COMPARATIVE ANALYSIS OF DAILY FLOW PATTERN HYDROGRAPHS USED TO DISAGGREGATE MONTHLY NATURALIZED FLOWS TO DAILY

A Thesis

by

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ABSTRACT

Observed and synthesized sequences of stream flow data are explored from the perspective of improving capabilities for disaggregating monthly naturalized flow volumes, representing natural undeveloped conditions, to daily volumes. The research investigates 1) characteristics of river flows and impacts of water resources development on flows, 2) capabilities for disaggregating monthly naturalized flows to daily, and 3) the sensitivity of water availability modeling results to the daily flow pattern hydrographs adopted in monthly-to-daily naturalized flow disaggregation.

The Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System consists of the Water Rights Analyses Package (WRAP) and input datasets for all the river basins of Texas. TCEQ sponsored research at Texas A&M University over the past several years has included development of a daily version of the monthly WRAP/WAM modeling system. The thesis research focuses on improving capabilities for developing daily pattern hydrographs for use in disaggregating monthly WAM naturalized flow sequences to daily within the daily WRAP modeling system.

Comparative statistical analyses are performed for observed and synthesized river flows at numerous gage sites in the Brazos, Trinity, Neches, and Sabine River Basins. The datasets of monthly and daily flows investigated in the thesis include observed flows at U.S. Geological Survey (USGS) gages, TCEQ WAM System naturalized flows, unregulated flows from a U.S. Army Corps of Engineers (USACE) reservoir operations modeling system, and flows generated with the Soil and Water Assessment Tool (SWAT) and Hydrologic and Water Quality System (HAWQS) watershed rainfall-runoff modeling systems. Daily WRAP simulations of the four case study river basins for a 1940-2015 hydrologic period-of-analysis are performed with alternative flow disaggregation schemes. The USACE Hydrologic Engineering Center (HEC) Data Storage System (DSS) and HEC-DSSVue are employed in the compilation and comparative analyses of datasets.

Stream flow throughout Texas is extremely variable temporally with the extremes of floods and droughts as well as seasonal and continuous variability. The impacts of water resources development on river flows vary greatly between different locations. Impacts of upstream development are very different across the range of low to median to high flows. The HEC-DSSVue based approach for compiling, analyzing, comparing, selecting, and combining datasets significantly enhances the WRAP/WAM modeling system.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. Ralph Wurbs (advisor) and Dr. Huilin Gao of the Department of Civil Engineering and Dr. Clyde Munster of the Department of Biological and Agricultural Engineering.

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NOMENCLATURE

DSS	Data Storage System
HEC	Hydrologic Engineering Center
HEC DSSVue	HEC DSS Virtual Utility Engine
GSA	Guadalupe-San Antonio
SB1	Senate Bill 1 enacted by Texas Legislature in 1997
SB2	Senate Bill 2 passed by Texas Legislature in 2001
SB3	Senate Bill 3 enacted by Texas Legislature in 2007
TCEQ	Texas Commission on Environmental Quality
TWDW	Texas Water Development Board
USACE	United States Army Corps of Engineers
USBR	United State Bureau of Reclamation
USGS	United States Geological Survey
WAM	Water Availability Model
WR	Water Rights
WRAP	Water Rights Analysis Package

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CHAPTER I

INTRODUCTION

The research reported in this thesis focuses on comparative analyses of observed and synthesized sequences of daily stream flow volumes from the perspective of improving capabilities for disaggregating monthly naturalized flow volumes to daily volumes. The research investigates (1) river flow characteristics and the impacts of water resources development on flow characteristics, (2) capabilities for disaggregating monthly naturalized flows to daily, and (3) the sensitivity of water availability modeling results to the daily flow pattern hydrographs adopted in monthly-to-daily naturalized flow disaggregation.

