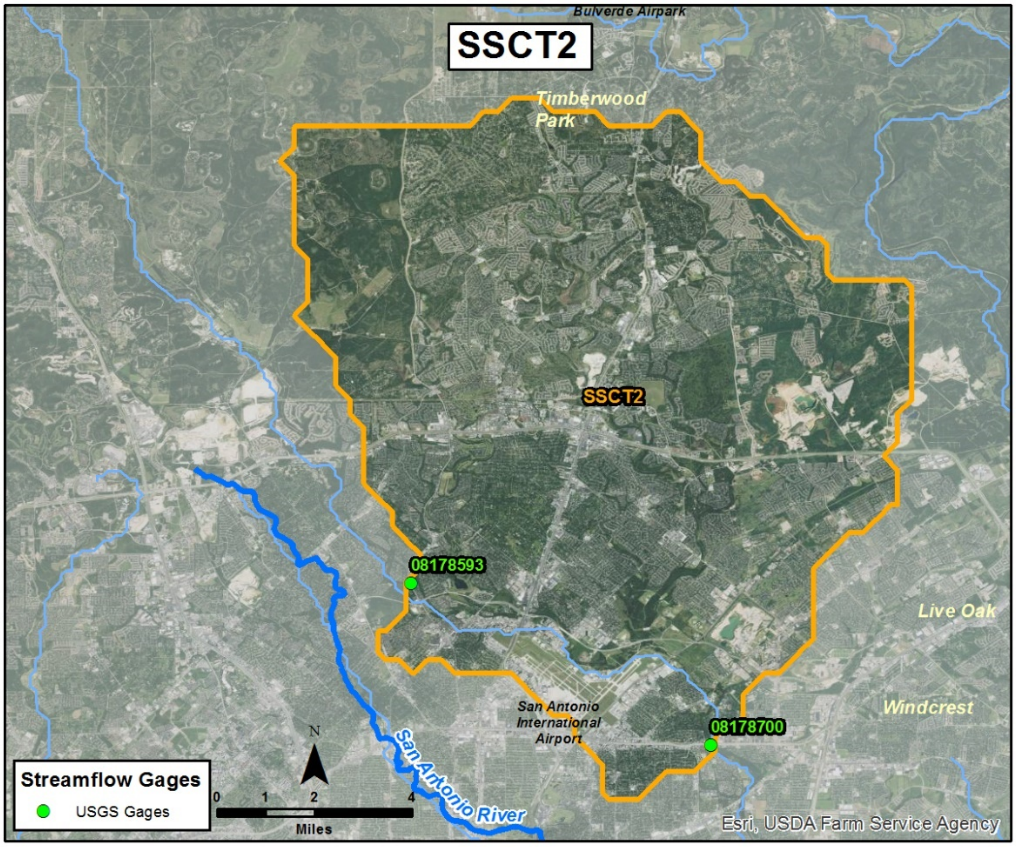
4.6.5 SSCT2: Salado Creek at Loop 410, San Antonio, TX

SSCT2 is a suburban local sub-basin located roughly 14 miles north of San Antonio proper within Bexar county, that drains approximately 106 mi^2 locally and 140 mi^2 total. The San Antonio communities of Timberwood Park, Stone Oak, and Hollywood Park as well as several other small neighborhoods are partially or wholly contained within the sub-basin boundaries. Despite being a local basin about 75% of its contributing area is local, with only a relatively small inflow from SDBT2, its one upstream basin. Table 136 summarizes the basin characteristics followed by Figure 76 which presents an aerial map of SSCT2.

Table 136. Basin Characteristics for SSCT2

Local/Total Basin Area (mi^2)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
106 / 140	1414 / 983 / 702	Edwards Plateau, Eastern Part; Texas Blackland Prairie, Northern Part	Clay: 77% Other: 20% Minor classes: 3%	A: 0%; B: 3%; C: 23%; D: 73%; W: 0%	Developed, Open Space: 23% Developed, Low Intensity: 19% Developed, Medium Intensity: 17% Evergreen Forest: 16% Other: 25%

Figure 76. SSCT2 Sub-basin Map



Observed streamflow data are available for USGS gage 08178700 (Salado Creek at Loop 410, San Antonio, TX) from February 2011 through December 2016. The average observed streamflow over this period is 22 cfs. The typical event peaks within a day or less and recedes back to baseflow levels within a day as well. The highest instantaneous flow ever recorded at the gage is 64,400 cfs, which occurred in October 1998. Much like its upstream basin SDBT2, events in SSCT2 are extremely flashy. Similarly there is virtually no baseflow.

Before investigating the SAC-SMA and UNIT-HG model parameters, Lag/K routing was performed for upstream basin SDBT2. Table 137 compares the pre-existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 137. Lag/Q and K/Q Pairs for Routing Reach SDBT2 to SSCT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**
	Orig.	3	800	2	5000	2	25000
Lag	Calib.	1	35	2	450	1	500
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**
	Orig.	6	-	-	-	-	-
K	Calib.	1	-	-	-	-	-

Testing of the existing model parameters from the CHPS-FEWS configuration provided by the WGRFC revealed that the models tended to over predicted runoff, failed to capture the peak timing in most instances, and over-simulated small events while under-simulating the largest. Therefore, the focus of calibration effort was aimed at capturing the flashy nature of the basin and fine tuning baseflow and percolation parameters. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be UZK and UZFWM (as well as UZTWM to a smaller extent). Accordingly, emphasis was placed on refining these parameters. UZK and UZFWM were set to be as high as physically reasonable in an attempt to capture the massive yet quickly forming peaks found sporadically throughout the period of record.

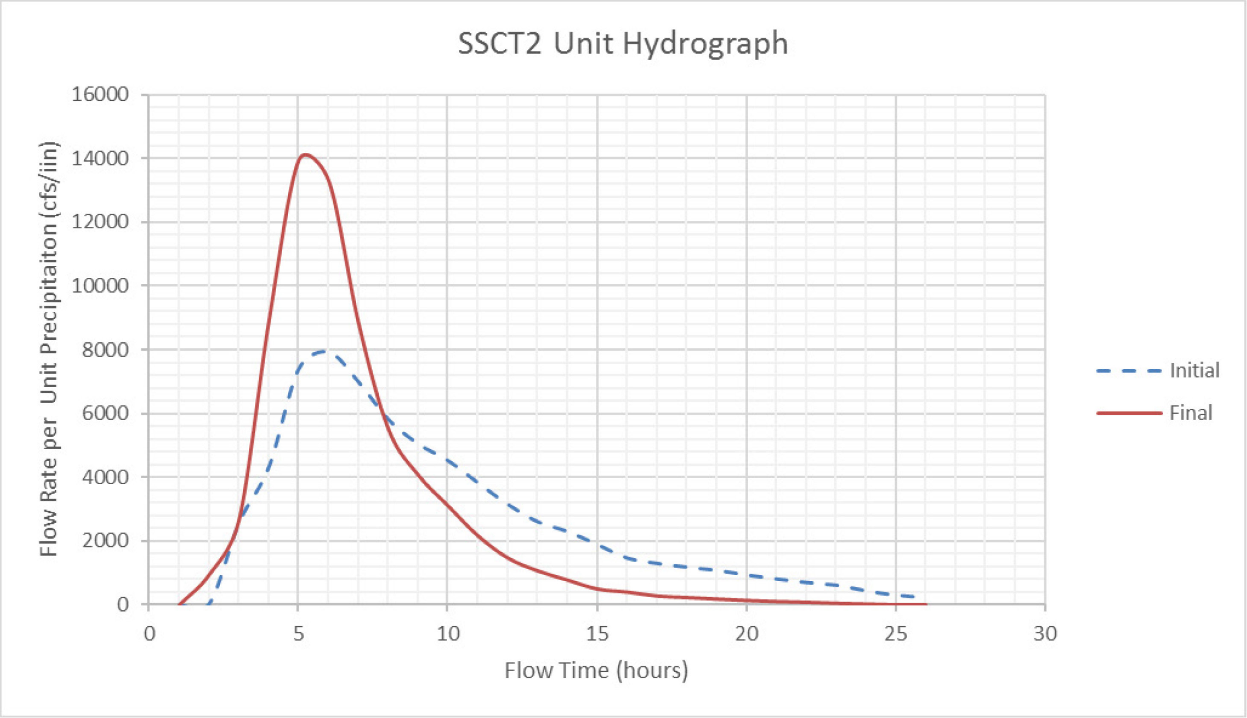
As a result of little to no baseflow, many lower zone parameters were estimated largely by regional trends and expected ranges based on physical characteristics. According to the USGS water year report, significant diversions linked to irrigation exist in the sub-basin. To model these diversions, a LOOKUP operation was utilized to gradually decrease losses as flows increased. This allowed for improvements in capturing the higher peak flows while not over simulating the smaller events. A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 138.

Table 138. Original Versus Calibrated SAC-SMA Parameters for SSCT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	0.892	22	43	0.40	0.010	0.05	0.001	36	1.04	367	23	350	0.100	0.007	0.11	0.3	0.00	4.75
Calib.	1.000	1.000	40	40	0.50	0.130	0.02	0.100	300	2.00	150	20	40	0.100	0.020	0.25	0.3	0.00	2.80

The unit hydrograph obtained from the original analysis, as described in Appendix B, did not seem to capture the steepness of the rising limb sufficiently, so the OPT3 program was run to optimize the unit hydrograph ordinates. It was then slightly adjusted manually to predict a peak flow within 5 hours, as seen in Figure 77. These adjustments to ordinates seemed to lead to better overall results.

Figure 77. SSCT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set is a clear improvement when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations are presented in Tables 139 and 140 for the local flow and total flow, respectively. It should be noted that total and local statistics are similar in this basin due to the small contribution from the only upstream basin, SDBT2. The tables show a significant improvement in biases, root-mean-square errors, and an increase in correlation coefficients greater than 20%.

Table 139. SSCT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	633.7	659.6	0.7	5.5	12.3	21.4	16.5	3.9	2435	18.1	0.577	-1.2	0.3	-1.06	0.33
Calib.	363.3	377.8	0.6	2.6	4.7	11.7	8.5	4.6	1632	9.0	0.743	-2.7	0.3	-0.21	0.30

Table 140. SSCT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	640.5	665.9	0.7	5.5	12.3	22.0	16.5	4.0	2493	18.6	0.577	-1.3	0.3	-1.03	0.32
Calib.	10.0	89.6	1.1	1.2	6.5	7.2	6.0	6.1	478.5	5.2	0.721	0.4	0.7	0.30	0.65

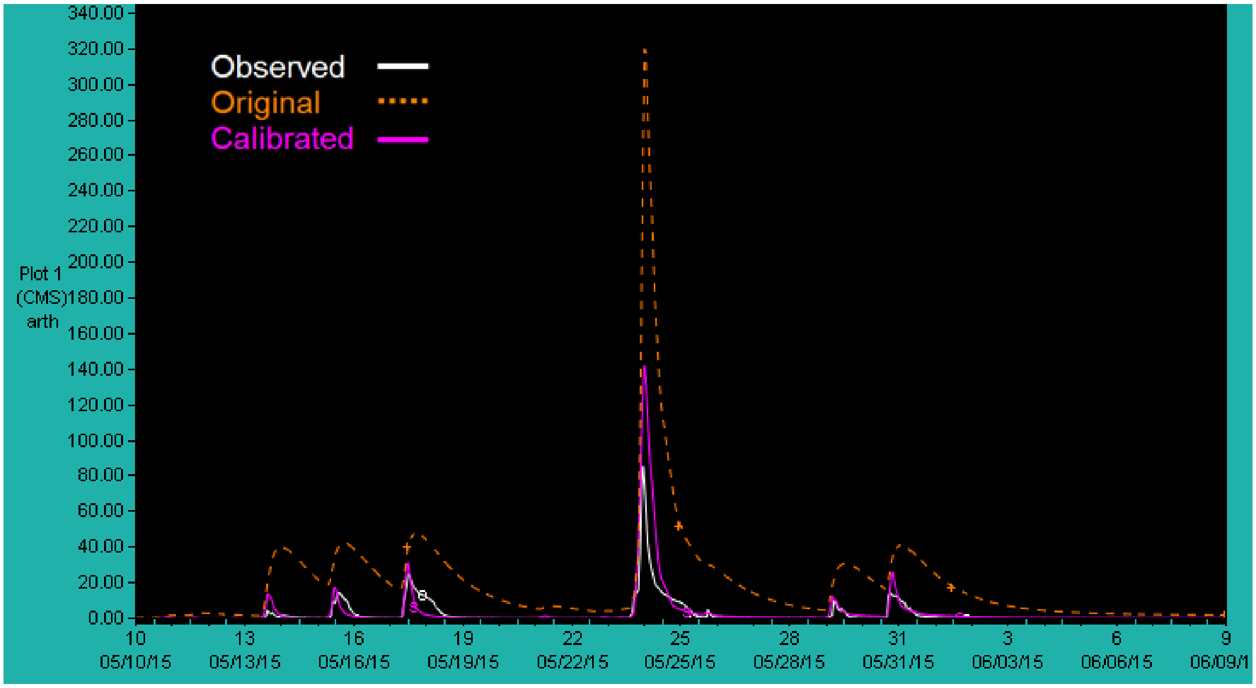
Peakflow data was used to further evaluate calibration results for flood events. These statistics (see Table 141) are based on the observed USGS instantaneous peakflow values reported. For all three events, there were no calculated timing errors and the most recent peak was simulated within 2% of the observed value. It is suspected that there are issues with the estimated precipitation and/or the observed upstream flows for the peakflow events in 2014 and 2015.

Table 141. SSCT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
214.0	6/25/2014	46.0	6/25/2014	0	-168.0	0.22
183.0	6/17/2015	67.6	6/17/2015	0	-115.0	0.37
215.0	9/26/2016	217.0	9/26/2016	0	2.0	1.01

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 78. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 78. **Sample plot comparing the original versus final calibration simulations for SSCT2**



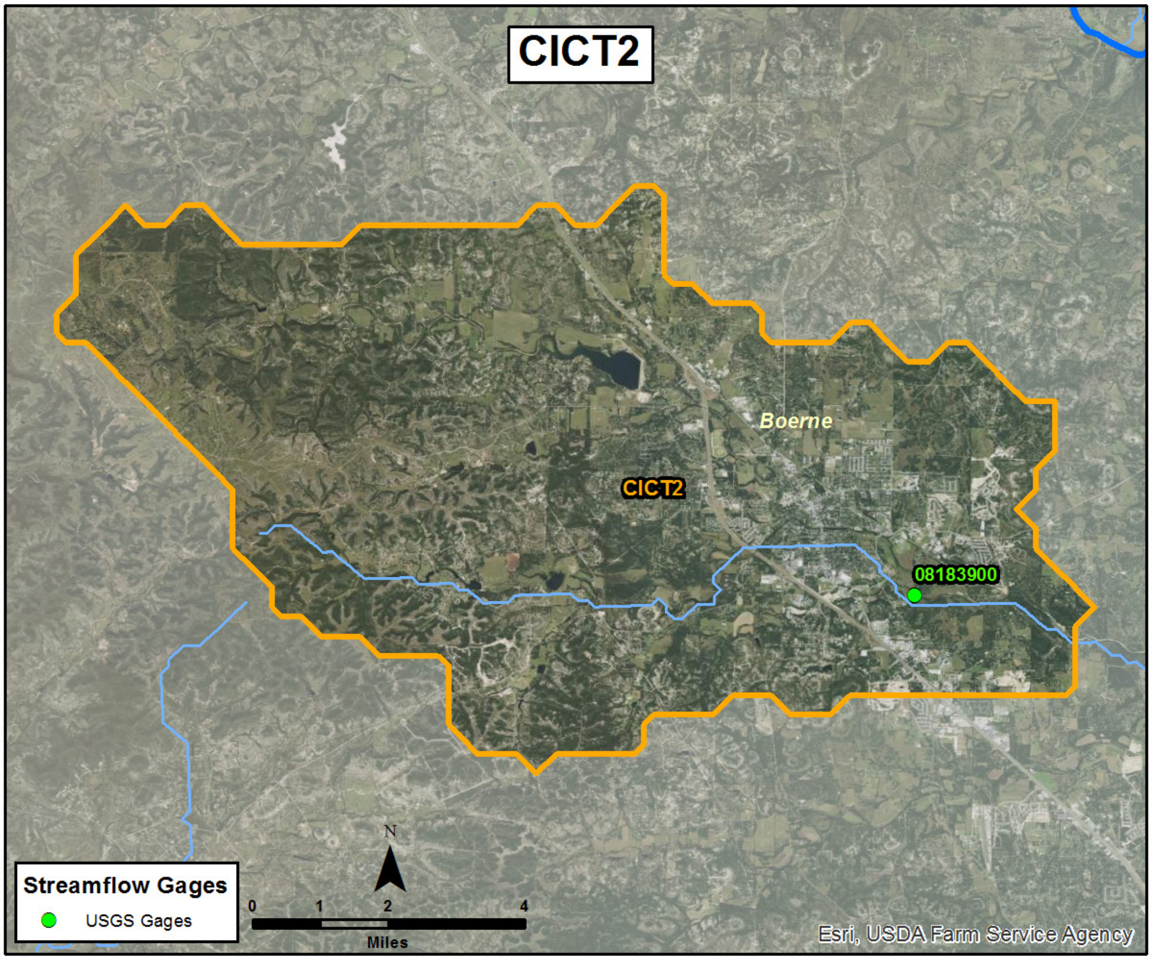
4.6.6 CICT2: Cibolo Creek near Boerne, TX

CICT2 is a rural headwater sub-basin located in the San Antonio River basin that drains approximately 70 mi^2. Residential/commercial development is minimal, with the town of Boerne (population 12,835) contained within the sub-basin boundary. There are many lakes/reservoirs within the basin (e.g. Boerne Lake and Lake Oz). Table 142 summarizes the basin characteristics followed by Figure 79 which presents an aerial map of CICT2.

Table 142. **Basin Characteristics for CICT2**

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
70 / 70	1985 / 1632 / 1302	Edwards Plateau, Eastern Part	Other: 35% Clay: 34% Loam: 22% Minor classes: 9%	A: 1%; B: 11%; C: 13%; D: 75%; W: 0%	Evergreen Forest: 38% Shrub/Scrub: 32% Grassland/Herbaceous: 12% Other: 18%

Figure 79. CICT2 Sub-basin Map



Consistent observed streamflow data are available for USGS gage 08183900 (Cibolo Creek near Boerne, TX) from October 2011 through January 2017. The average observed streamflow over this period is 30 cfs. The typical event peaks within 1.5-3.5 hours, and takes approximately 5-7 hours to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 36,400 cfs in September 1964.

Testing of the existing model parameters from the CHPS-FEWS configuration provided by the WGRFC revealed that the models perform relatively well for the peaks, but the baseflow was under simulating. Therefore, the focus of calibration effort was aimed at improving the baseflow while retaining or possibly enhancing the peakflows.

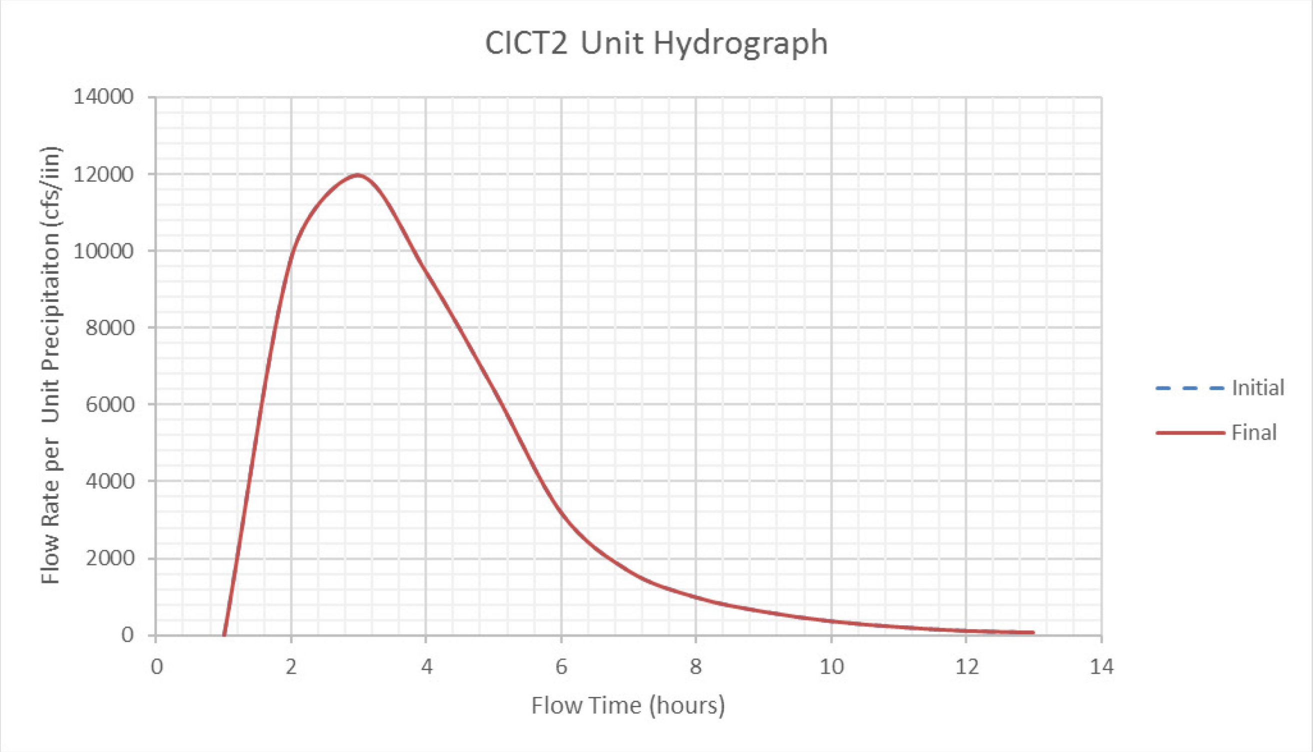
The UZTWM was reduced to from 103 to 50 to avoid over-simulating dry events, while PCTIM and ADIMP were increased to simulate small runoff events during dry seasons. A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 143.

Table 143. Original Versus Calibrated SAC-SMA Parameters for CICT2

Sim.	PXADJ	PEADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE	PBASE
Orig.	1.000	0.900	103	43	0.50	0.000	0.00	0.100	40	2.00	150	30	75	0.050	0.034	0.11	0.3	19.00	4.05
Calib.	1.000	1.000	50	50	0.30	0.025	0.05	0.000	60	1.50	75	30	40	0.100	0.015	0.05	0.3	0.00	3.60

Initial unit hydrograph ordinates were derived from 5 historical events, as described in Appendix B. The ordinates were not changed during calibration with the SAC-SMA as seen in Figure 80.

Figure 80. CICT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set shows significant improvements when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations are presented in Table 144.

Table 144. CICT2 Original Versus Calibrated Simulation Statistics (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	151.2	226.6	0.9	2.3	9.4	12.9	10.3	5.7	837.3	7.6	0.821	0.3	0.6	-0.45	0.60
Calib.	4.1	62.9	0.9	0.9	9.4	9.6	10.3	10.1	379.3	3.4	0.934	0.9	0.9	0.04	0.92

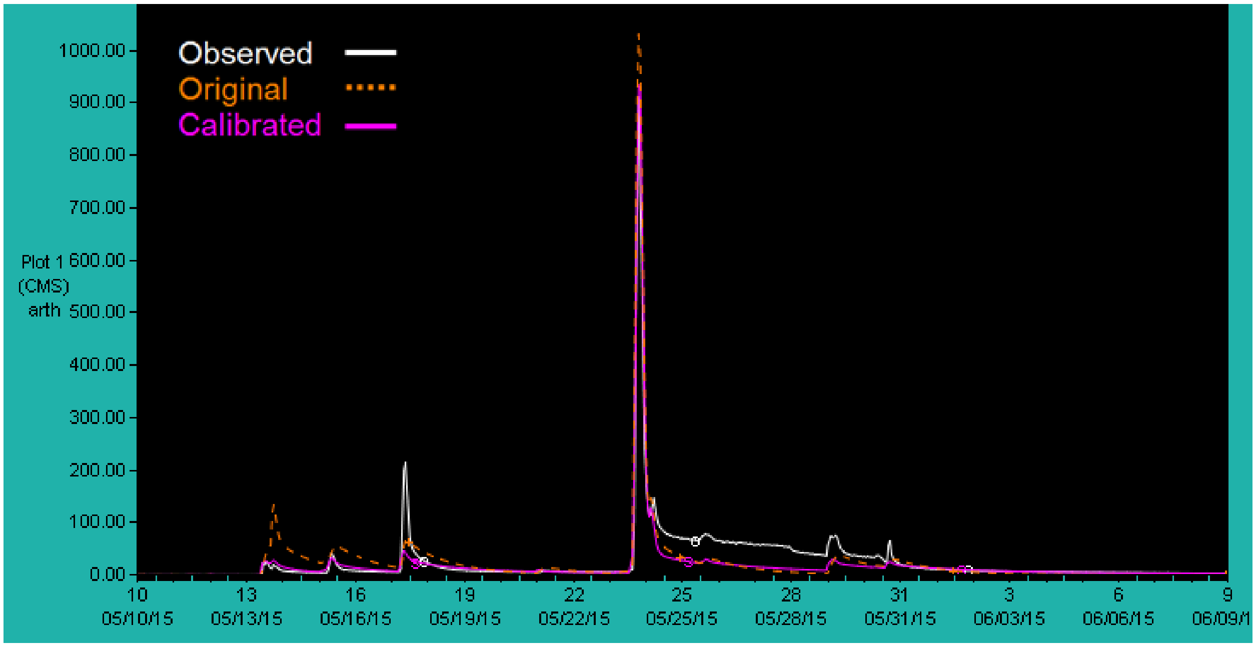
In addition to considering the STAT-Q output, the PEAKFLOW operation was used during the calibration analysis to evaluate model performance for the recent large flood events, as shown in Table 145. The PEAKFLOW operation uses observed instantaneous peak streamflow values as reported by the USGS. There were four peakflow events reported for gage 08183900. Two of these events were not large enough to include in the context of flood simulation and the third was the May 2013 event, where the MAPX data is believed to be underestimating the precipitation in the region. The May 2015 in Table 145 shows no timing error and a 2% difference between peak magnitudes.

Table 145. CICT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
912.0	5/23/2015	933.0	5/23/2015	0	21.0	1.02

A sample plot from ICP of the final calibration compared with the original model simulation is provided in Figure 81. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 81. Sample Plot Comparing the Original Versus Final Calibration Simulations for CICT2



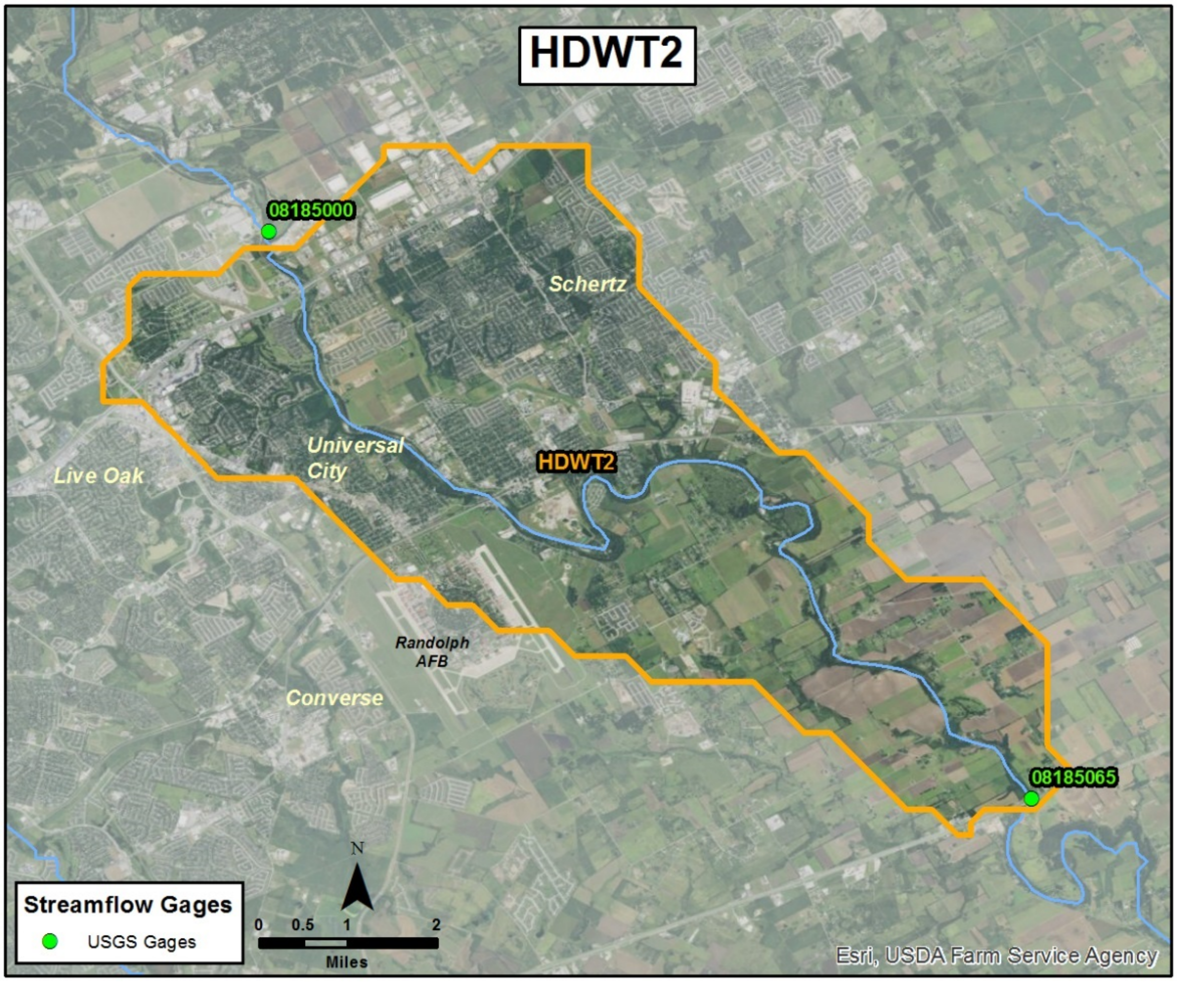
4.6.7 HDWT2: Cibolo Creek near Saint Hedwig, TX

HDWT2 is a suburban/rural local sub-basin located roughly 14 miles northeast of San Antonio proper, straddling Bexar and Guadalupe counties, that drain approximately 32 mi^2 locally and 308 mi^2 total. Portions of Selma, Universal City, Cibolo, Schertz, and Randolph Air Force Base are all contained within the sub-basin boundary. Table 146 summarizes the basin characteristics followed by Figure 82 which presents an aerial map of CICT2.

Table 146. Basin Characteristics for HDWT2

Local/Total Basin Area (mi²)	Elevation (ft) max/mean/min	Major Land Resource Area(s)	Soil Texture	Soil Hydraulic Groups	Predominant Land Cover (NLCD 2011)
32 / 308	899 / 734 / 607	Texas Blackland Prairie, Northern Part	Clay: 97% Minor classes: 3%	A: 0%; B: 26%; C: 14%; D: 60%; W: 0%	Developed, Open Space: 19% Cultivated Crops: 14% Developed, Low Intensity: 14% Developed, Medium Intensity: 14% Shrub/Scrub: 10% Other: 29%

Figure 82. HDWT2 Sub-basin Map



Observed streamflow data are available for USGS Gage 08185065 (Cibolo Creek near Saint Hedwig, TX) from December 2005 through December 2016. The average observed streamflow over this period is 34 cfs. The typical event peaks within half a day, and takes approximately 1-2 days to recede back to baseflow levels. The highest instantaneous flow ever recorded at the gage is 20,100 cfs, which occurred in August 2007.

Runoff response is flashy, as characteristic of an urbanized basin, with steep rising limbs that often peak within 6 hours. High-intensity, short-duration precipitation events seem to result in much quicker receding limbs compared to an average storm. Approximately 70% of soils within HDWT2 fall into hydrologic soil group type D, indicating very low infiltration rates and very high runoff potential. A consistent, albeit low, baseflow is observed throughout the period of record.

Streamflow data seems reasonably accurate with the exception of three large runoff events on 10/31/13, 5/24/15, and 10/31/15 that plateau where a large peak is expected, but then recede as normal. The largest events from year to year are normally in May/June and October/November with moderate or no activity in other seasons.

Before investigating SAC-SMA and UNIT-HG model parameters, Lag/K routing was performed for upstream basin SELT2. Table 147 compares the pre-existing Lag-Q and K-Q pairs with the final calibrated Lag-Q and K-Q pairs.

Table 147. Lag/Q and K/Q Pairs for Routing Reach SELT2 to HDWT2 (All Lag and K in Hours and All Q in cfs)

	Sim.	**Lag1**	**Q1**	**Lag2**	**Q2**	**Lag3**	**Q3**	**Lag4**	**Q4**	**Lag5**	**Q5**	**Lag6**	**Q6**
Lag	Orig.	6	1	6	12000	4	23000	9	53000	12	500000	9	999999
	Calib.	6	700	5	8000	3	16000	-	-	-	--	-	-
	Sim.	**K1**	**Q1**	**K2**	**Q2**	**K3**	**Q3**	**K4**	**Q4**	**K5**	**Q5**	**K6**	**Q6**
K	Orig.	3	1	6	9000	9	16000	12	28000	18	999999	-	-
	Calib.	1	700	5	8000	1	16000	-	-	-	--	-	-

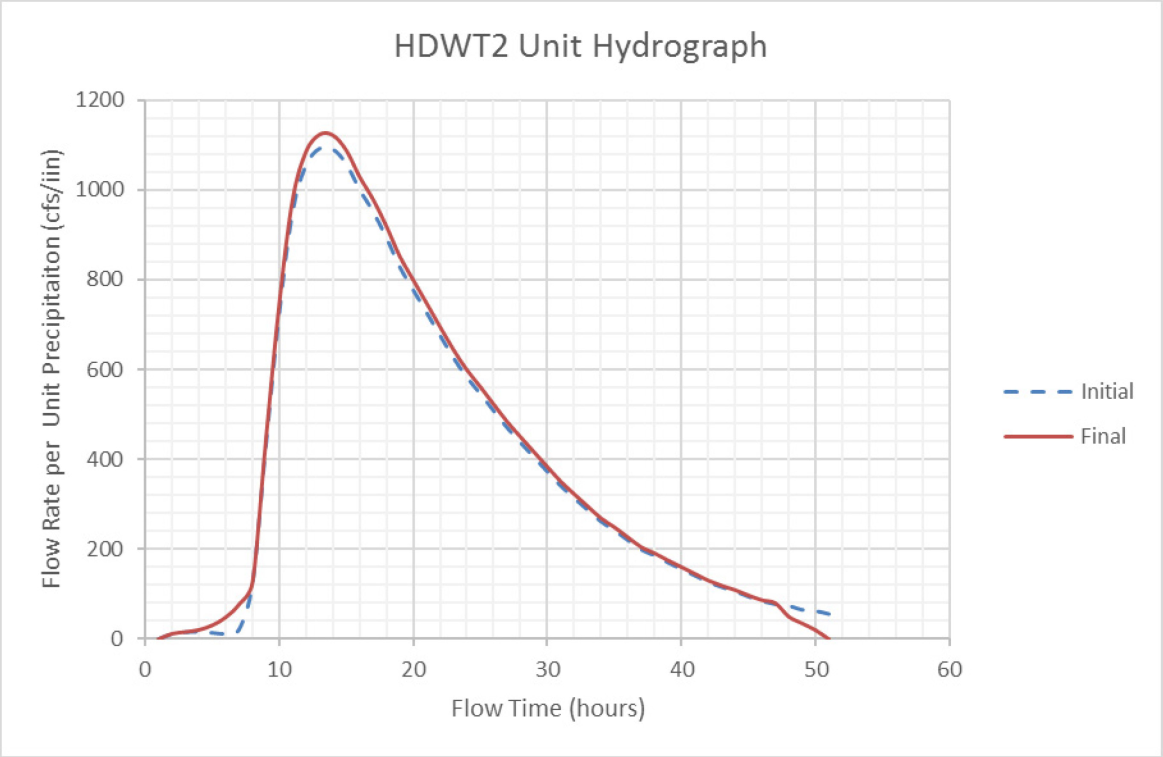
Testing of the existing model parameters from the CHPS-FEWS configuration provided by the WGRFC revealed that the models tended to under simulate baseflow and all but the largest events. In addition, peaks tended to be early, even for a basin with relatively high impervious proportions. The focus of early calibration efforts was aimed at predicting reasonable baseflow which facilitated the determination of the remaining parameters controlling runoff events. Over the course of the calibration effort, the most sensitive SAC-SMA parameters were found to be those controlling the upper zone, namely UZTWM, UZFWM, and UZK. A SIDE value of 0.15 was specified to account for local runoff losses, possibly related to karst formations. A summary of the SAC-SMA parameter changes from the calibration analysis are provided in Table 148.

Table 148. Original Versus Calibrated SAC-SMA Parameters for HDWT2

Sim.	**PXADJ**	**PEADJ**	**UZTWM**	**UZFWM**	**UZK**	**PCTIM**	**ADIMP**	**RIVA**	**ZPERC**	**REXP**	**LZTWM**	**LZFSM**	**LZFPM**	**LZSK**	**LZPK**	**PFREE**	**RSERV**	**SIDE**	**PBASE**
Orig.	1.000	0.950	103	43	0.50	0.000	0.00	0.100	40	2.00	150	30	75	0.050	0.034	0.11	0.3	19.00	4.05
Calib.	1.000	1.000	35	10	0.45	0.05	0.15	0.010	220	2.80	80	40	300	0.080	0.002	0.50	0.3	0.15	3.80

The ordinates for the initial UNIT HG were based on five historical events, as described in Appendix B. Figure 83 demonstrates the final adjustments made to the UNIT HG during calibration using both manual and optimizer techniques.

Figure 83. HDWT2 Initial and Final Calibrated UNIT HG



The final calibrated parameter set is a modest improvement when compared to the existing parameters extracted from the WGRFC operational system. A summary of statistical differences of the original versus calibrated simulations for local and total flows are presented in Tables 149 and 150, respectively. These demonstrate a small increase in R but much improved total percent biases. Locally, a large negative bias is seen but can mostly be explained by the incorrect gage readings during certain flood events.

Table 149. HDWT2 Original Versus Calibrated Simulation Statistics for Local Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	8.8	129.0	1.0	1.1	6.9	3.7	7.1	3.5	635.3	6.2	0.450	0.2	0.2	0.09	0.83
Calib.	-51.0	72.0	1.0	0.5	6.9	2.1	7.1	4.3	632.6	6.1	0.492	0.2	0.1	0.19	1.64

Table 150. HDWT2 Original Versus Calibrated Simulation Statistics for Total Flow (Reported from STAT-Q)

Sim.	% Bias	Abs. % Bias	Obs. Qmean CMS	Sim. Qmean 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
Orig.	63.5	123.2	1.0	1.6	6.9	9.9	7.1	6.2	572.4	5.6	0.843	0.3	0.6	0.04	0.59
Calib.	3.2	47.7	1.0	1.0	6.9	9.4	7.1	9.4	487.3	4.7	0.876	0.5	0.6	0.33	0.64

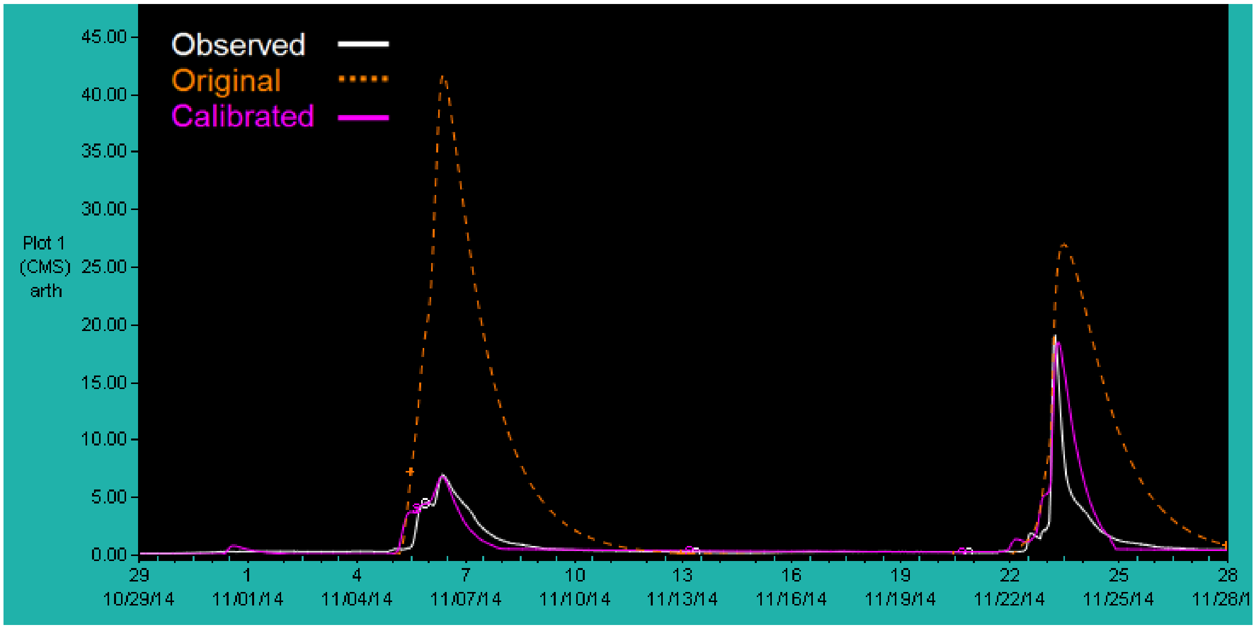
In addition to STAT-Q, peakflow data were used to evaluate timing and magnitude of results for flood events as summarized in Table 151. As mentioned previously, the apparent over-simulation of the floods on 10/31/13 and 5/24/15 can be explained by the questionable gage readings obtained during those events. With this taken into consideration, the remaining two events are within 2 and 3 percent of the observed peakflow values.

Table 151. HDWT2 Final Calibrated Peakflow Results (Observed Peaks Reported by USGS)

Observed Peak		Simulated Peak		Timing Error (Days)	Discharge Error (CMS)	Discharge Ratio (Sim/Obs)
Q (CMS)	Date	Q (CMS)	Date			
197.0	5/25/2013	200.0	5/25/2013	0	3.0	1.02
201.0	10/31/2013	255.0	10/31/2013	0	54.0	1.27
231.0	5/24/2015	613.0	5/24/2015	0	382.0	2.65
265.0	5/20/2016	272.0	5/20/2016	0	7.0	1.03

A sample plot from ICP of the final calibration compared with the original model simulation is provided Figure 84. Overall, the final calibrated models should provide improved predictive performance over those in the current forecast system.

Figure 84. **Sample Plot Comparing the Original Versus Final Calibration Simulations for HDWT2**



5. CONCLUSIONS

During this study, RTI completed several tasks in support of TWDB's effort to improve flood forecasting for 23 sub-basins in Central Texas. 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 2011 – 2016 was selected. 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) and LOOKUP operations and through use of the SIDE parameter within the SAC-SMA model. 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.

Water balance results revealed there are potential observed streamflow volume issues in three sub-basins (CRUT2, FPCT2, and GWCT2) in the Colorado River basin and one sub-basin (HDWT2) in the San Antonio. These issues, however, did not inhibit the calibration of the models to the observed peaks. Irrigation diversion data from the Lower Colorado River Authority (LCRA), as well as karst maps and other data on flood control structures and water operations in the study area, helped to parameterize the diversion and gain/loss modeling.

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 to evaluate how well the models replicate the highest yearly instantaneous streamflow at USGS stream gage locations. Within the Colorado River basin, the average peak flow simulation bias for the major flood events within the calibration period ranged from -19% to 20%. For the sub-basins within Guadalupe River basin, the model simulations produced an average peak flow bias of -10%, and for the sub-basins within the San Antonio River basin, the model simulations resulted in an average peak flow bias ranging from -55% to 49% (omitting two events with potentially underestimated precipitation or upstream flows for SSCT2). Comparing the simulations to the hourly observations over the calibration period yields total flow correlation values of 0.503 to 0.999 and volume bias values of -13% to 15% (omitting headwater sub-basin SDBT2). 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 should also be significantly improved with fully calibrated model parameters as well as the accounting for volume gains and losses within the sub-basins. Finally, the results for this study provide the WGRFC with models for newly established forecast points, allowing for more accurate information at more locations.