1.1 Modeling Systems and Datasets Employed in the Research

The motivation for the research is the recent inclusion of daily modeling capabilities in the Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System to support analyses of environmental instream flow issues. The TCEQ WAM System consists of the generalized Water Rights Analysis Package (WRAP) modeling system and monthly WRAP simulation input datasets for all the river basins of Texas. WRAP and an input dataset for a particular river basin is called a water availability model (WAM). The WAM System routinely applied by the Texas water management community uses a monthly computational time step. The TCEQ has sponsored development of a daily version of WRAP at Texas A&M University (TAMU) over the past several years. WAM datasets of monthly naturalized flow volumes are disaggregated to daily volumes within the WRAP simulation model based on replicating the pattern of daily flow pattern hydrographs while preserving the monthly volumes.

Watershed rainfall-runoff modeling with the Soil and Water Assessment Tool (SWAT) and Hydrologic and Water Quality System (HAWQS) is one of the several alternative strategies for developing streamflow input for the WAMs investigated in the thesis. HAWQS is designed to simplify the application of SWAT as discussed in Chapter IV.

The Brazos, Trinity, Neches, and Sabine River Basin water availability models (WAMs) serve as case studies for the research. The modeling and comparative analyses studies presented in the thesis deal with the following monthly and daily stream flows at gauging station sites in the case study river basins.

- Observed daily flows at U.S. Geological Survey (USGS) gauging stations available from the National Water Information System (NWIS) website maintained by the USGS and monthly aggregations thereof.
- Monthly naturalized flows from the TCEQ WAM System developed by the TCEQ and its contractors by adjusting observed flows to remove the effects of water resources development, regulation, and use.
- Extensions (updates) through 2015 of the WAM naturalized flows developed at TAMU using a WRAP hydrologic model and other alternative methods.
- Unregulated daily flows from a U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) reservoir operations modeling system developed by the USACE by adjusting observed flows to remove the effects of reservoir regulation.

- Daily flows for natural conditions synthesized from observed daily rainfall using the SWAT and HAWQS watershed rainfall-runoff modeling systems.

Naturalized flows represent natural river system hydrology without the effects of reservoirs, water supply diversions, return flows, and other human activities. The literature also uses the terms virgin, unimpaired, or unregulated flows to refer to naturalized flows. The Texas WAM System includes datasets of monthly naturalized streamflow volumes. The WRAP simulation model includes an algorithm for disaggregating monthly naturalized flow volumes to daily volumes based on daily flow pattern hydrographs while preserving the monthly volumes. The thesis research focuses on developing WRAP input datasets of daily pattern hydrographs.

The research focuses on daily flows but also addresses issues that are relevant to both monthly and daily flows such as period-of-analysis updates (extensions), filling in gaps of missing data, and adjusting gauged flow to develop naturalized flow, as well as disaggregating monthly naturalized flows to daily.

In addition to improving WRAP/WAM modeling capabilities, the research also contributes to a better understanding of the characteristics of daily flows and their long-term changes due to human water development and use. Long-term changes in low flows are very different than changes in high flows and median flows. Flow characteristics are viewed here largely from the perspective of flow regimes relevant to environmental instream flow requirements and issues.

1.2 Flow Disaggregation Methods Reported in the Literature

Various approaches for disaggregating monthly flows to daily have been reported in the literature. Several representative strategies and applications are cited as follows.

Many stochastic hydrology models reported in the literature synthesize long sequences of annual or monthly flows based on reproducing statistical characteristics of historical flows and then in some cases disaggregating the synthesized annual flows to monthly or disaggregating monthly flows to daily based on preserving prescribed statistics (Hann, 2002; Mejia & Rousselle, 1976; Kumar et al., 2000; Portela & Silva, 2016).

Acharya & Ryu, (2013) disaggregated streamflow from monthly to daily using an elementary and adaptive method applied in northwestern states such as Idaho and Wyoming for both regulated and unregulated waterways. Target and source stations are chosen based on minimum error criteria. Daily streamflow indexes are calculated at the source station which are then used to calculate daily streamflow at the target station, preserving both statistical characteristics and mass balance.