6. ACKNOWLEDGMENTS

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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
Colorado Basins																	
DRWT2	PRISM	34.79	39.45	45.01	22.73	51.48	19.75	23.44	49.02	14.01	35.39	36.75	17.20	30.53	40.40	28.17	52.71
	MAPX	28.15	32.01	44.3	19.25	49.81	17.96	21.66	46.99	13.63	30.37	34.43	15.84	28.47	40.09	31.43	55.52
	% Diff	-19%	-19%	-2%	-15%	-3%	-9%	-8%	-4%	-3%	-14%	-6%	-8%	-7%	-1%	12%	5%
ONIT2	PRISM	35.27	40.53	45.03	22.80	50.04	21.77	24.55	44.91	17.63	35.16	36.39	19.52	35.61	48.32	35.06	59.99
	MAPX	33.45	37.5	40.11	17.72	46.68	19.62	23.95	43.81	17.11	29.01	34.52	18.49	31.68	46.65	36.94	57.65
	% Diff	-5%	-7%	-11%	-22%	-7%	-10%	-2%	-2%	-3%	-17%	-5%	-5%	-11%	-3%	5%	-4%
BDUT2	PRISM	35.15	39.77	43.22	21.97	48.82	20.88	25.28	46.08	18.07	36.28	39.07	19.30	33.89	48.16	35.07	56.90
	MAPX	28.52	39.24	42.35	19.39	44.97	19.1	24.62	47.64	18.33	31.11	33.43	17.8	35.37	49.63	40.3	63.06
	% Diff	-19%	-1%	-2%	-12%	-8%	-9%	-3%	3%	1%	-14%	-14%	-8%	4%	3%	15%	11%
ATIT2	PRISM	34.69	40.88	40.43	22.69	47.69	21.32	26.34	50.81	17.39	35.57	36.18	18.11	36.60	45.10	36.09	58.51
	MAPX	28.33	36.8	37.03	17.91	45.31	18.82	25.84	47.79	16.96	30.96	35.65	17.03	34.44	48.48	40.47	62.51
	% Diff	-18%	-10%	-8%	-21%	-5%	-12%	-2%	-6%	-2%	-13%	-1%	-6%	-6%	7%	12%	7%
CRWT2	PRISM	34.31	42.40	38.63	23.87	47.53	21.09	28.51	45.91	15.28	32.01	30.37	17.84	35.26	39.68	31.75	58.42
	MAPX	26.63	37.18	38.61	20.37	44.53	19.68	27.18	42.34	15.11	28.8	30.99	16.4	35.41	39.99	36.4	63.94
	% Diff	-22%	-12%	0%	-15%	-6%	-7%	-5%	-8%	-1%	-10%	2%	-8%	0%	1%	15%	9%
CRUT2	PRISM	34.77	42.15	40.17	24.38	46.82	23.24	30.42	48.87	14.61	32.57	29.16	17.97	37.33	35.69	29.57	56.15
	MAPX	25.39	34.46	37.08	20.17	41.84	20.79	28.64	45.16	14.09	29.25	29.3	15.96	36.51	36.17	32.93	59.46
	% Diff	-27%	-18%	-8%	-17%	-11%	-11%	-6%	-8%	-4%	-10%	0%	-11%	-2%	1%	11%	6%
BRTT2	PRISM	35.35	42.83	42.78	27.92	46.65	24.81	32.75	50.77	15.33	33.14	29.99	19.13	34.33	32.47	31.26	56.25
	MAPX	27.87	36.67	40.86	25.13	42.07	23.08	29.52	45.55	14.61	29.24	30.45	17.03	33.57	32.59	34.06	59.57
	% Diff	-21%	-14%	-4%	-10%	-10%	-7%	-10%	-10%	-5%	-12%	2%	-11%	-2%	0%	9%	6%
CKBT2	PRISM	34.95	41.55	40.79	23.68	45.39	24.70	30.29	51.44	14.57	33.07	29.83	18.67	38.23	39.18	29.21	53.84
	MAPX	25.21	30.74	36.58	19.83	39.4	20.71	29.4	48.34	13.74	29.28	28.45	16.55	36.33	39.47	31.84	57.2
	% Diff	-28%	-26%	-10%	-16%	-13%	-16%	-3%	-6%	-6%	-11%	-5%	-11%	-5%	1%	9%	6%
WURT2	PRISM	35.06	41.33	41.78	24.43	43.48	25.08	30.66	52.21	14.67	34.82	29.39	18.32	36.65	35.50	27.64	52.04
	MAPX	27.96	29.24	37.34	20.01	37.57	20.81	27.5	48.05	13	29.77	27.28	15.28	33.3	35.98	29.46	54.66
	% Diff	-20%	-29%	-11%	-18%	-14%	-17%	-10%	-8%	-11%	-15%	-7%	-17%	-9%	1%	7%	5%
FPCT2	PRISM	39.11	42.36	50.81	34.78	53.94	27.86	30.33	58.02	23.24	40.73	32.62	17.19	36.75	31.86	34.42	59.14
	MAPX	37.31	43.8	51.94	34.57	51.05	24.22	26.8	52.78	21.6	36.92	33.44	15.41	35.98	31.45	36.89	61.57
	% Diff	-5%	3%	2%	-1%	-5%	-13%	-12%	-9%	-7%	-9%	3%	-10%	-2%	-1%	7%	4%

Basin	Data	Year															
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
ACLT2	PRISM	43.34	47.33	54.08	41.13	59.59	39.32	36.11	60.43	21.24	37.24	34.32	17.00	42.23	37.66	42.49	65.83
	MAPX	48.6	48.26	51.29	36.77	55.26	38.11	33.75	54.81	20.26	36.42	34.53	14.76	39.53	38.4	43.12	65.92
	% Diff	12%	2%	-5%	-11%	-7%	-3%	-7%	-9%	-5%	-2%	1%	-13%	-6%	2%	1%	0%
GWCT2	PRISM	42.48	47.26	56.11	40.67	60.65	38.34	36.97	61.79	21.27	38.58	35.34	18.28	37.78	36.74	42.24	65.56
	MAPX	49.99	51.51	57.12	37.36	57.01	36.05	33.83	57.45	20.9	37.77	34.99	16.02	35.69	37.35	43.35	66.93
	% Diff	18%	9%	2%	-8%	-6%	-6%	-8%	-7%	-2%	-2%	-1%	-12%	-6%	2%	3%	2%
CDOT2	PRISM	46.62	51.33	64.30	48.99	72.69	41.66	43.68	59.07	34.50	38.26	43.78	18.72	44.17	35.68	38.07	62.03
	MAPX	45.97	60.17	65.88	53.17	68.04	40.48	39.76	52.57	33.8	39.84	43.91	15.72	40.55	35.14	43.93	70.47
	% Diff	-1%	17%	2%	9%	-6%	-3%	-9%	-11%	-2%	4%	0%	-16%	-8%	-2%	15%	14%
Guadalupe Basins																	
GRTT2	PRISM	35.42	39.07	53.14	28.90	55.13	24.83	24.70	51.62	16.89	37.73	42.90	20.39	34.39	38.99	27.38	57.47
	MAPX	33.36	33.79	49.25	25.22	46.3	20.03	20.94	45.03	13.29	28.55	38.98	16.83	27.6	37.17	27.78	56.02
	% Diff	-6%	-14%	-7%	-13%	-16%	-19%	-15%	-13%	-21%	-24%	-9%	-17%	-20%	-5%	1%	-3%
SEGT2	PRISM	33.73	35.78	59.11	27.99	54.44	21.32	19.35	45.95	15.75	31.97	33.00	19.22	32.49	29.36	24.65	42.26
	MAPX	38.1	36.41	61.85	26.51	44.99	16.49	16.93	39.7	11.68	23.92	29.02	13.43	25.64	31.09	27.98	42.67
	% Diff	13%	2%	5%	-5%	-17%	-23%	-12%	-14%	-26%	-25%	-12%	-30%	-21%	6%	14%	1%
SGGT2	PRISM	33.67	35.69	57.56	26.47	52.45	21.41	20.10	45.15	15.25	31.60	33.26	19.03	31.58	30.28	25.47	43.76
	MAPX	38.08	36.85	56.12	24.19	43.62	17.05	16.86	39.29	12.15	25.37	29.66	14	26.43	32.04	29.3	45.17
	% Diff	13%	3%	-2%	-9%	-17%	-20%	-16%	-13%	-20%	-20%	-11%	-26%	-16%	6%	15%	3%
San Antonio Basins																	
CICT2	RIS	35.97	42.40	62.12	29.43	57.89	25.68	22.68	56.48	13.48	30.54	39.61	16.30	30.93	29.45	29.06	51.33
	AP	32.39	35.43	61.37	24.41	50.51	20.3	19.24	49.39	10.75	24.64	32.13	12.87	26.52	26.57	27.22	50.3
	% Diff	-10%	-16%	-1%	-17%	-13%	-21%	-15%	-13%	-20%	-19%	-19%	-21%	-14%	-10%	-6%	-2%
MMDT2	PRISM	31.13	33.05	54.74	28.03	51.11	19.54	16.44	57.08	18.05	27.26	35.87	16.03	29.10	26.20	24.36	41.49
	MAPX	32.52	30.72	60.71	25.29	42.53	15.57	14.4	49.91	15.23	22.97	31.2	12.34	27.76	25.09	24.35	41.83
	% Diff	4%	-7%	11%	-10%	-17%	-20%	-12%	-13%	-16%	-16%	-13%	-23%	-5%	-4%	0%	1%
SDBT2	PRISM	34.01	41.63	55.48	25.51	52.28	23.81	19.51	56.85	14.33	33.14	38.01	18.43	33.13	33.21	28.39	50.36
	MAPX	33.31	39.73	58.11	23.08	45.83	18.72	18.51	51.46	12.48	29.4	35.82	15.47	30.74	31.88	30.17	51.7
	% Diff	-2%	-5%	5%	-10%	-12%	-21%	-5%	-9%	-13%	-11%	-6%	-16%	-7%	-4%	6%	3%
MTST2	PRISM	32.25	37.50	51.57	28.82	47.91	21.00	19.50	52.53	14.32	31.00	37.46	17.94	38.33	32.62	29.67	46.42
	MAPX	37.79	37.46	55.15	25.37	42.36	17.15	19.73	49.58	12.26	27.33	35.35	15.5	37.43	33.9	30.83	48.57
	% Diff	17%	0%	7%	-12%	-12%	-18%	1%	-6%	-14%	-12%	-6%	-14%	-2%	4%	4%	5%
SSCT2	PRISM	33.48	40.52	50.96	29.46	49.03	22.16	19.92	49.92	14.55	33.79	39.63	17.85	35.85	33.58	30.14	47.75
	MAPX	33.27	39.38	55.36	27.27	42.63	18.14	18.68	45.32	12.94	30.1	39.36	15.79	33.94	31.62	32.64	50.49
	% Diff	-1%	-3%	9%	-7%	-13%	-18%	-6%	-9%	-11%	-11%	-1%	-12%	-5%	-6%	8%	6%

Basin	Data	Year															
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
SNPT2	PRISM	30.96	34.43	53.13	27.30	45.92	20.49	18.48	51.55	13.37	28.48	34.16	16.85	36.48	29.45	27.44	44.81
	MAPX	40.04	33.29	59.66	25.12	40.21	16.17	17.81	49.35	12.69	24.43	30.83	14.03	35.38	30.19	28.49	46.55
	% Diff	29%	-3%	12%	-8%	-12%	-21%	-4%	-4%	-5%	-14%	-10%	-17%	-3%	3%	4%	4%
HDWT2	PRISM	32.24	37.35	51.68	26.66	50.07	22.28	19.14	42.16	17.06	32.29	39.23	17.13	33.93	28.82	26.10	45.91
	MAPX	34.12	38.79	54.37	22.97	44.81	17	17.75	37.15	14.07	27.94	37.01	15.02	29.92	28.01	28.72	48.38
	% Diff	6%	4%	5%	-14%	-11%	-24%	-7%	-12%	-18%	-13%	-6%	-12%	-12%	-3%	10%	5%

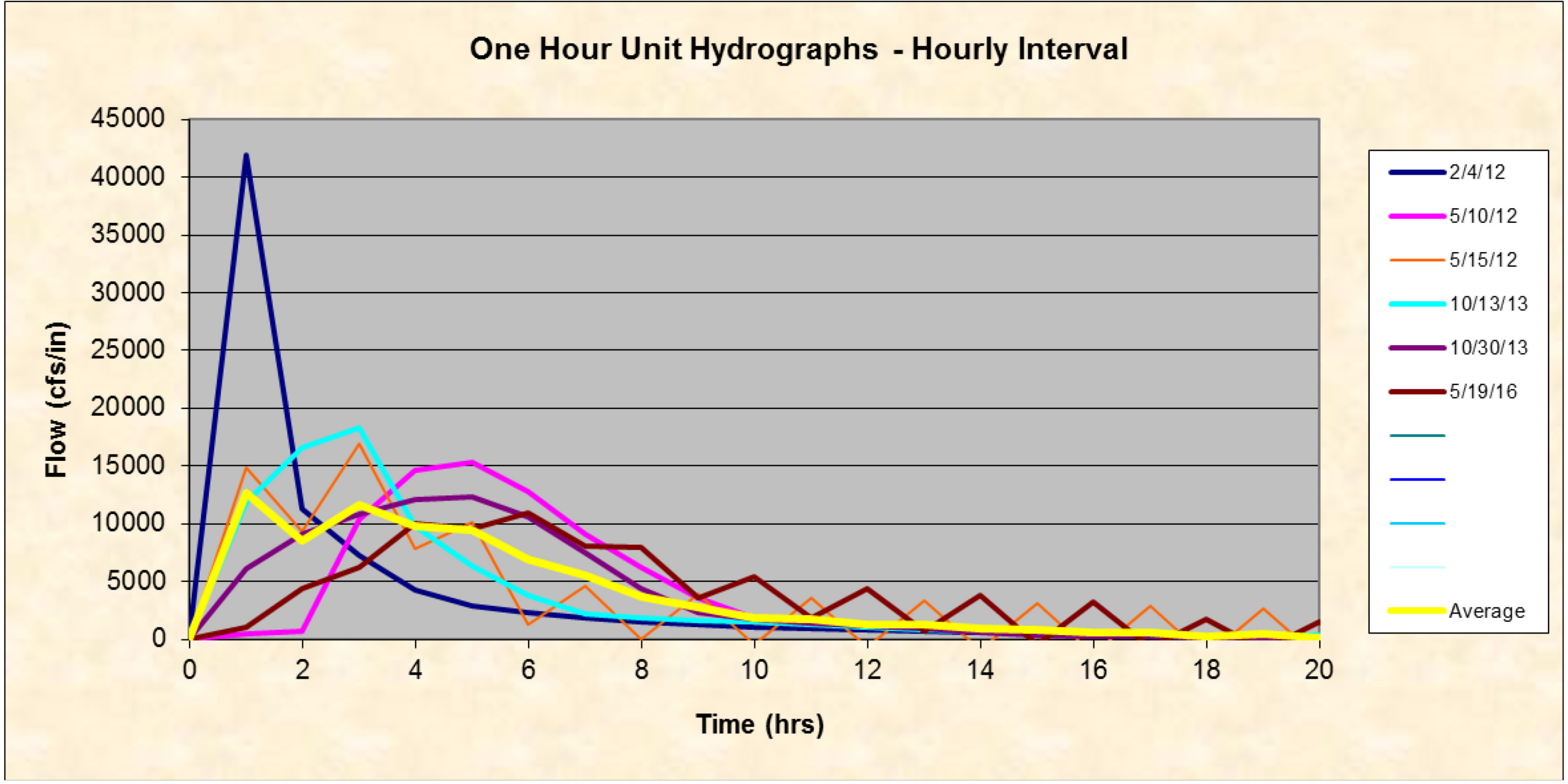
Appendix B:
Unit Hydrograph Analysis

Appendix B presents results of the initial Unit Hydrograph development for each sub-basin. Most of the initial Unit Hydrographs were developed using the manual procedure but a few were derived using the GIS procedure. Both methods are described in Section 4.3. The final calibrated Unit hydrograph ordinates are presented for each sub-basin in Section 5.

Colorado Basin

DRWT2

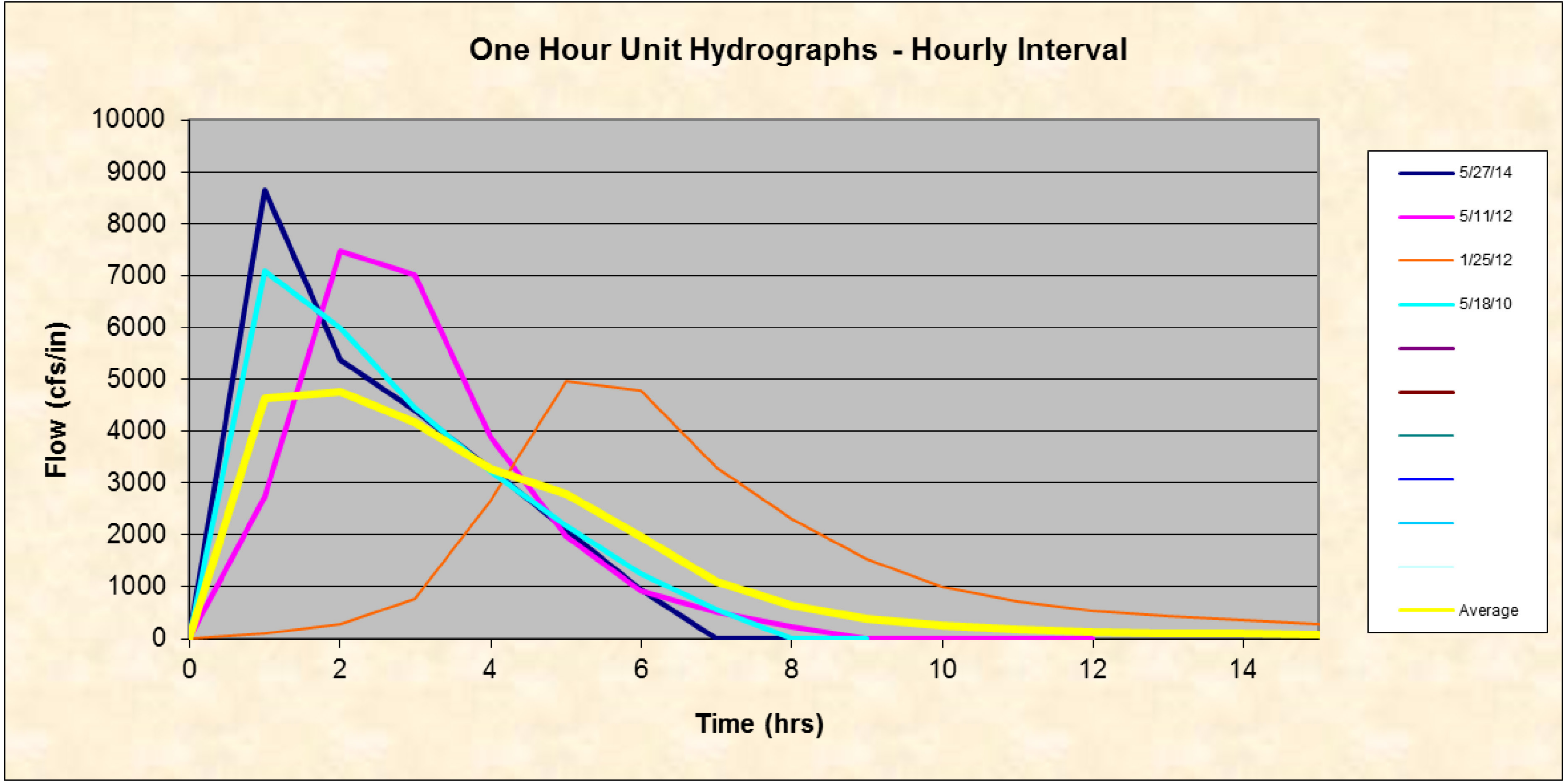
DRWT2 is a headwater with a basin area of 128 mi^2. The largest event is 12,900 cfs. Six events were selected for the analysis which peak at 2,060 cfs, 3,650 cfs, 2,150 cfs, 4,410 cfs, 12,900 cfs and 5,030 cfs. Rainfall durations varied from 1 to 4 hours. The basin exhibited fast, flashy runoff characteristics. An event in October 2013 with peak flow of 12,900 cfs produced a runoff depth of 1 inch in the basin. Hence, the unit hydrograph calculated based on this event was used as the unit hydrograph initially placed into the calibration deck.



DRWT2 unit hydrographs from each event and resulting average unit hydrograph

BDUT2

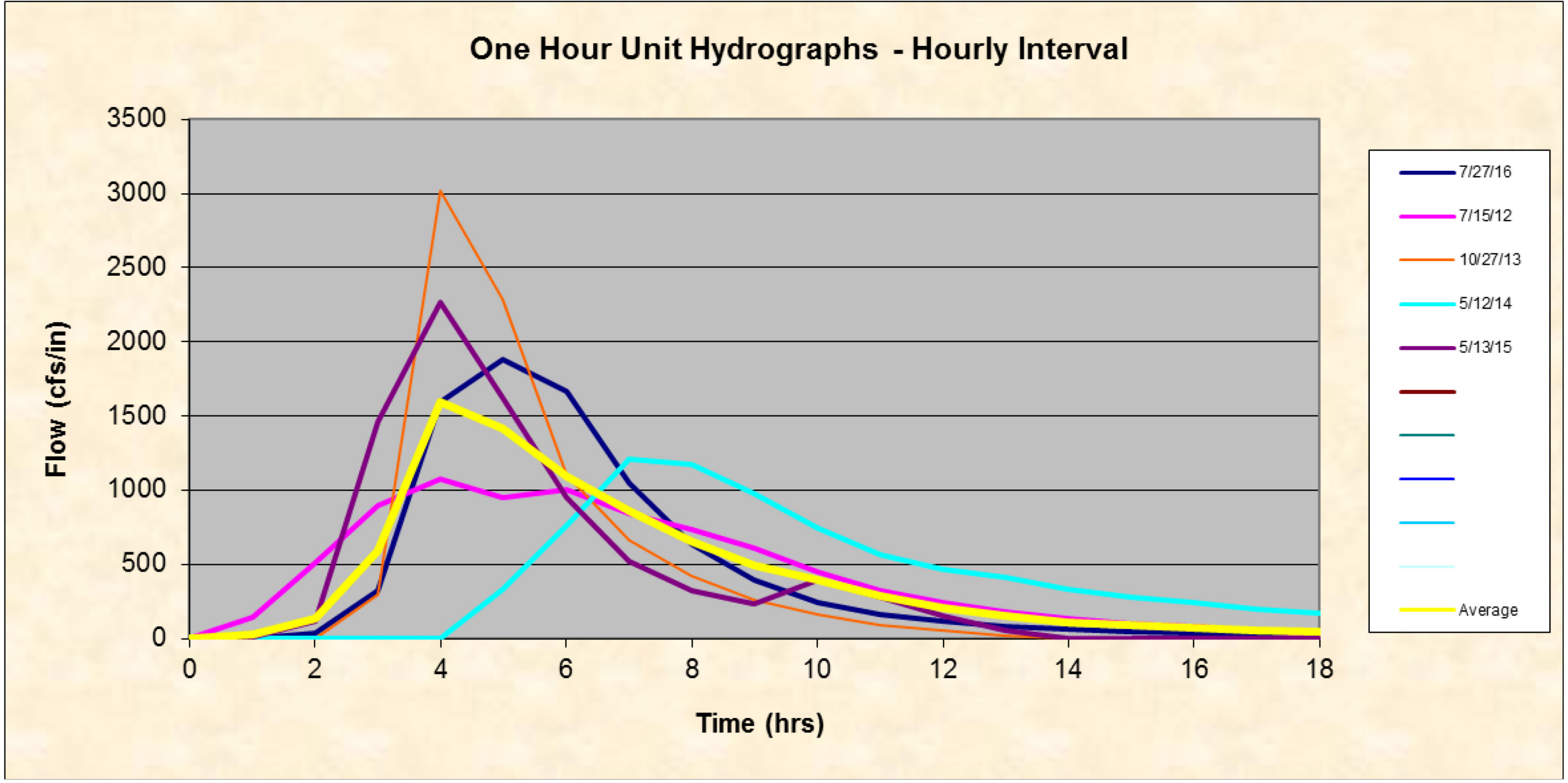
BDUT2's local and total drainage areas are 38 mi^2 and 166 mi^2, respectively. Its largest event on record was 28641 cfs. The four events selected for the analysis peak at roughly 1400, 1600, 2200, and 420 cfs. Rainfall durations varied from 3 to 7 hours for these events. During the baseflow analysis an unrealistically high recession constant was estimated, likely because the true baseflow is not adequately represented in the runoff data after routed flows from upstream were subtracted. Recession constants from the analyses of nearby headwaters were used to obtain a more reasonable estimate. Of the four events, 3 of the derived unit hydrographs seem consistent among each other. The event on 1/25/2012 should was disregarded due to its smaller peak and more gradual rising and receding limbs.



BDUT2 unit hydrographs from each event and resulting average unit hydrograph

ONIT2

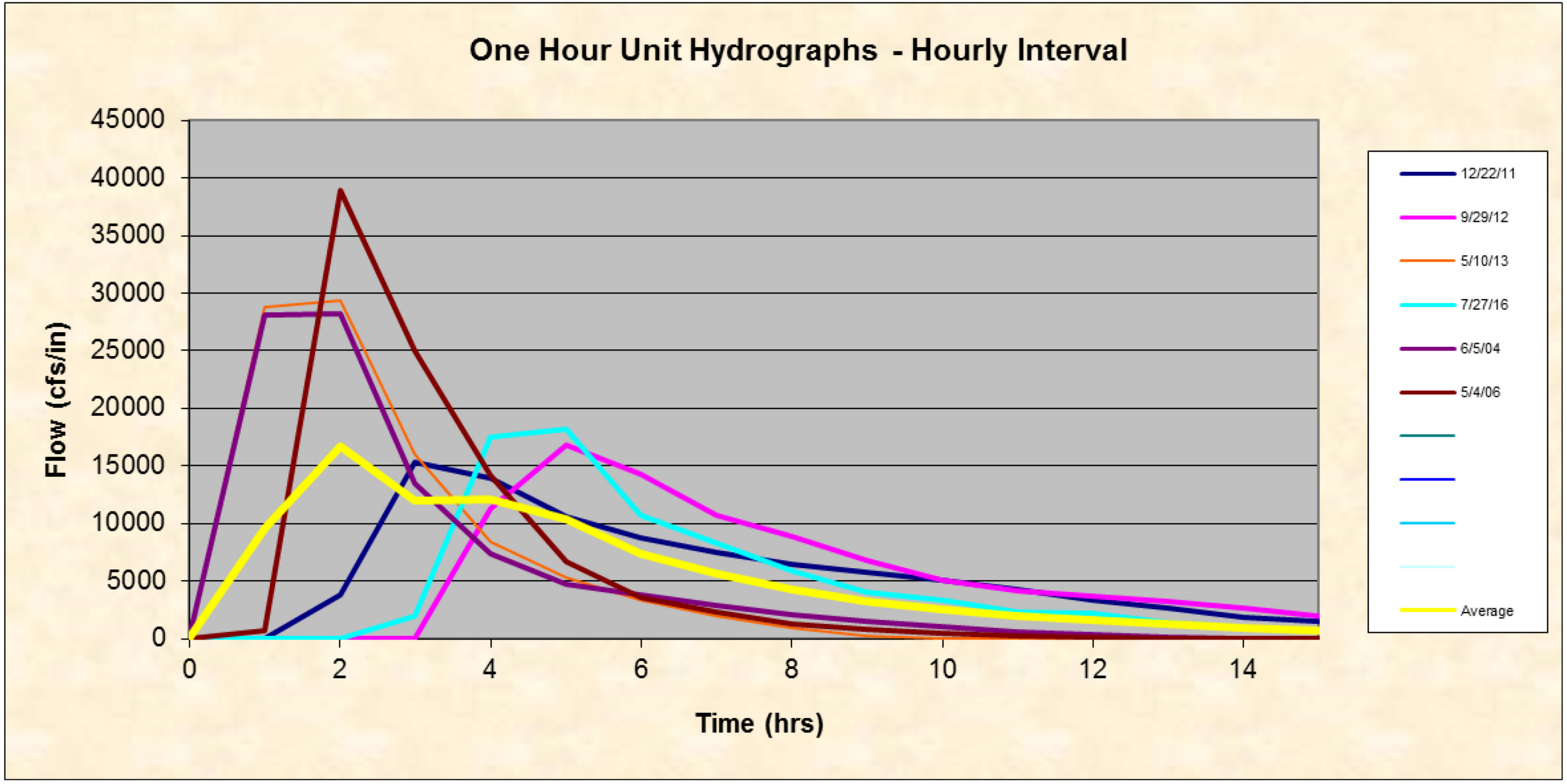
ONIT2's local and total drainage areas are 13 mi^2 and 179 mi^2, respectively. Its largest event on record was 18200 cfs. Five events were selected for the analysis which peak at approximately 930, 1550, 1140, 170, and 520 cfs. Rainfall durations varied from 4 to 8 hours. Resulting unit hydrographs for ONIT2 were mixed. Each of the five events produced varying peak magnitudes and timing. However, three of the events were somewhat similar. The events from 7/15/2012 and 5/12/2014 were not included in the final average hydrograph used for calibration.



ONIT2 unit hydrographs from each event and resulting average unit hydrograph

ATIT2

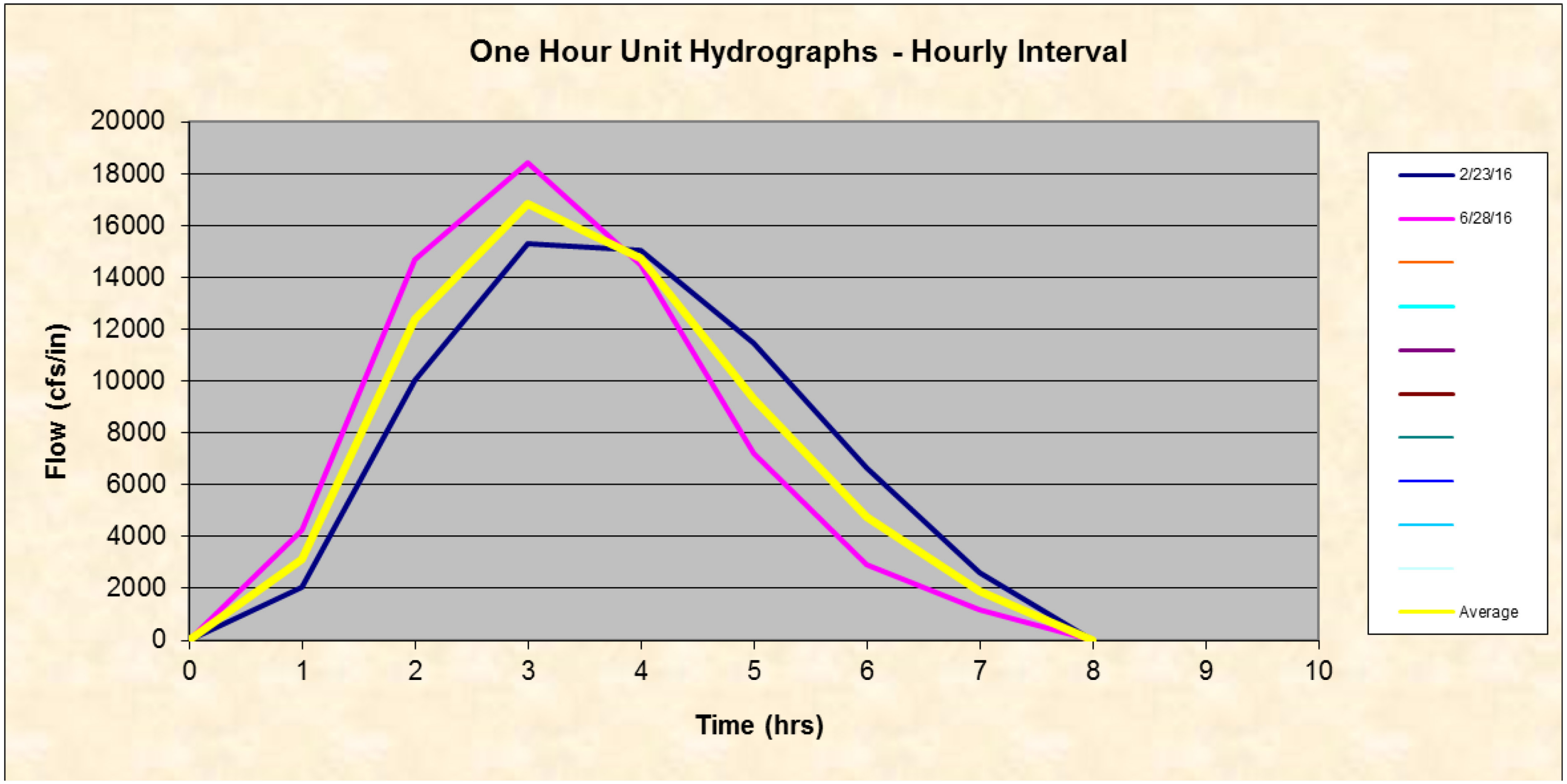
ATIT2's local and total drainage areas are 146 mi^2 and 326 mi^2, respectively. Its largest event on record was 120000 cfs. The six events selected for the analysis peak at about 360, 320, 1060, 2900, 1360, and 1170 cfs. Rainfall durations varied from 3 to 6 hours for these events. The average hydrograph from the six events seems fairly reasonable, but it appeared that the faster-peaking events were more physically realistic. As such only the events on 6/5/2004, 5/10/2013, and 5/4/2006 were used to derive the unit hydrograph entered into the calibration deck.



ATIT2 unit hydrographs from each event and resulting average unit hydrograph

CRWT2

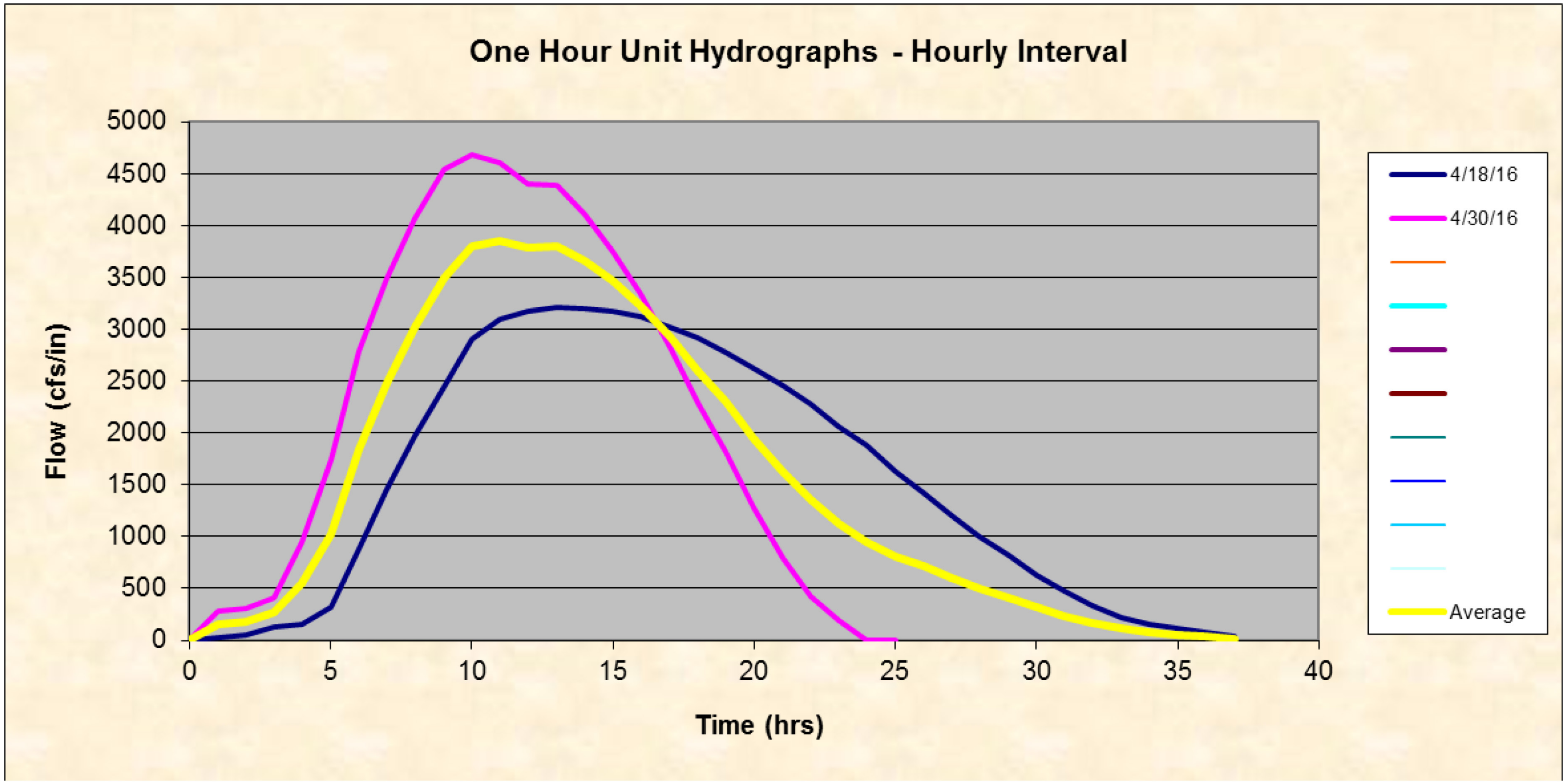
CRWT2’s local and total drainage areas are 98 mi^2 and 37110 mi^2, respectively. Its largest event on record was 30171 cfs. The two events selected for the analysis peak roughly at 630 and 490 cfs. The rainfall duration for these two events were 3 and 4 hours. During the baseflow analysis an unrealistically high recession constant was estimated, likely because the true baseflow is not adequately represented in the runoff data after routed flows from upstream were subtracted. Recession constants from the analyses of nearby headwaters were used to obtain a more reasonable estimate. There is a very small period of record for CRWT2 (about one year) so events with acceptable routing results leading to adequate data quality is scarce. The results from these two events were an adequate starting point for calibration despite lower confidence due to a small sample size.



CRWT2 unit hydrographs from each event and resulting average unit hydrograph

CRUT2

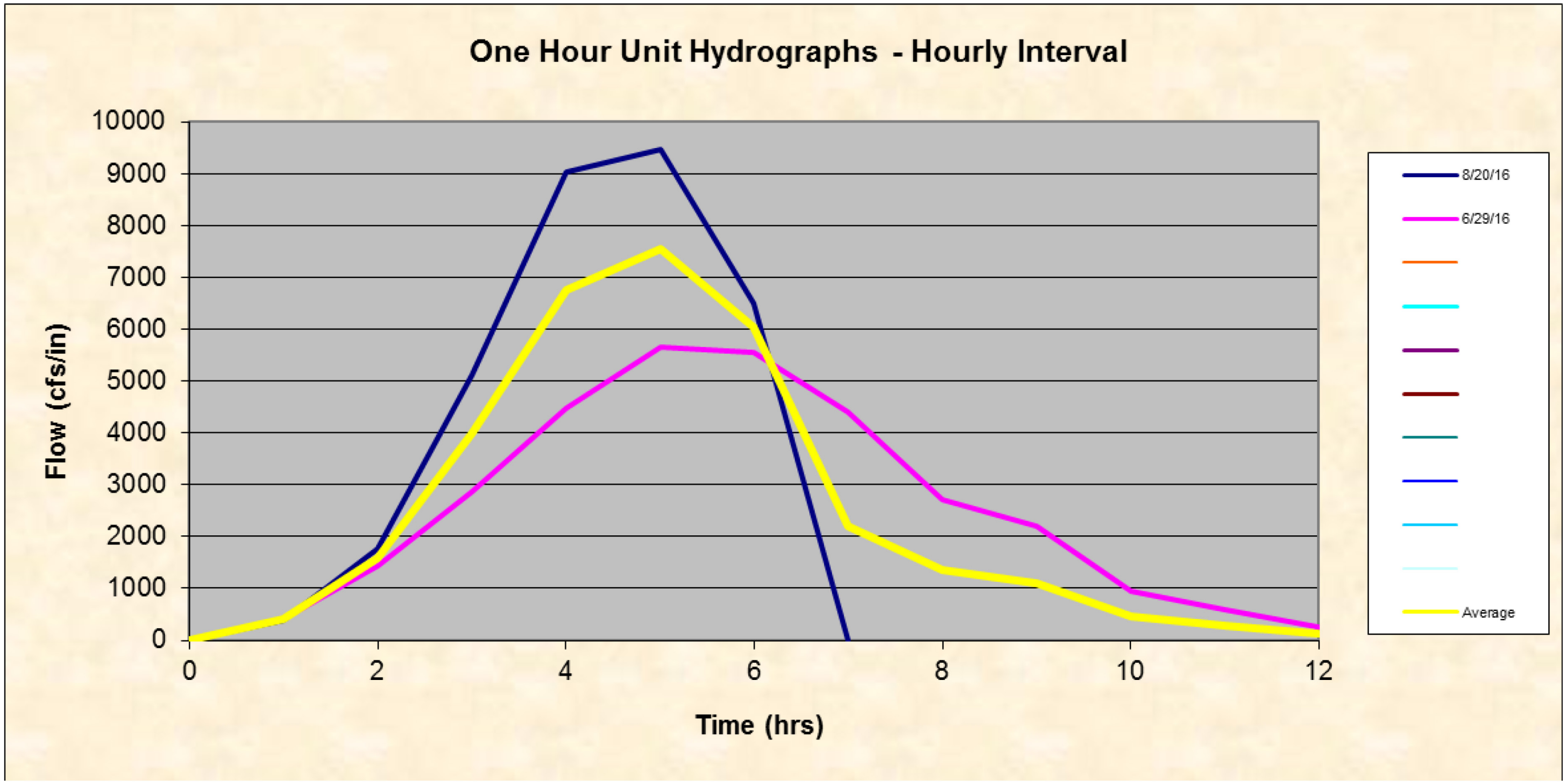
CRUT2's local and total drainage areas are 89 mi^2 and 37199 mi^2, respectively. Its largest event on record was 31925 cfs. Two events were selected for the analysis which peak at about 5000 and 780 cfs. The rainfall duration for these events were 1 and 3 hours. During the baseflow analysis an unrealistically high recession constant was estimated, likely because the true baseflow is not adequately represented in the runoff data after routed flows from upstream were subtracted. Recession constants from the analyses of nearby headwaters were used to obtain a more reasonable estimate. There is a very small period of record for CRWT2 (about one year) so events with acceptable routing results leading to adequate data quality is scarce. The results from these two events were an adequate starting point for calibration despite lower confidence due to a small sample size.