Smakhtin (2000) estimated daily flow duration curves from monthly streamflow in South Africa. Flow duration curves are proposed as a valid substitute for complete time series under certain circumstances. The method is stated to be especially useful for regions having large gaps of missing data or observed data available for only very short durations.

Many studies reported in the literature combine watershed rainfall-runoff models with flow disaggregation techniques. Asefa et al. (2014) developed a model for assessing water supply capabilities of a complex surface water system in Florida that included stochastically generating 300 years of monthly streamflows at multiple sites that were then disaggregated to daily flows using a non-linear multi-variate nonparametric disaggregation procedure. Meza et al. (2012) evaluated the impacts of climate change on the reliability of irrigation water rights in Chile with a complex model that incorporated rainfall-runoff modeling and stochastic stream disaggregation to synthesize annual, monthly, and daily flows.

Hughes and Slaughter (2015) report methods developed to disaggregate monthly flows to daily in South Africa that combine a monthly rainfall-runoff model and a daily rainfall based disaggregation technique to simulate daily flows. Daily flows were computed from simulated monthly flows using different rainfall datasets. Satellite data were used as a substitute for missing data as well as for interpolation purposes. Monthly flows generated using the Pitman model were disaggregated using different rainfall products on a regional basis covering different climatic and topographic characteristics at a catchment level.

Slaughter et al. (2015) report other work in South Africa involving incorporation of a monthly-to-daily stream flow disaggregation model into a water quality model. The streamflow input data for the water quality model was synthesized through a multiple-step procedure based on generating monthly and daily flow duration relationships.

Kim (2015) used SWAT to produce daily pattern hydrographs for input to WRAP for use in disaggregating monthly naturalized flows to daily. The research study performed at Tarleton State University in Texas used the Upper Oyster Creek near the City of Houston as a case study. As discussed later in this thesis, Ryu (2015) applied SWAT to develop daily pattern hydrographs for the Neches, Sabine, and Guadalupe-San Antonio (GSA) WAMs for use in the WRAP disaggregation of monthly naturalized flows to daily.

Wurbs (2017) reviews the literature dealing with assessing the impacts of development on river flows and discusses flow characteristics and changes in flow characteristics of the rivers of Texas. Long-term trends as well as seasonal and continuous variability in precipitation, evaporation, and annual, monthly, and daily river flows in Texas are explored.

1.3 Research Scope and Objectives

The overall objectives of the research are (1) to develop an improved understanding of characteristics of observed river flows and naturalized flows generated using alternative methods and (2) to improve WRAP/WAM monthly-to-daily naturalized flow disaggregation capabilities. The research includes the following tasks.

- Strategies and methods for compiling daily flow pattern hydrographs for input to the daily WAMs are reviewed. Key issues such as gaps in missing data and dealing with varying degrees of flow alteration at different sites over different time periods are explored.
- Comparative analyses of observed and synthesized flows in the case study river systems (Brazos, Trinity, Neches, and Sabine Rivers and their tributaries) are performed to study daily flow characteristics and the impacts of water resources development on daily flow characteristics and assess alternative strategies for compiling WAM daily flow pattern hydrographs. The analyses include time series plots and statistical frequency metrics.

- The feasibility of employing SWAT and HAWQS to synthesize daily flows is investigated. Comparative analyses of flows generated with SWAT and HAWQS versus observed flows and adjusted observed flows are performed. Calibration issues are addressed.
- WRAP simulation studies employing the Brazos, Trinity, Neches, and Sabine daily WAMs are performed to assess modeling issues and the effects on simulation results of choices regarding daily flow pattern hydrographs provided as model input.