CRUT2 unit hydrographs from each event and resulting average unit hydrograph

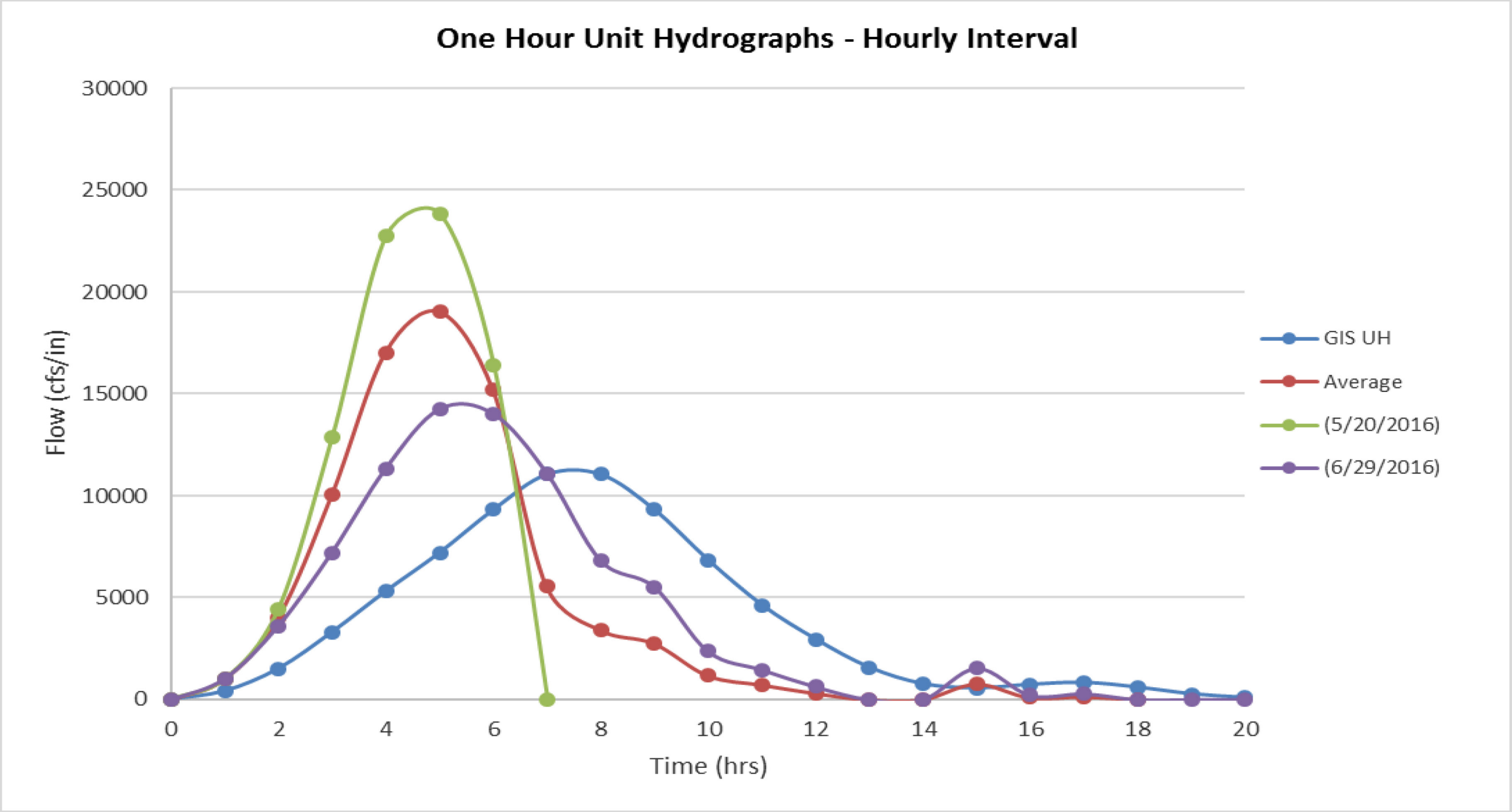
BRTT2

BRTT2's local and total drainage areas are 126 mi^2 and 37551 mi^2, respectively. Its largest event on record was 61600 cfs. Two events were selected for the analysis which peak at about 2470 and 460 cfs. The rainfall lasted 2 and 3 hours for these events. There is a very small period of record for CRUT2 (less one year) so events with acceptable routing results leading to adequate data quality is scarce. The two unit hydrographs derived from this analysis were mediocre. Besides the small sample size they are inconsistent with each other. For this reason GeoTool was also employed for a better estimate of the unit hydrograph in this basin.



BRTT2 unit hydrographs from each event and resulting average unit hydrograph

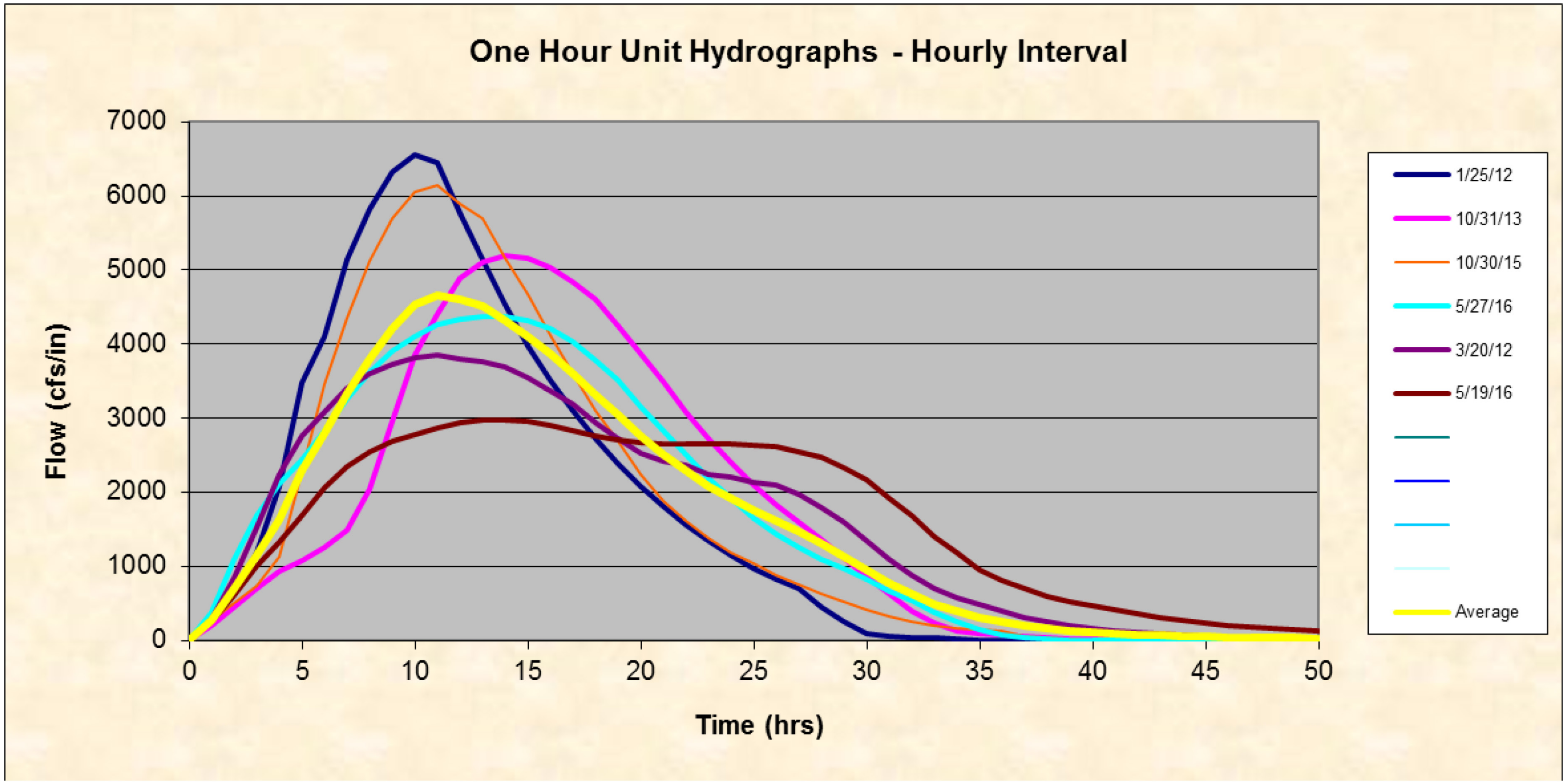
From the field measurements at the outlet of BRTT2 and river reach slope calculation, a b-value of 0.52 and a Manning's n of 0.14 were estimated. Compared to the average unit hydrograph obtained by subtracting routed upstream flows, the GeoTool hydrograph rises and recedes more gradually with a smaller peak. The attenuation of a small part of the basin by Lake Bastrop is also captured about 17 hours into the event.



BRTT2 unit hydrograph from GeoTool compared to hydrographs derived from total minus routed runoff events

CKBT2

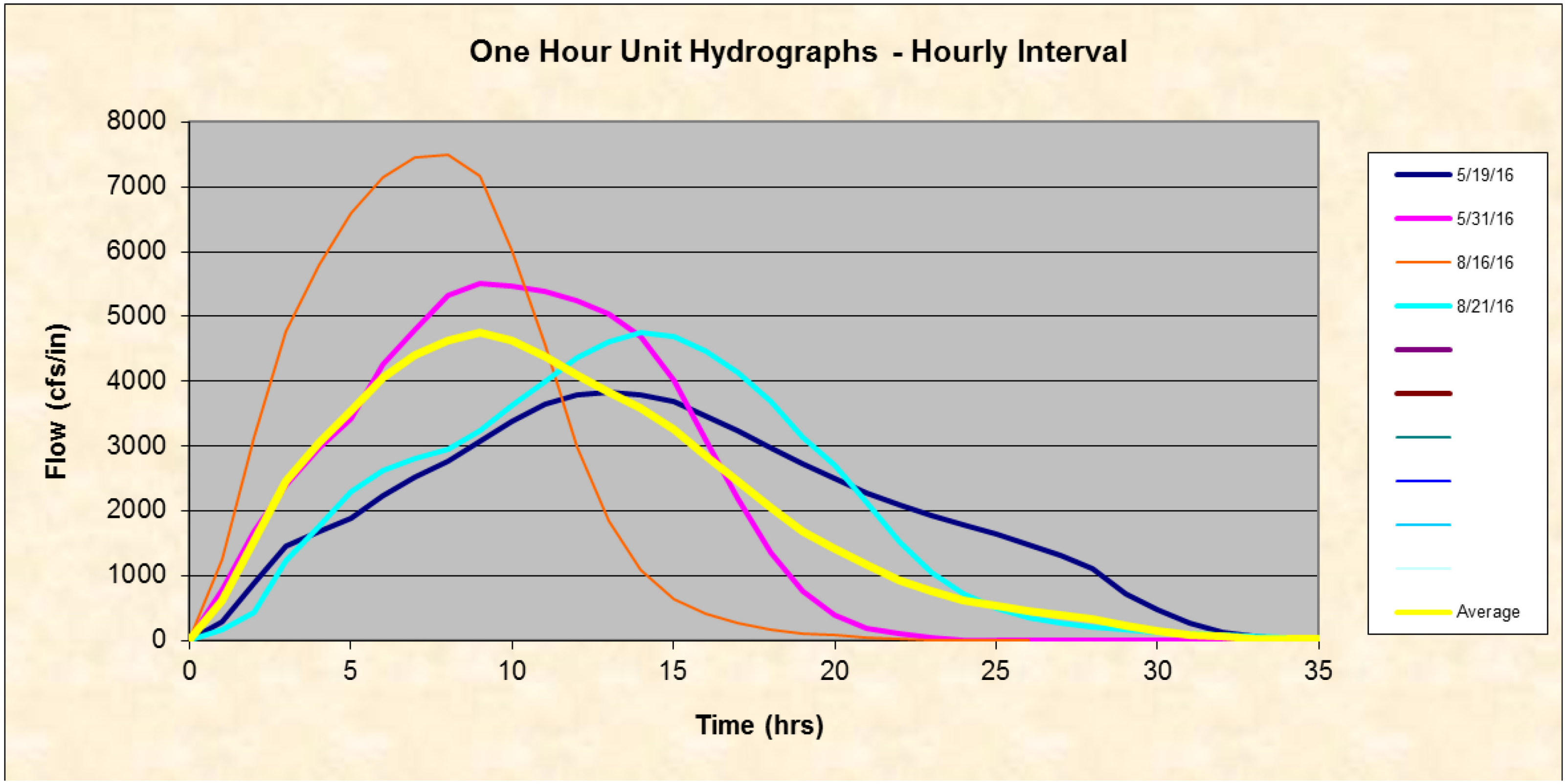
CKBT2 is a headwater with a basin area of 131 mi^2. The largest event is 30,573 cfs. Six events selected for the analysis peak at 22,065 cfs, 21,932 cfs, 30,573 cfs, 28,098 cfs, 5,096 cfs and 4,385 cfs. Rainfall durations varied from 1 to 3 hours. Events in March 2012 and May 2016 with peak flows near 5,000 cfs produced runoff depths less than 1.4 inches in the basin. The final average unit hydrograph looks reasonable, with good consistency between each event.



CKBT2 unit hydrographs from each event and resulting average unit hydrograph

WURT2

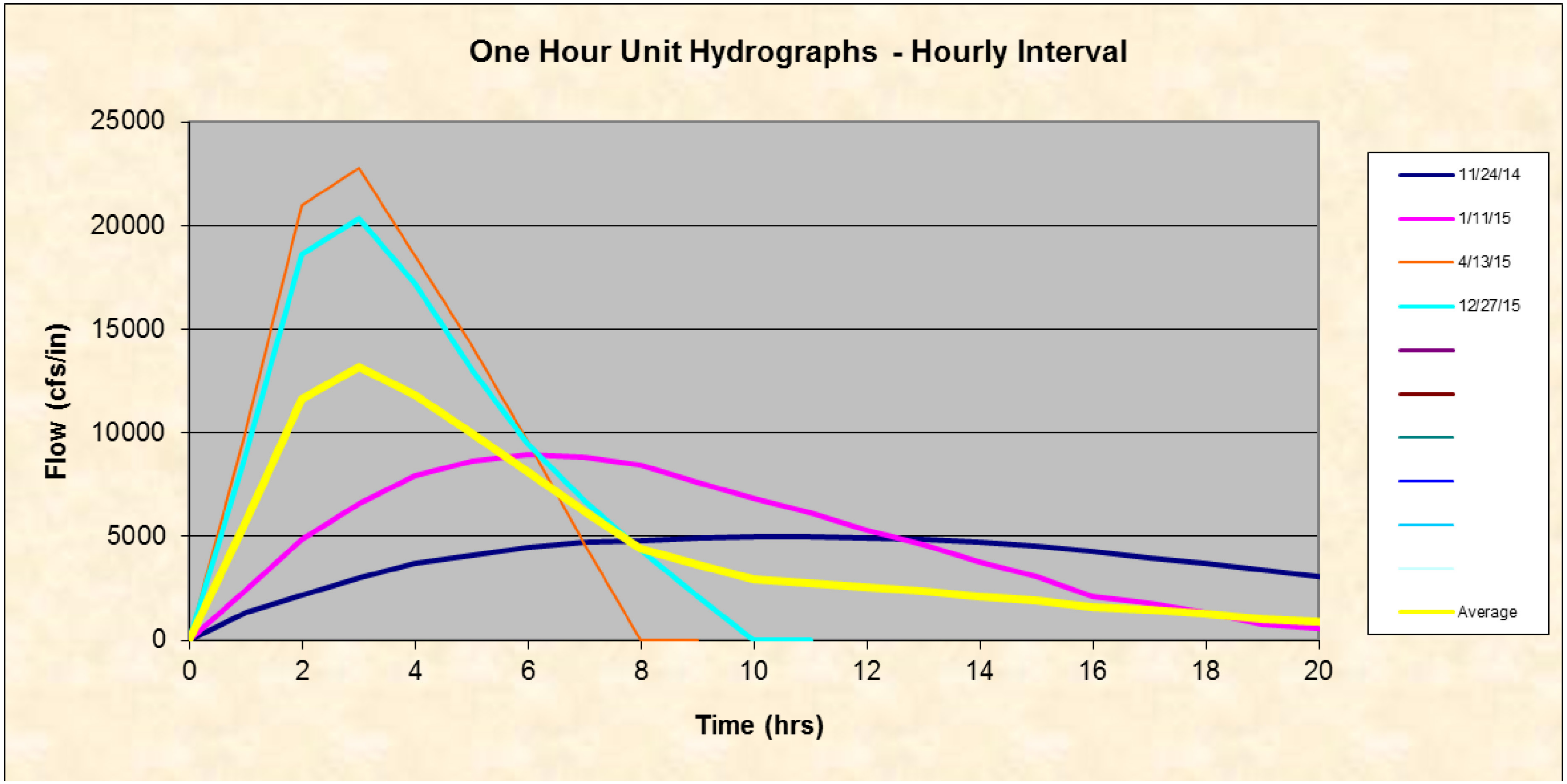
WURT2 is a headwater with a basin area of 107 mi^2. The largest event is about 23,000 cfs. Four events selected for the analysis peak at 8,709 cfs, 2,773 cfs, 1,203 cfs, and 2,729 cfs. Rainfall durations varied from 1 to 2 hours. The final average unit hydrograph looks reasonable, with good consistency between each event.



WURT2 unit hydrographs from each event and resulting average unit hydrograph

FPCT2

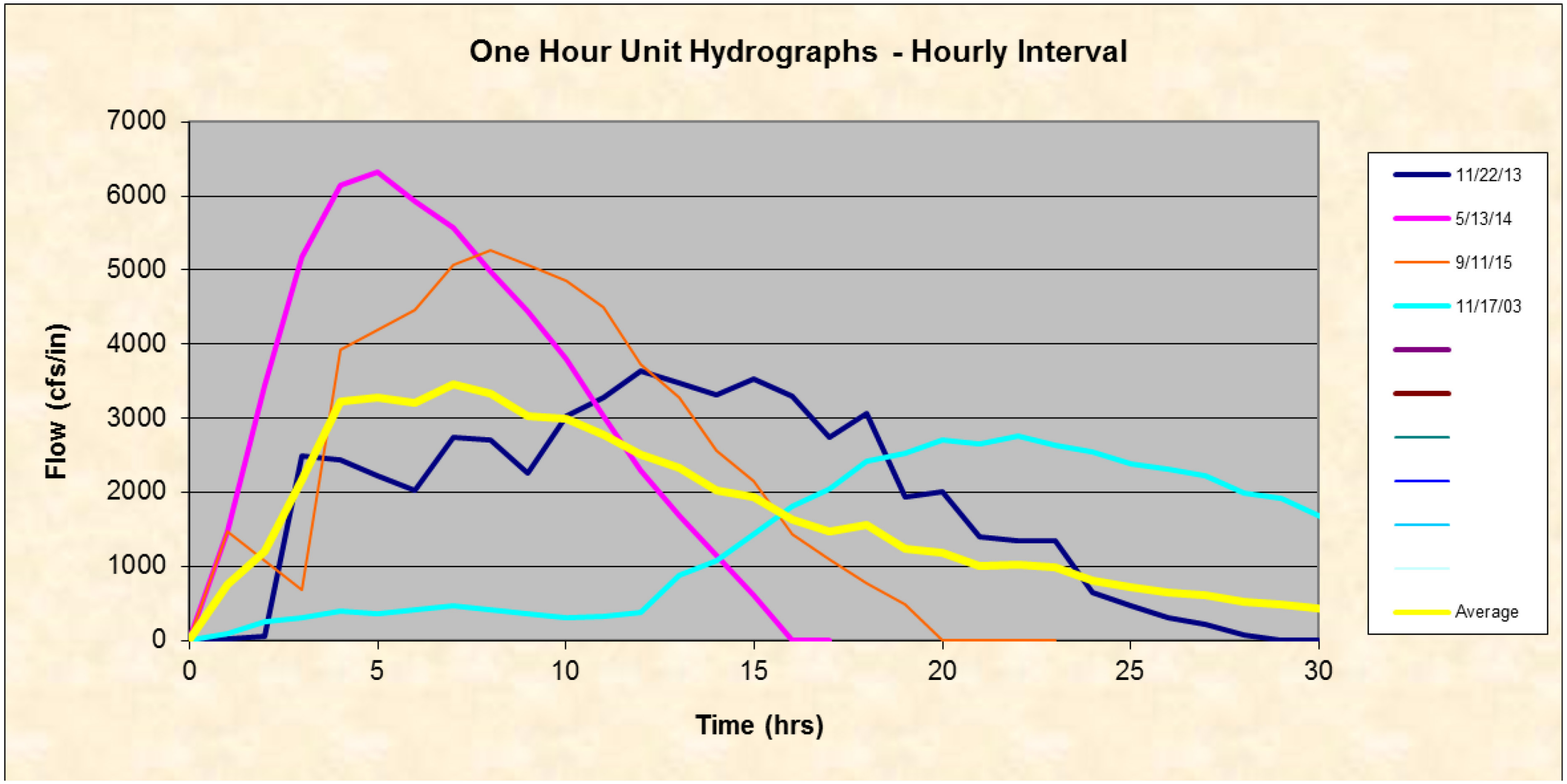
FPCT2's local and total drainage areas are 156 mi^2 and 38692 mi^2, respectively. Its largest event on record was 94180 cfs. The four events selected for the analysis peak at approximately 2630, 1220, 390, and 3900 cfs. The rainfall duration varied from 4 to 8 hours for these events. During the baseflow analysis an unrealistically high recession constant was estimated, likely because the true baseflow is not adequately represented in the runoff data after routed flows from upstream were subtracted. Recession constants from the analyses of nearby headwaters were used to obtain a more reasonable estimate. Unit hydrograph results were mixed; two of the events provided unit hydrographs that peaked quickly with a larger flow rate while two peaked and receded slowly with lower flow rates. However, the two that peaked more quickly are overall more similar than the more sluggish two are similar to each other, perhaps suggesting that the first two are more valid results. Nonetheless all four events were used to create the initial composite unit hydrograph which was then altered as needed throughout calibration.



FPCT2 unit hydrographs from each event and resulting average unit hydrograph

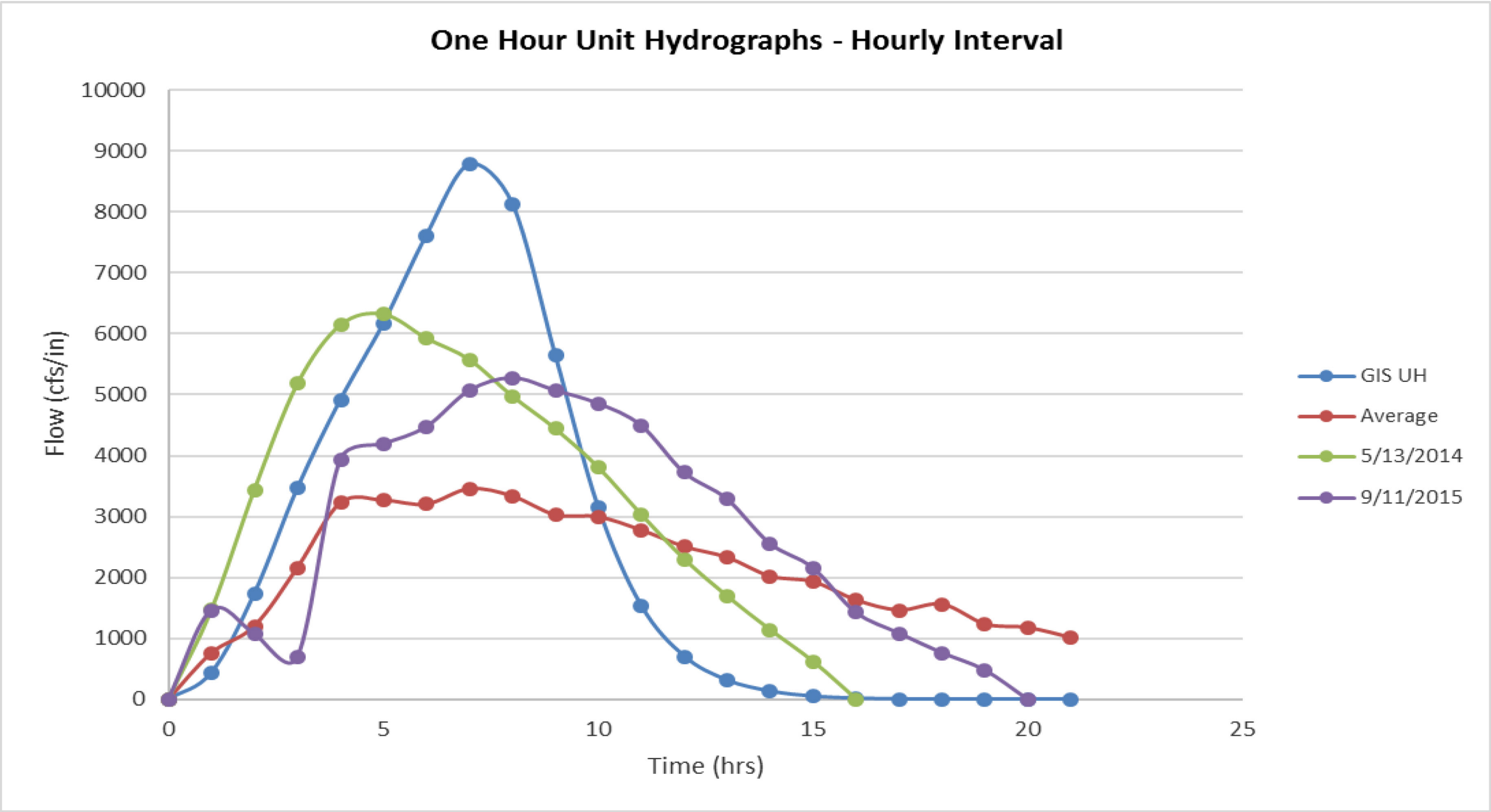
ACLT2

ACLT2's local and total drainage areas are 87 mi^2 and 39292 mi^2, respectively. Its largest event on record was 76231 cfs. The four events selected for the analysis peak at roughly 170, 2600, 210, and 1040 cfs. Rainfall durations varied from 2 to 8 hours for these events. Results for this basin were much poorer than average, likely due to uncertainties involved in routing the upstream basin CBST2. Since ACLT2 is far downstream on the Lower Colorado River, significant "noise" occurs from upstream due to runoff from various precipitation events throughout its large drainage area arriving at unpredictable times (among other potential sources). Each of the four events produced substantially different unit hydrographs with different peak times and overall lengths as well as shaky, erratic shapes. For this reason GeoTool was also employed for a better estimate of the unit hydrograph in this basin.



ACLT2 unit hydrographs from each event and resulting average unit hydrograph

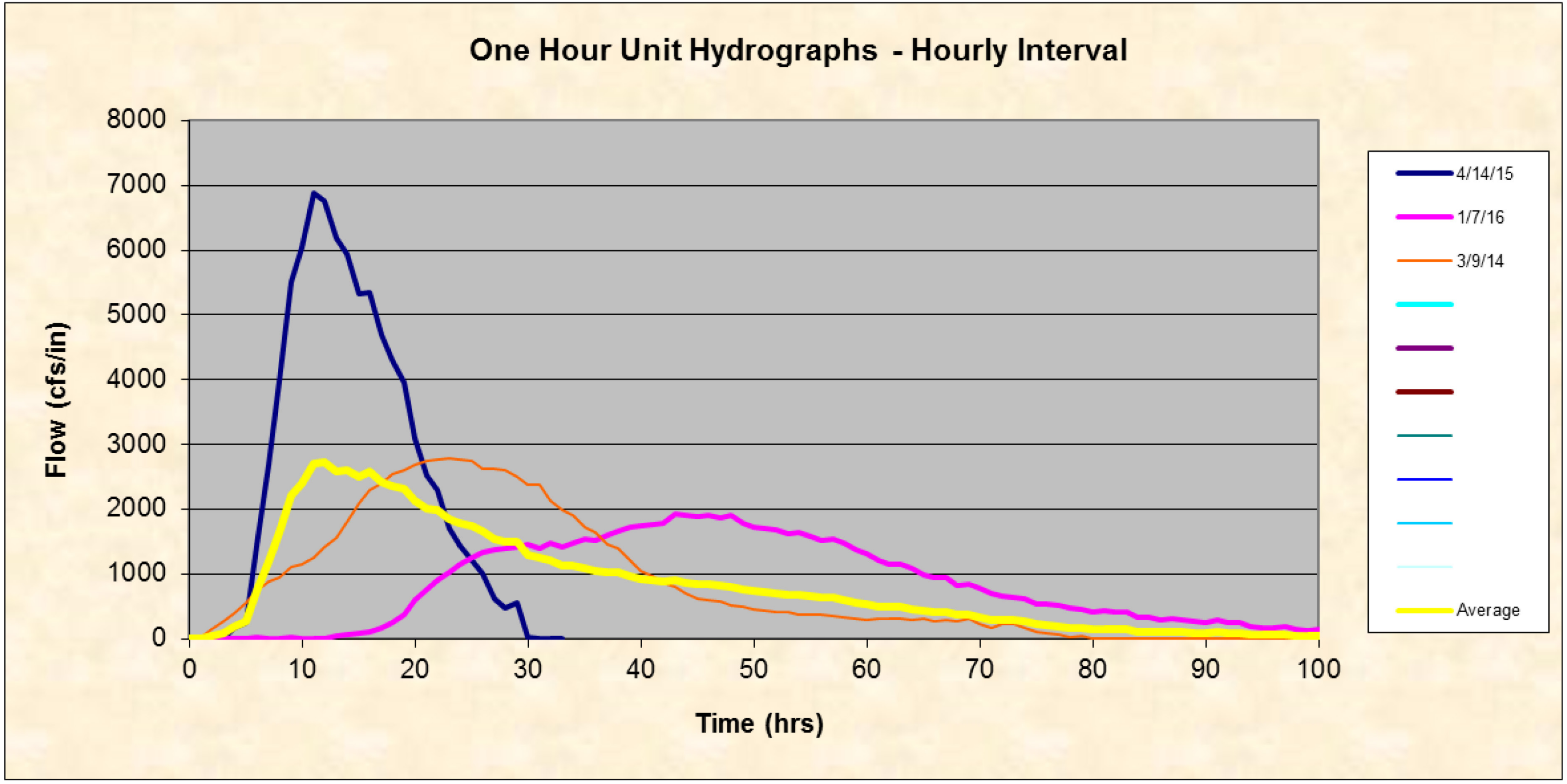
ACLT2 has no USGS gauge at its outlet and hence no field measurements from which to estimate the hydraulic radius. Measurements from nearby USGS gauge 08161000 were used assuming that the river shares similar characteristics at each location. From the field measurements and river reach slope calculation a b-value of 0.64 and a Manning's n of 0.11 were estimated. Compared to the average unit hydrograph obtained by subtracting routed upstream flows, the GeoTool hydrograph peaks about the same time at a higher magnitude, but then recedes much quicker.



ACLT2 unit hydrograph from GeoTool compared to hydrographs derived from total minus routed runoff events

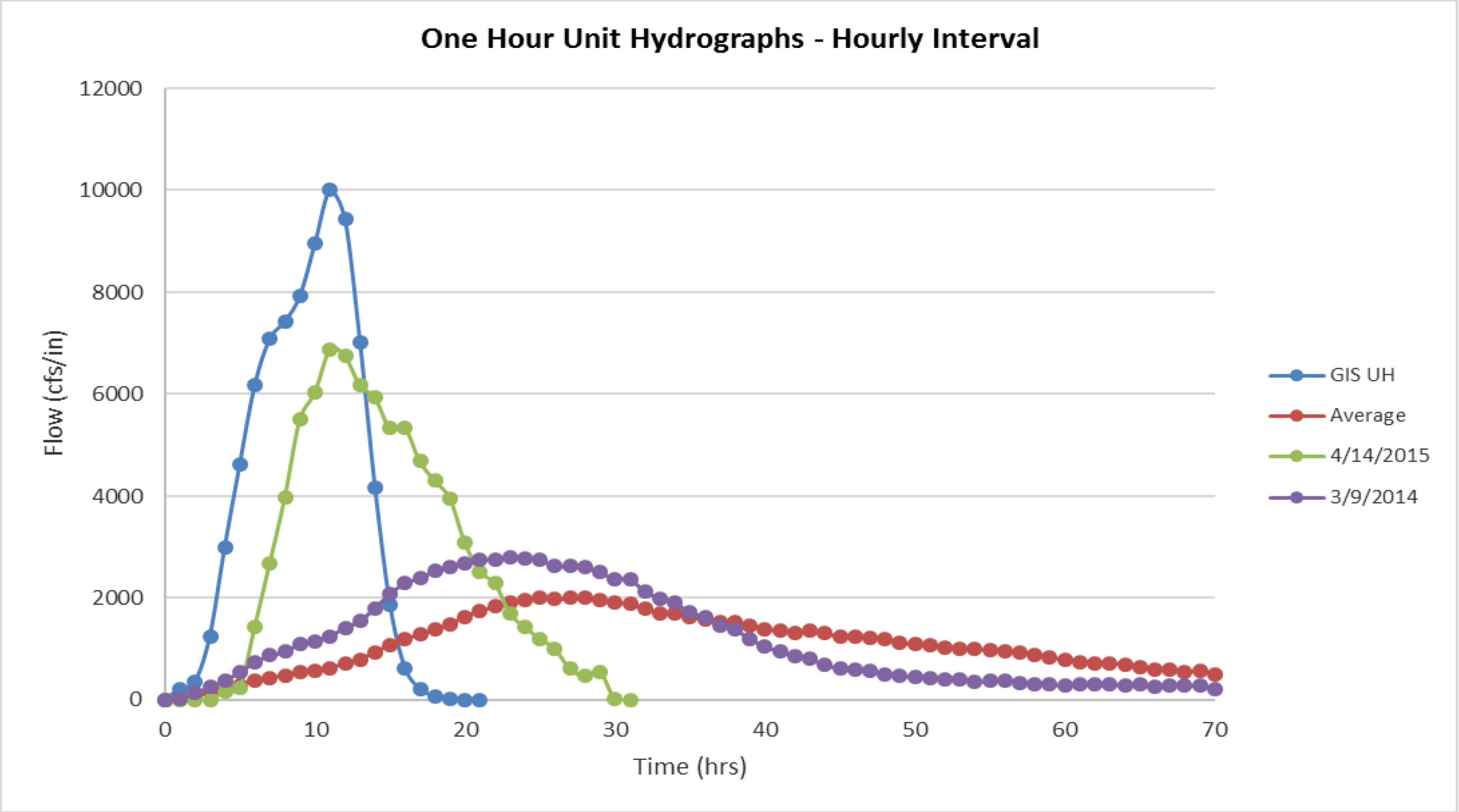
GWCT2

GWCT2's local and total drainage areas are 131 mi^2 and 39423 mi^2, respectively. Its largest event on record was 71607 cfs. The three events selected for the analysis peak at about 630, 1520, and 2790 cfs. Rainfall durations varied from 6 to 11 hours for these events. Results for this basin were much poorer than average, likely due to uncertainties involved in routing the upstream basin ACLT2. Since GWCT2 is far downstream on the Lower Colorado River, significant "noise" occurs from upstream due to runoff from various precipitation events throughout its large drainage area arriving at unpredictable times (among other potential sources). Each of the three events produced substantially different unit hydrographs with different peak times and overall lengths as well as shaky, erratic shapes. For this reason GeoTool was also employed for a better estimate of the unit hydrograph in this basin.



GWCT2 unit hydrographs from each event and resulting average unit hydrograph

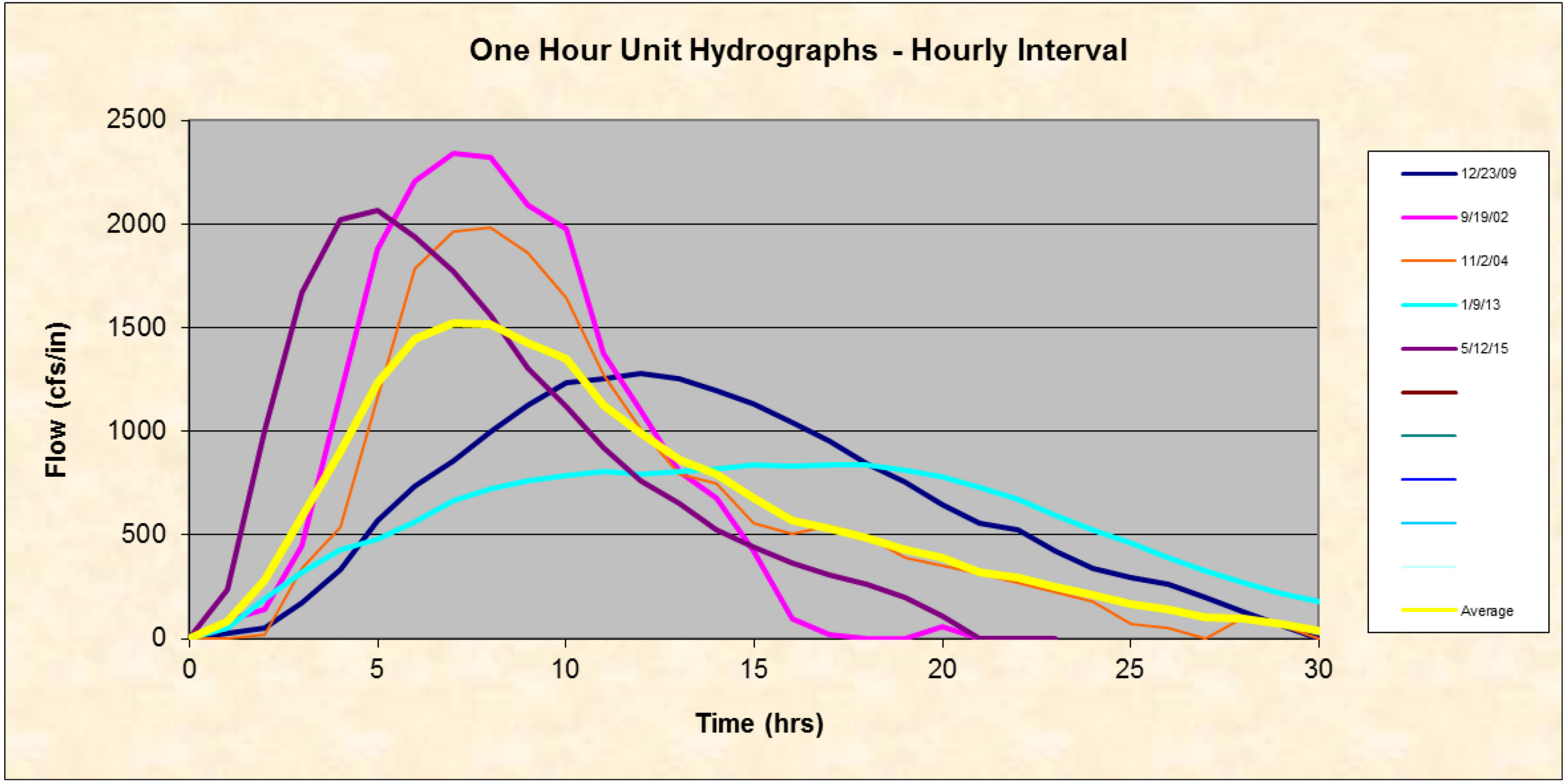
GWCT2 has no USGS gauge at its outlet and hence no field measurements from which to estimate the hydraulic radius. Measurements from nearby USGS gauge 08161000 were used assuming that the river shares similar characteristics at each location. From the field measurements and river reach slope calculation a b-value of 0.60 and a Manning's n of 0.11 were estimated. Compared to the average unit hydrograph obtained by subtracting routed upstream flows, the GeoTool hydrograph peaks and recedes much more quickly and at higher magnitudes. This is similar to Event 2 on 1/7/2016, perhaps signifying that Event 2 is more representative of the local hydrologic response within GWCT2. The average and Event 3's unit hydrographs were possibly heavily influenced by delayed hydrologic responses from distant upstream basin locations as a result of inadequate routing.



GWCT2 unit hydrograph from GeoTool compared to hydrographs derived from total minus routed runoff events

CDOT2

CDOT2's local and total drainage areas are 30 mi^2 and 39635 mi^2, respectively. Its largest event on record was 72541 cfs. The five events selected for the analysis peak at approximately 370, 540, 670, 530, and 1270 cfs. Rainfall durations varied from 2 to 3 hours for these events. During the baseflow analysis an unrealistically high recession constant was estimated, likely because the true baseflow is not adequately represented in the runoff data after routed flows from upstream were subtracted. Since there were no analyzed headwaters nearby, the recession constant was assumed to be 0.01/hr. The resulting unit hydrographs are decent quality, particularly for a basin so far downstream on the Lower Colorado River. Three of the events that peak and recede earlier are quite consistent among each other, so the remaining two events (on 12/23/2009 and 1/9/2013) were discarded when deriving the average unit hydrograph to initialize calibration efforts.

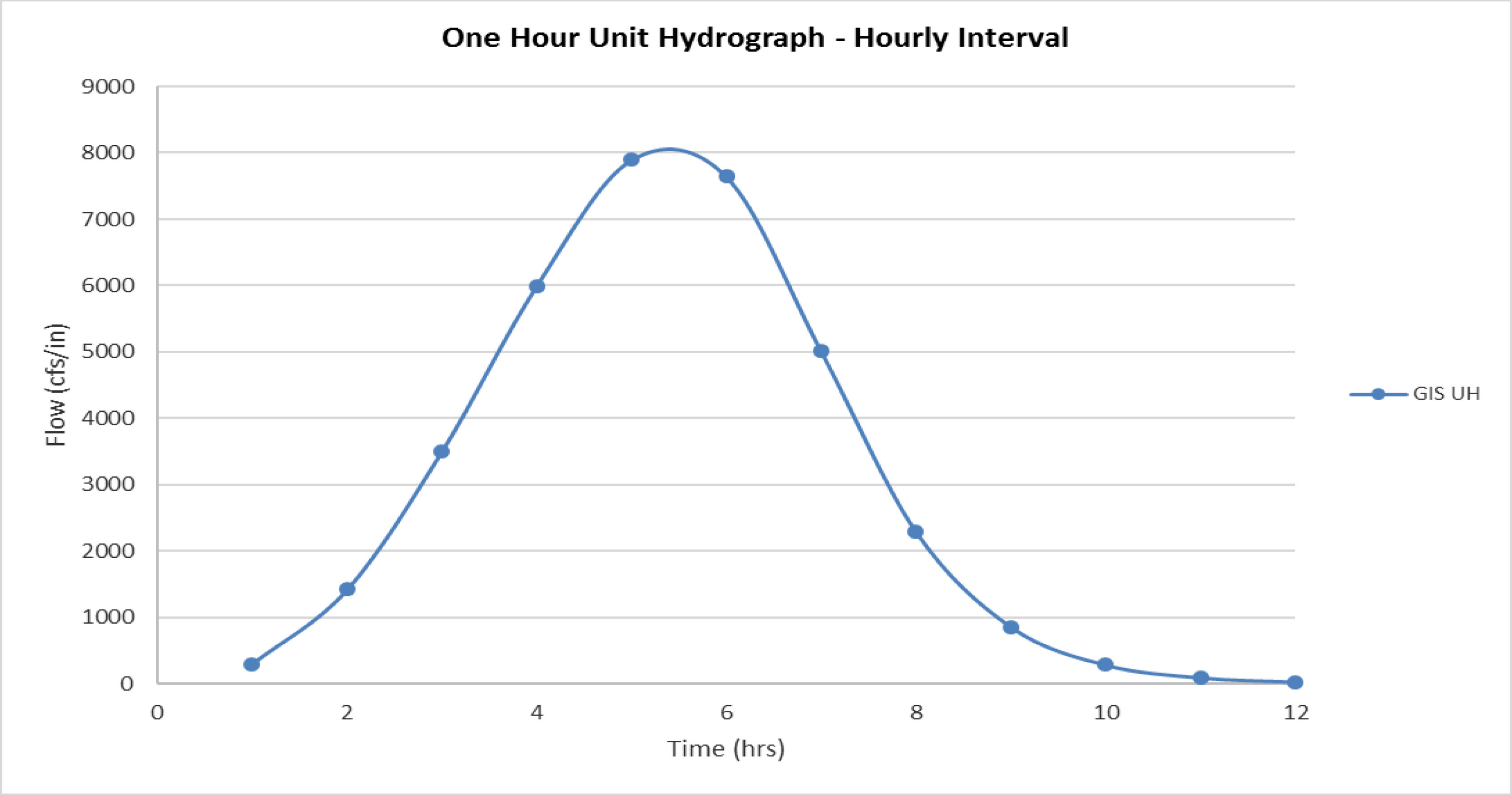


CDOT2 unit hydrographs from each event and resulting average unit hydrograph

Guadalupe Basin

GRTT2

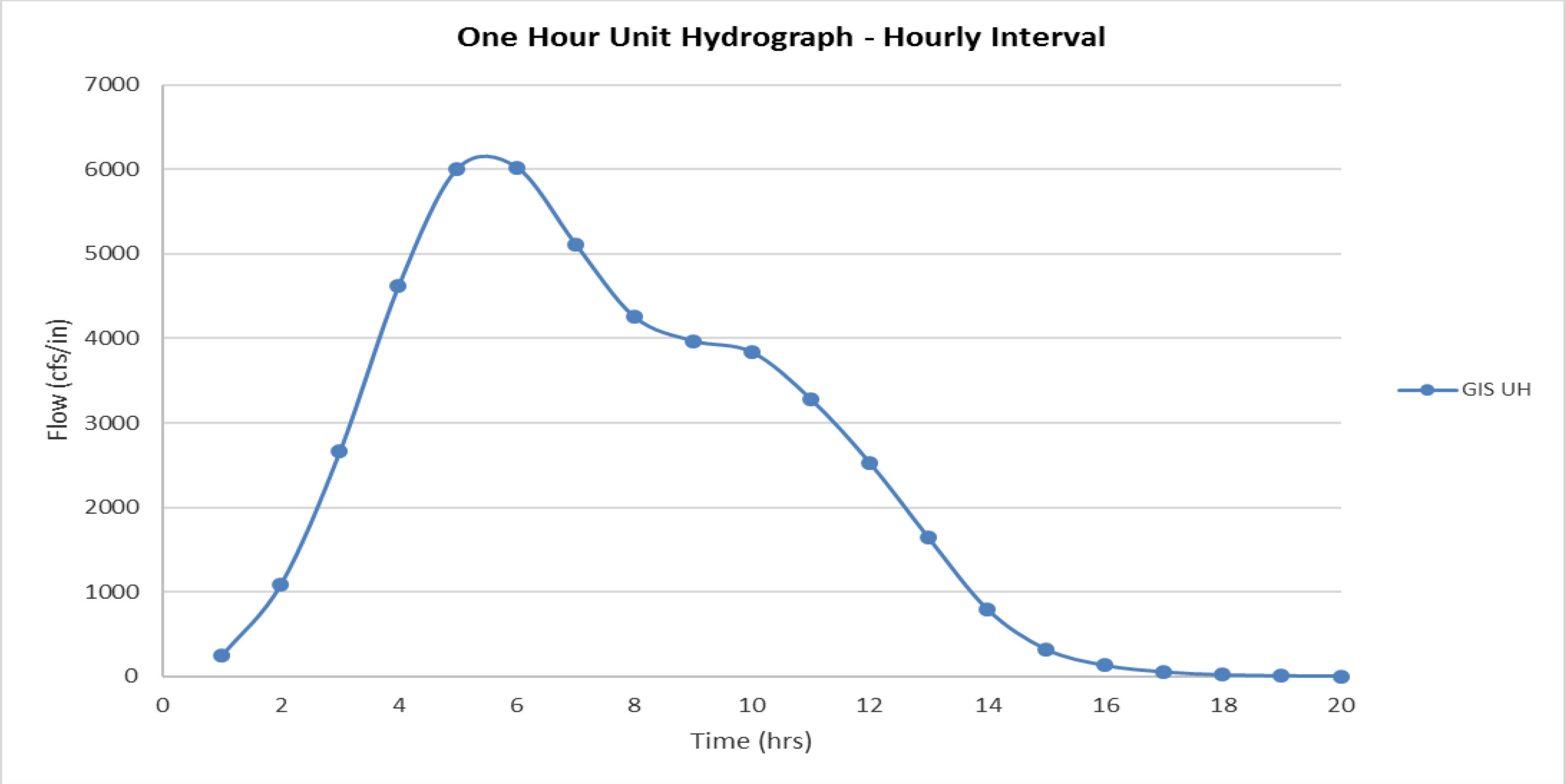
GRTT2 has no USGS gauge at its outlet and hence no field measurements from which to estimate the hydraulic radius. Measurements from nearby USGS gauge 08168500 were used assuming that the river shares similar characteristics at each location. From the field measurements and river reach slope calculation a b-value of 0.41 and a Manning's n of 0.17 were estimated. There was no streamflow data from gauges of any source/authority to compare the GeoTool results to; however, the final unit hydrograph seems physically reasonable.