The thesis is organized as follows. The WRAP and WAM modeling systems are discussed in Chapter 2 focusing on WRAP modeling features and WAM hydrology datasets that are particularly relevant to the thesis research. The four case study river basins and their WAMs are described in Chapter 3. Alternative datasets of monthly and daily stream flow at sites in the four case study river systems available from different sources are described in Chapter IV. An investigation of the recently developed HAWQS as another alternative for acquiring daily flow data is presented in Chapter V. Comparative analyses of observed daily flows and synthesized daily flows generated by alternative methods are presented in Chapter VI. Chapter VII provides an analysis of the sensitivity the WRAP/WAM simulation results to different sets of daily pattern hydrographs. The research is summarized, and conclusions are discussed in the final Chapter VIII.

CHAPTER II

WATER RIGHTS ANALYSIS PACKAGE (WRAP) AND TEXAS WATER AVAILABILITY MODELING (WAM) SYSTEM

2.1 Water Rights Analysis Package (WRAP) Modeling System

WRAP combines a defined scenario of river/reservoir system development, management, allocation, regulation, and use with hydrologic period-of-analysis natural river system hydrology (Wurbs 2015a, 2015b, 2015c, Wurbs and Hoffpauir, 2015). The simulation model produces naturalized flows, regulated flows, unappropriated flows, reservoir storages, water supply diversions, hydroelectric energy, and other relevant quantities for each computational time step (month or day) of a long hydrologic period-of-analysis, such as 1940-2015. Water supply reliability metrics and flow and storage frequency statistics are computed for the various time series quantities generated in the simulation. The WRAP software and manuals and related datasets and reports can be found at https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm .

WRAP is comprised of the computer programs described in Table 1. Executable files are available for use on desktop PCs with the Microsoft Windows working framework. WinWRAP is a user interface which connects executable programs and data files. The simulation model SIM employs a monthly computational time step. The daily simulation model SIMD has all the modeling capabilities of SIM plus major additional features required and/or enabled by the conversion from a monthly to daily time step. The post-simulation program TABLES provides for options for performing reliability and frequency analyses and otherwise organizing and analyzing SIM and SIMD simulation results.

Table 1 WRAP programs (Wurbs, 2015)

Program	Description
WinWRAP	Interface for applying WRAP on personal computers with the Microsoft Windows operating system.
SIM	Monthly time step model for simulating water resources development, allocation, regulation, management, and use.
SIMD	Expanded version of SIM with additional features for sub-monthly (such as daily) time steps, flow forecasting and routing, and flood control reservoir operations.
TABLES	Post-simulation program for developing frequency relationships, reliability indices, and various user-specified tables and tabulations for organizing, summarizing, analyzing, and displaying simulation results.
HYD	Pre-simulation program for developing monthly naturalized stream flow and reservoir net evaporation-precipitation rate data for SIM hydrology input files.
DAY	Pre-simulation program for calibrating routing parameters and disaggregating monthly to daily flows for SIMD input.
SALT	Salinity simulation component of WRAP modeling system.

The monthly WRAP has been routinely applied within the TCEQ WAM System since about 2002. The TCEQ sponsored development at Texas A&M University of the daily WRAP modeling capabilities during the past several years to address environmental instream flow requirements (Wurbs and Hoffpauir, 2013, 2015). The daily version of WRAP is still in a developmental testing phase.

2.2 Water Availability Modeling (WAM) System

The Texas Commission of Environmental Quality (TCEQ), Texas Water Development Board (TWDB), and Texas Park and Wildlife Department (TPWD) and their contractors (two universities and ten engineering consulting firms) originally implemented the WAM System during 1997-2002 in accordance with water management legislation called Senate Bill 1 (SB1) enacted by Texas Legislature in 1997 (Wurbs, 2005, 2016). The WAM System maintained by the TCEQ consists of the generalized WRAP modeling system and WRAP input datasets for all of the river basins of Texas. WRAP combined with a dataset from the WAM System for a particular river basin is called a water availability model (WAM). The WAMs are routinely applied in regional and statewide planning, administration of the statewide water rights permit system, and other water management activities.