GRTT2 unit hydrograph from GeoTool

SEGT2

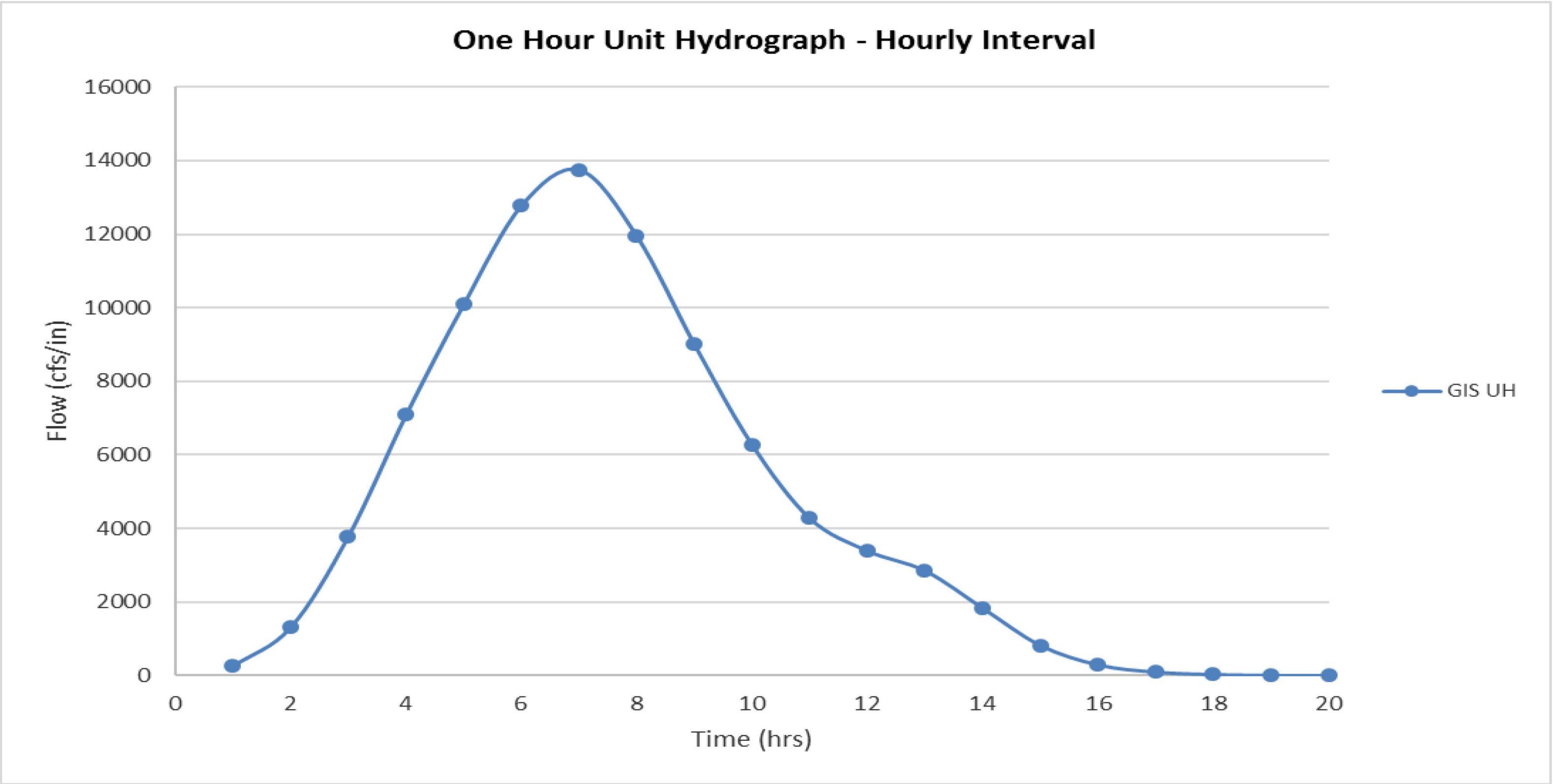
SEGT2 has no USGS gauge at its outlet and hence no field measurements from which to estimate the hydraulic radius. Measurements from nearby USGS gauge 08169792 were used assuming that the river shares similar characteristics at each location. From the field measurements and river reach slope calculation a b-value of 0.65 and a Manning's n of 0.13 were estimated. There was no streamflow data from gauges of any source/authority to compare the GeoTool results to; however, the final unit hydrograph seems physically reasonable. The delay in recession from hours 7-10 is likely from attenuation as runoff passes through Lakes McQueeney and Placid within SEGT2.



SEGT2 unit hydrograph from GeoTool

SGGT2

From the field measurements and river reach slope calculation a b-value of 0.58 and a Manning's n of 0.13 were estimated. Although a USGS stream gauge exists at the outlet of SGGT2, SEGT2 immediately upstream of SGGT2 has no gauge data and therefore was not routed. Because of this the local contribution to the flow at the basin outlet could not be estimated, so there are no results to compare the GeoTool output to. However, the final unit hydrograph seems physically reasonable. A small flattening of the receding limb from hours 11-13 can likely be attributed to runoff from a long, narrow portion at a remote upstream location of the local basin arriving significantly later than the rest of the runoff.

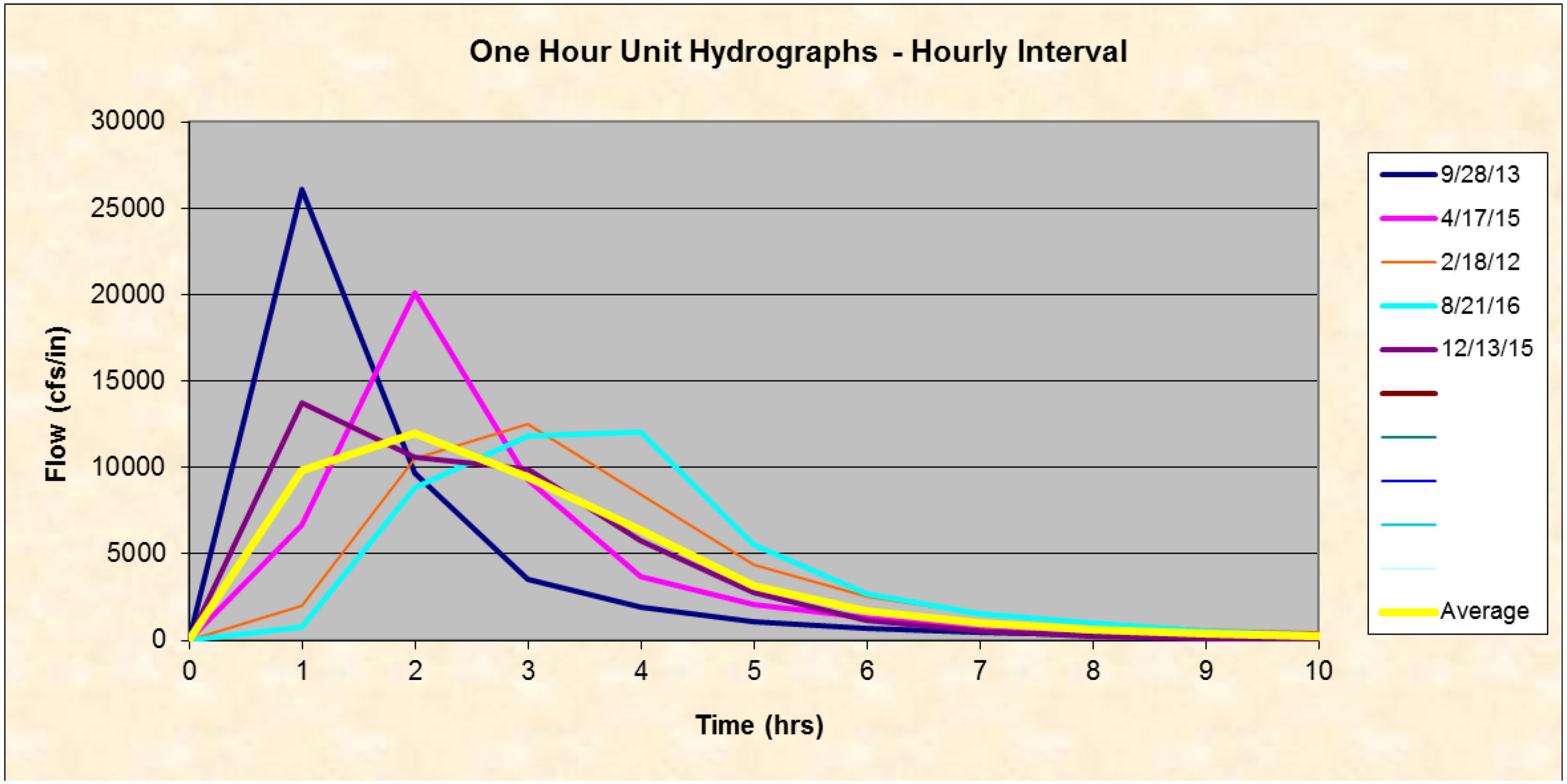


SGGT2 unit hydrograph from GeoTool

San Antonio Basin

CICT2

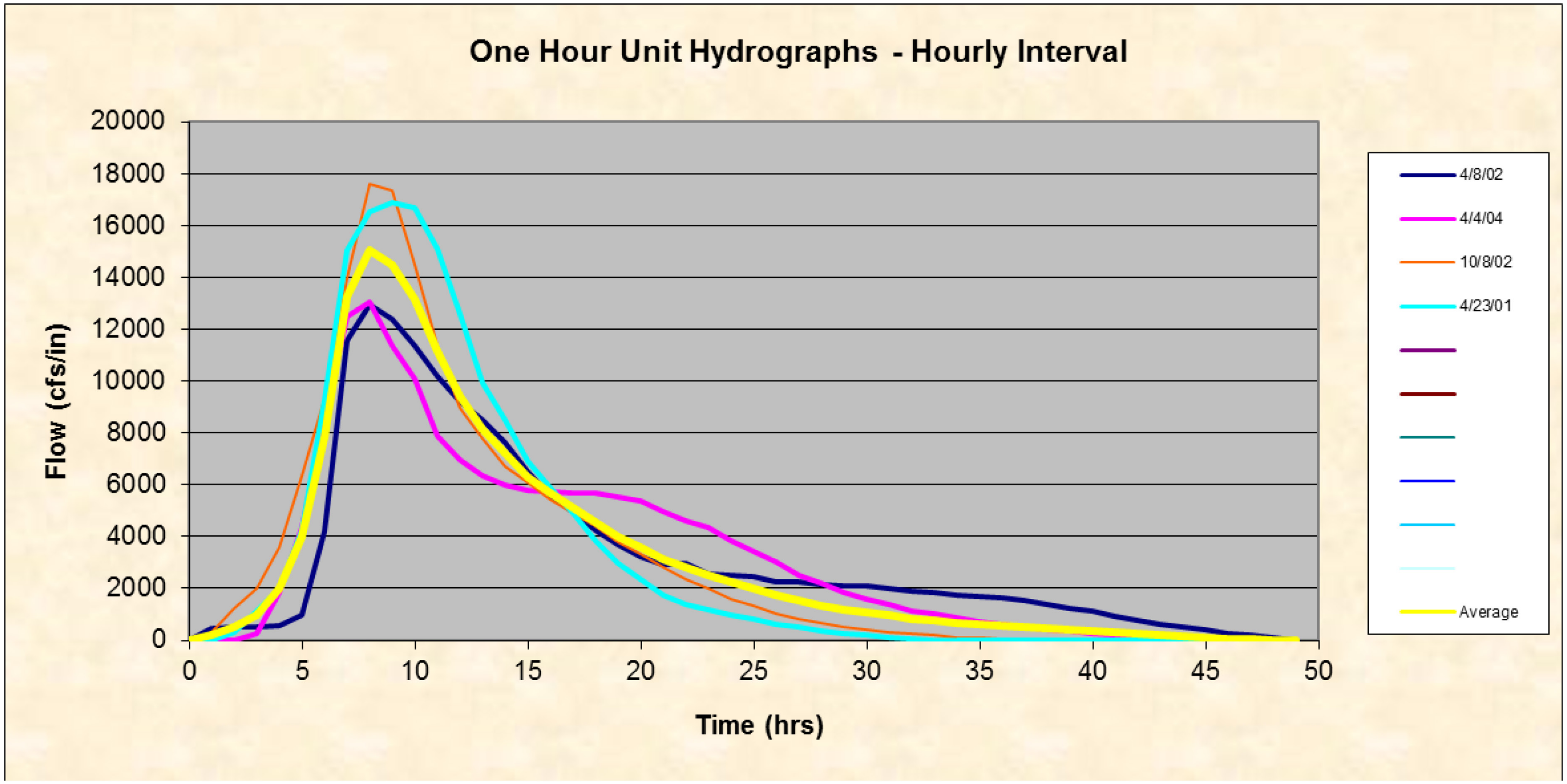
CICT2 is a headwater with a basin area of 70 mi^2. The largest event is 26150 cfs. Five events selected for the analysis peak at 26150 cfs, 20138 cfs, 12523, cfs, 12070 cfs, and 13726 cfs. Rainfall durations varied from 3 to 6 hours for these events. The resulting average unit hydrograph appears reasonable despite the 9/28/2013 appearing to be somewhat of an outlier.



CICT2 unit hydrographs from each event and resulting average unit hydrograph

MMDT2

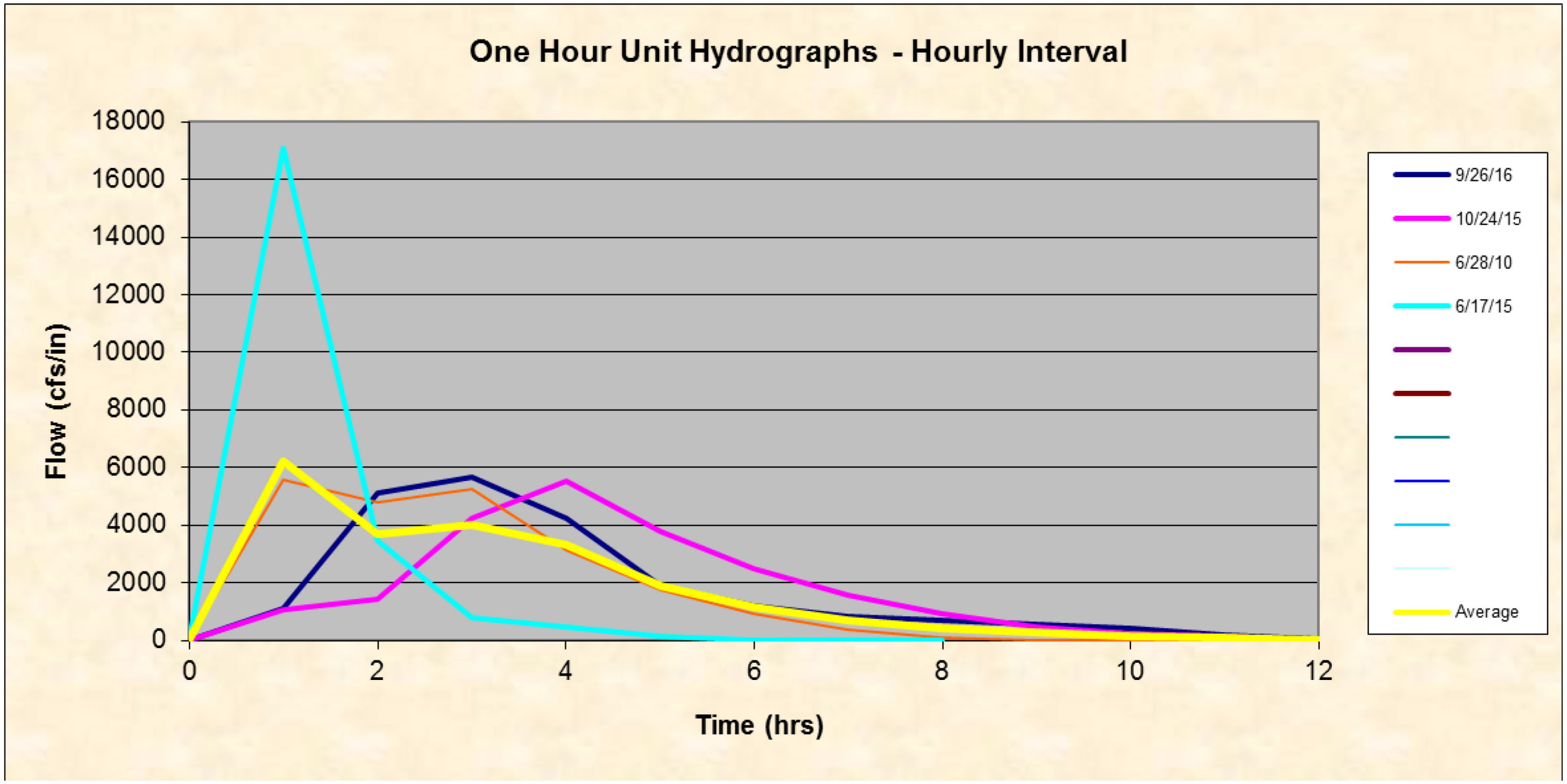
MMDT2's local and total drainage areas are 253 mi^2 and 894 mi^2, respectively. Its largest event on record was 55200 cfs. Four events were selected for the analysis peak at about 520, 2190, 4180, and 3100 cfs. Rainfall durations varied from 6 to 11 hours for these events. Resulting unit hydrographs for MMDT2 were above average. Because there is minimal contribution to the overall downstream flow from the upstream basins and/or the upstream flow was routed well for the selected events, the quality of data is comparable to that of a headwater basin. As a result the four events have a respectable level of consistency among each other.



MMDT2 unit hydrographs from each event and resulting average unit hydrograph

SDBT2

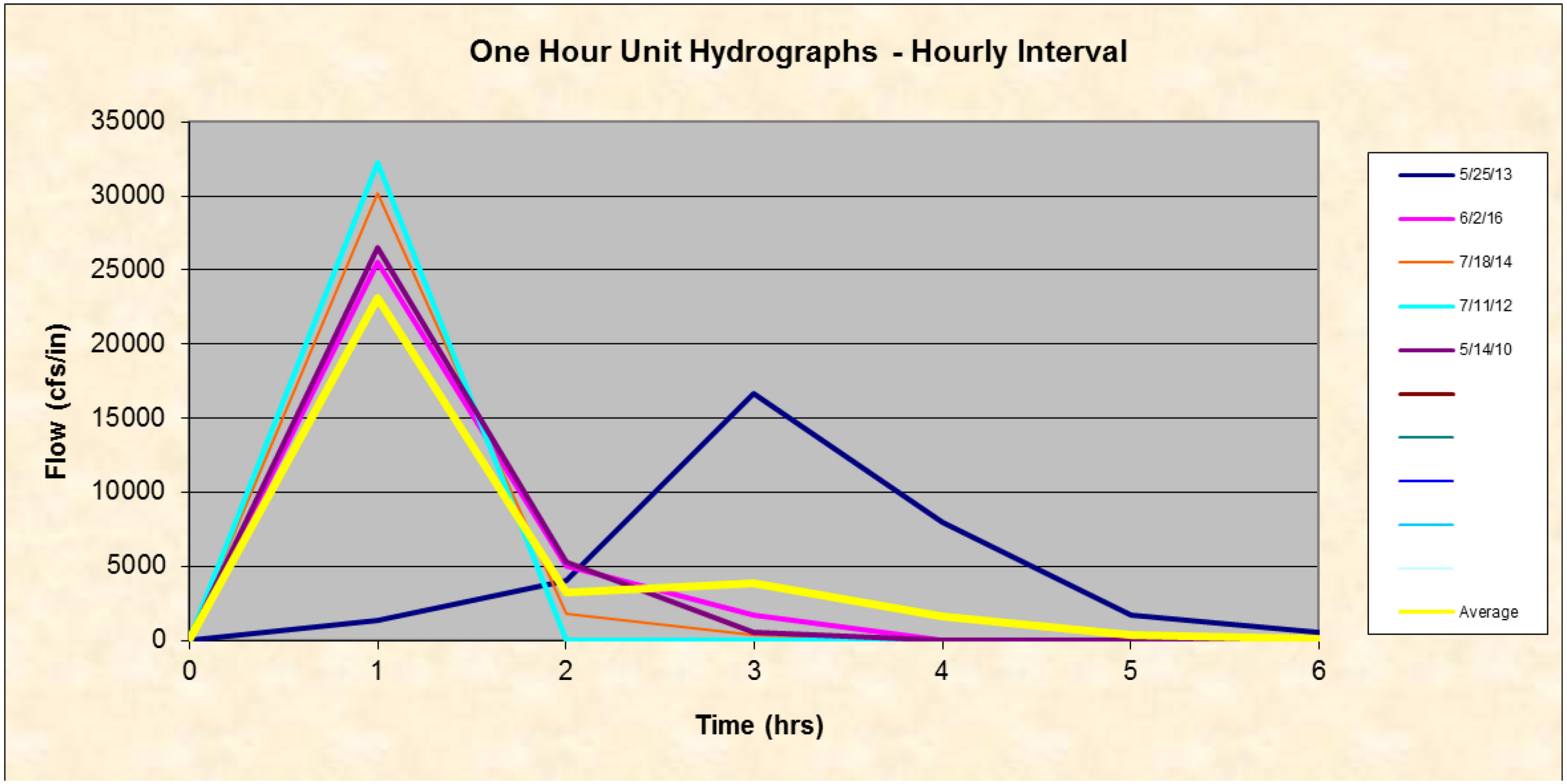
SDBT2 is a headwater with a basin area of 50 mi^2. The largest event is 2,200 cfs. Four events selected for the analysis peak at 2,100 cfs, 406 cfs, 410 cfs, and 331 cfs. Rainfall durations varied from 1 to 6 hours for these events. The hydrograph arising from the 6/17/2015 storm was not included in the initial average unit hydrograph placed into the UNIT-HG operation.



SDBT2 unit hydrographs from each event and resulting average unit hydrograph

MTST2

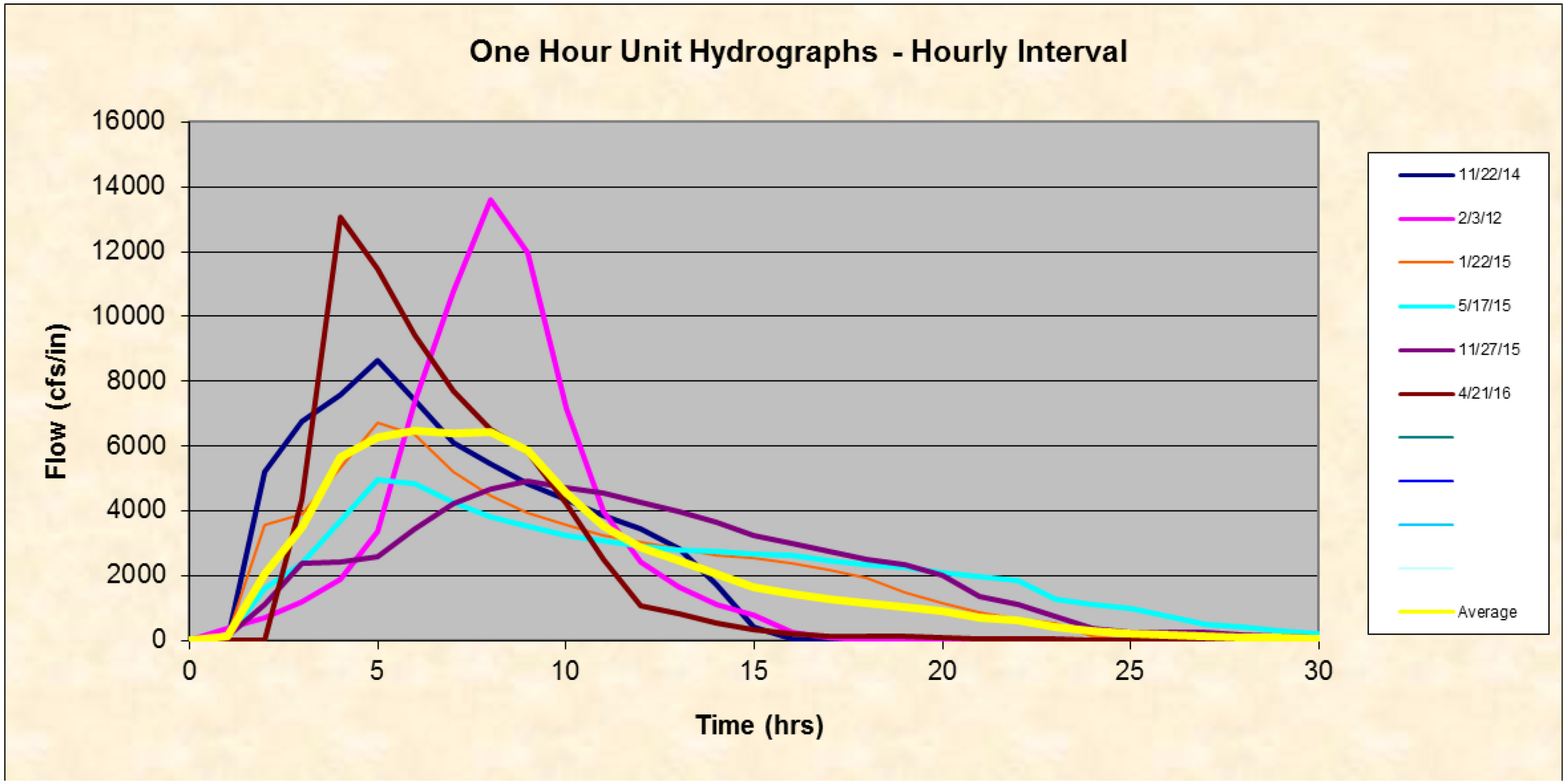
MTST2 is a headwater with a basin area of 50 mi^2. The largest event is 2,180 cfs. Four events selected for the analysis peak at 2,180 cfs, 1,180 cfs, 623 cfs, and 606 cfs. Rainfall durations varied from 1 to 2 hours for these events. The resulting average unit hydrograph looks reasonable, with good consistency between events.



MTST2 unit hydrographs from each event and resulting average unit hydrograph

SSCT2

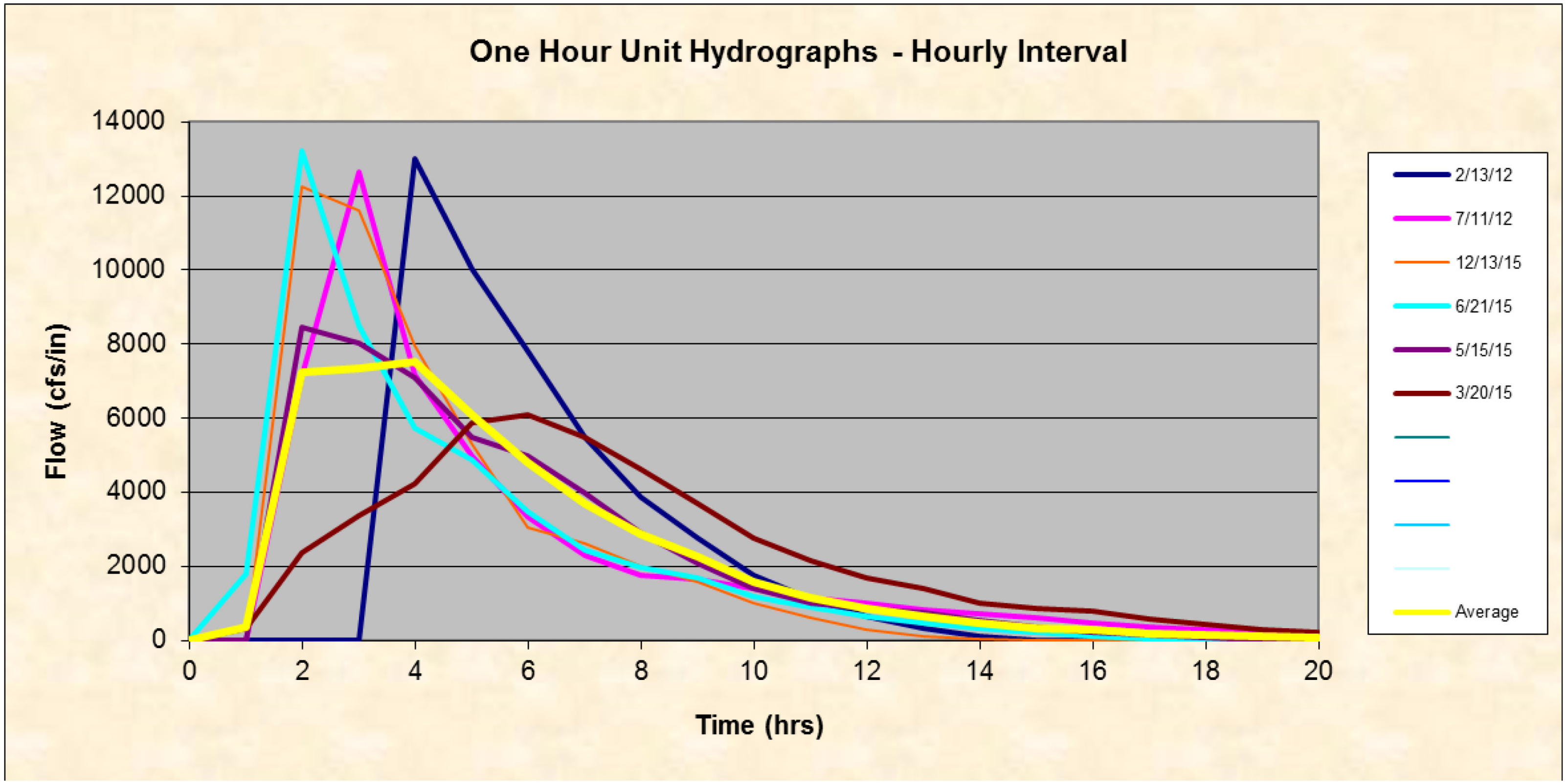
SSCT2's local and total drainage areas are 106 mi^2 and 140 mi^2, respectively. Its largest event on record was 43400 cfs. Six events were selected for the analysis which peak at about 760, 1490, 860, 830, 670, and 620 cfs. Rainfall durations varied from 2 to 10 hours for these events. The resulting unit hydrographs were about average. The event from 2/3/2012 was larger than the rest while the event from 11/27/2015 was smaller than the rest; both arrived late and have unique shapes. These two were not included in the average unit hydrograph placed into the calibration deck.



SSCT2 unit hydrographs from each event and resulting average unit hydrograph

SNPT2

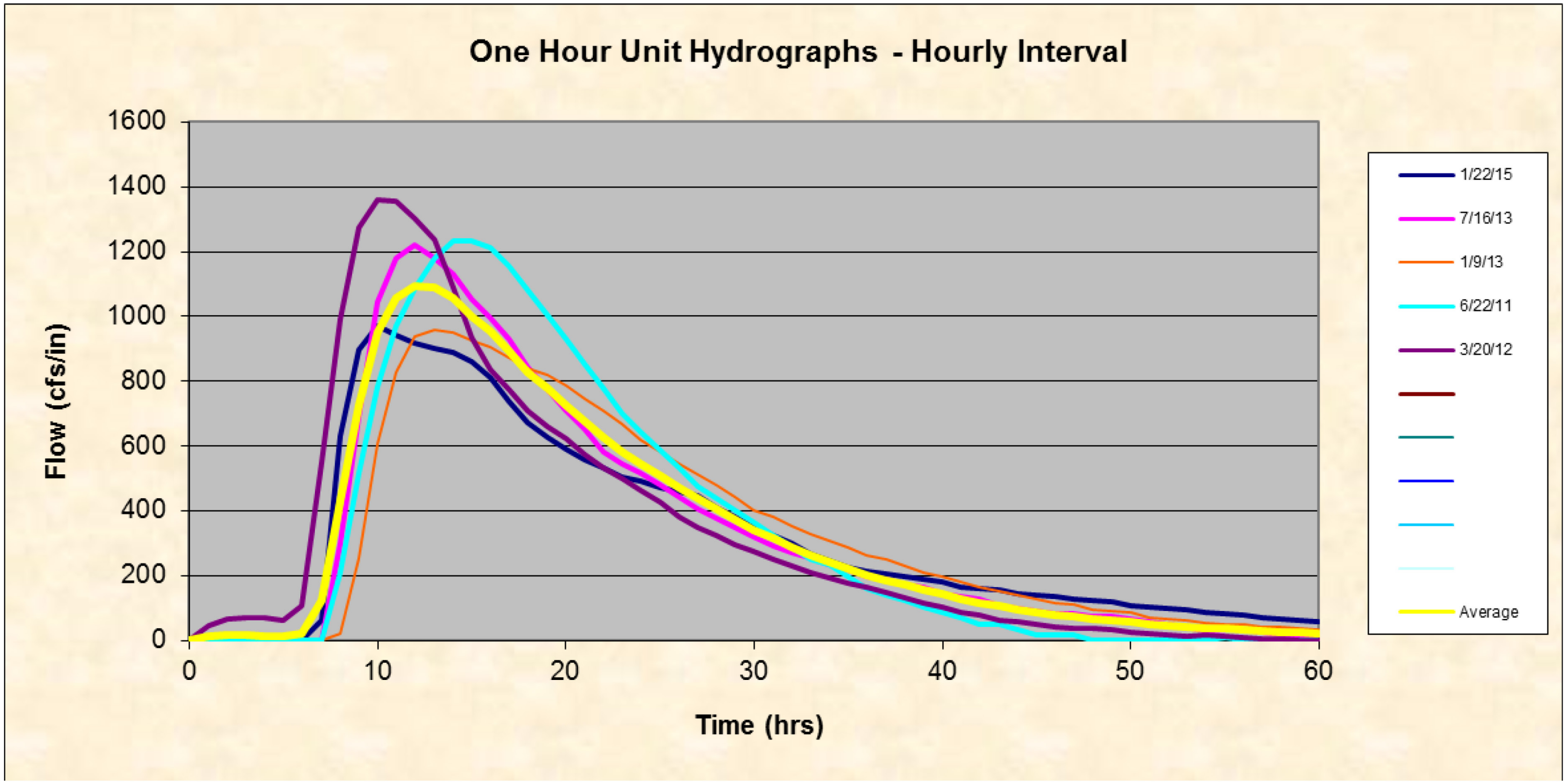
SNPT2's local and total drainage areas are 75 mi^2 and 125 mi^2, respectively. Its largest event on record was 81400 cfs. Six events were selected for the analysis which peak at roughly 1790, 11000, 2230, 2235, 3620, and 2770 cfs. Rainfall durations varied from 2 to 12 hours. Overall the results were good for four out of six events. Runoff from precipitation on 2/13/2012, 3/20/2015, and 5/15/2015 did not seem as representative as the other three (which have strong apparent consistency), so they were excluded from the average unit hydrograph.



SNPT2 unit hydrographs from each event and resulting average unit hydrograph

HDWT2

HDWT2's local and total drainage areas are 32 mi^2 and 308 mi^2, respectively. Its largest event on record was 17900 cfs. Five events were selected for the analysis which peak at roughly 230, 140, 160, 80, and 310 cfs. Rainfall durations varied from 2 to 5 hours for these events. Resulting unit hydrographs for HDWT2 were above average. Because there is minimal contribution to the overall downstream flow from the only two upstream basins (CICT2 and SELT2) and/or the upstream flow was routed well for the selected events, the quality of data is comparable to that of a headwater basin. As a result the five events have a respectable level of consistency among each other.



HDWT2 unit hydrographs from each event and resulting average unit hydrograph

Appendix C:
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 Antonio, Guadalupe, and Colorado Rivers in Texas
Draft-final report to the Texas Water Development Board

Contract number 15400012068

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 correct the following references to erroneous sections of the report:
   a. Section 4.5 and 5.0 on page ES-1.
   b. Section 5.1 and 5.2 on page ES-2.
   c. Section 0 on pages 3-18, 4-2, and 4-4.

   RTI Response: These items have been corrected.
2. Please recheck the document and correct typos such as the following:
   a. Page 1-1, 1st paragraph, 3rd sentence, "within both basin" should be "within both basins".
   b. Page 3-8, 1st paragraph, last sentence, "(USDA-NRCS 2006a)" should be "(USDA-NRCS 2006)".
   c. Page 3-21, 1st paragraph, 2nd sentence, "one the sub-basins" should be "one of the sub-basins".
   d. Page 3-25, 3rd paragraph, 4th sentence, "GBTC2" should be "GBCT2".
   e. Page 3-31, Table 12 and page 3-33, Table 13, 4th column heading, "MAP Local [in]" should be "MAPX Local [in]".
   f. Page 3-32, 2nd paragraph, 3rd sentence, "MAP/Local runoff" should be "Local runoff/MAPX".
   g. Page 4-8, 9th paragraph, 2nd sentence, "in some cases. new" should be "in some cases, new".
   h. Page 4-27, Figure 22 title, "FPCT2" should be "ONIT2".
   i. Page 4-29, 1st paragraph, 1st sentence, "138,000 cfs" should be "135,000 cfs".
   j. Page 4-50, 1st paragraph, last sentence, "DRWT2" should be "CKBT2".
   k. Page 4-63, title of Table 76, "SELT2" should be "ACLT2".
   l. Page 4-91 to 4-92, there are several references to "SEG", "SGG" and "GBC" that should be "SEGT2", "SGGT2", and "GBCT2", respectively.
   m. Page 4-116, 1st paragraph, 3rd sentence, "peaks within 1 days" should be "peaks within 1 day".
   n. Page 7-2, 1st reference, "(n.d.)" should be "2017".

   RTI Response: These items have been corrected.
3. Please adjust sub-basin names in Table 1 on pages 1-2 to 1-3 to match US Geological Survey naming conventions.
   RTI Response: Names have been updated to match the USGS.

4. Section 3.5.1 of the report states that "the analysis incorporates the precipitation from the MAPX data described in Section 3.2." However, the MAPX data in Tables 12 and 13 do not match the MAPX data in Table 7. Please provide an explanation in Section 3.5.1 of the difference in the MAPX used in this Section and that described in Section 3.2.
   RTI Response: Values are different in these tables because the analysis period is slightly different. This has been clarified in the report in Section 3.5.1. The following text was added, "The average annual volumes shown in Table 12 (and subsequently in Table 13) were calculated for the common calibration period, which is January 2011 to December 2016; therefore, the values for precipitation (MAPX) and streamflow are slightly different than values provided elsewhere in this report."
5. In several locations in the report (for example Section 4.4.5 on page 4-33 and in Section 4.4.6 on page 4-38 to 4-39), soil groups B and D are described as having "moderate, variable infiltration rates and with average runoff potential." Please describe these two soil groups separately, as their infiltration rates and runoff potentials are significantly different.
   RTI Response: Addressed. Separate descriptions for the two hydrologic soil group types were added for the applicable sections.

6. Page 4-68, Table 82, entry for original value of UZFWM is listed as "b." Please provide the correct original value.
   RTI Response: Corrected.
7. There appear to be several cases where values for the highest recorded instantaneous flow stated in the report do not match peak flow data available from the US Geological Survey. For example, Section 4.6.4 on page 4-116, states "the highest instantaneous flow ever recorded at the gage is 2,100 cfs." However, USGS peak flow data for this gage lists a peak flow of 3,490 cfs on May 25, 2013. Similarly, Section 4.6.5, page 4-120, states "the highest instantaneous flow ever recorded at the gage is 43,400 cfs." USGS data for this location lists a peak flow of 64,400 cfs on Oct. 17, 1998. Section 4.6.7 lists a maximum instantaneous flow of 17,900 cfs but the USGS data lists a peak flow of 20,100 cfs on August 17, 2007. Please double check statements about highest instantaneous flows within the document and correct as necessary.
   RTI Response: These values have been corrected as needed and additional information on when the event occurred was added to the text.
8. Please provide a reference in Section 7.0 related to "(NLCD 2011)" cited in the heading of the 7th column of Tables 2, 3, and 4 on pages 3-2 to 3-7 and also cited in other tables throughout the report.
   RTI Response: This reference was added.

SUGGESTED CHANGES

9. Page 4-5, Table 15. It would be helpful to have an additional column in this table providing a description of each of the parameters listed in column 1.
   RTI Response: The recommended column was added to the table.
10. Suggest modifying the title of Tables 12 and 13 to indicate the water balance was based on annual volumes.
    RTI Response: The titles were updated to clarify that the water balance is based on average annual volumes.
11. For clarity, suggest specifying the basin pairs associated with routing parameters in titles for tables associated with Lag/Q and K/Q (such as Tables 26, 31, 37, 43, 44 45, 46, 51, etc).
    RTI Response: The sub-basin pairs for the routing reaches were added to the table heading.
12. In order to distinguish the tables from one another, suggest specifying the basin in the title of parameter comparison tables (such as Tables 22, 27, 32, 38, 47 etc.).
    RTI Response: The sub-basin names were added to the table captions.
13. On page 4-51, last paragraph, first sentence, the statement is made that "models tended to over-predict the number and magnitudes of responses to storm events." It is not clear how the models over-predicted the number of responses to storm events. For clarity, consider rewording or describing in greater detail.
    RTI Response: This statement was edited to read, "Testing of the model parameters from the existing CHPS configuration provided by the WGRFC demonstrated that the models tended to over-predict the frequency of runoff events and the magnitudes of the streamflow peaks."
14. To provide consistency with the write-ups for other locations, please consider providing a table of SAC-SMA parameters for basin SEGT2 in Section 4.5.2.
    RTI Response: A table (Table 101) with SAC-SMA parameters for SEGT2 was added.