The Texas Instream Flow Program was created by Senate Bill 2 (SB2) enacted by the Texas Legislature in 2001. Senate Bill 3 (SB3) enacted in 2007 created a process for establishing environmental flow standards and incorporating the standards in the TCEQ WAM System. The original WRAP/WAM modeling system is based on a monthly computational time step. A daily modeling time step is required to accurately model the SB3 environmental flow standards incorporated in the WAMs and to support continuing SB2 environmental flows studies. This motivated sponsorship by the TCEQ of development of daily WRAP capacities at TAMU over the past several years. WRAP has been expanded and developmental daily WAMs have been developed for the Brazos, Trinity, Neches, Sabine, Guadalupe-San Antonio (GSA), and Colorado WAMs.

The TCEQ WAM System consists of WRAP and 20 WRAP input datasets covering the 15 major river basins and 8 coastal basins of Texas shown in Figure.1 The WAM datasets include the following major components: (1) hydrologic period-of-analysis sequences of monthly naturalized stream flows and reservoir net evaporation-precipitation rates, (2) parameters for distributing monthly naturalized flows from known-flow (gaged) to unknown-flow (ungaged) sites, and (3) information describing water resources development, management, allocation, and use. The daily WAM datasets include the addition of routing parameters, monthly-to-daily disaggregation specifications, and daily pattern hydrographs used within SIMD in disaggregating monthly naturalized flow volumes to daily volumes.

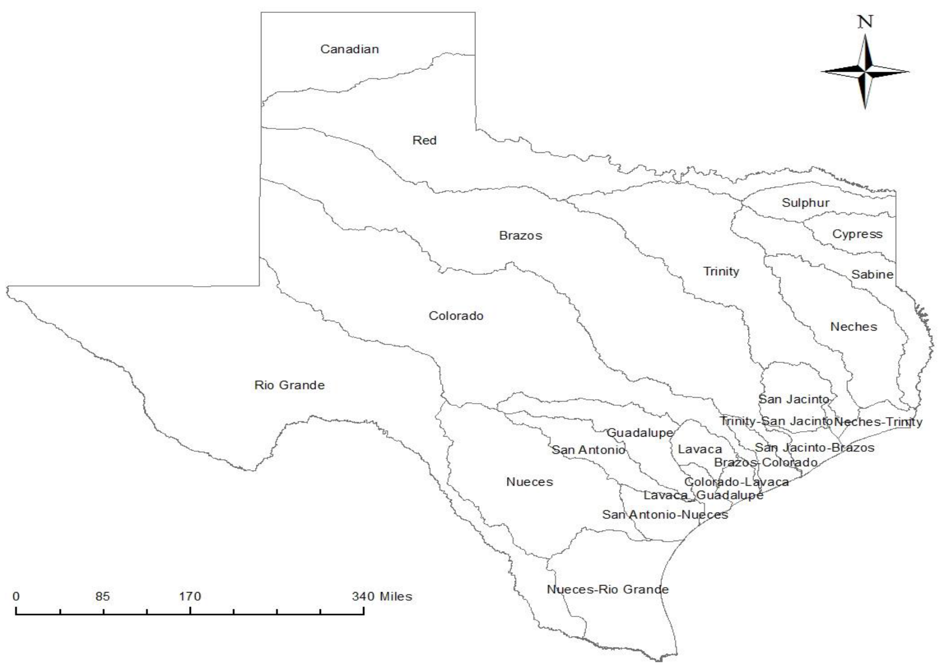

Figure 1. Texas WAM River Basins

2.3 USACE HEC Data Storage System (DSS) and HEC-DSSVue

The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) has developed a number of generalized hydrologic, hydraulic, and water management simulation models that are available for download free-of-charge from the HEC website http://www.hec.usace.army.mil/. HEC models are applied extensively by government agencies and engineering companies throughout the United States and various other countries.

The HEC Data Storage System (DSS) is used routinely with HEC simulation models and is also used with other non-HEC modeling systems including WRAP. Data is stored in DSS files in a direct access binary format. DSS files can be created, written to, and read only with software with DSS capabilities. Capabilities for creating and accessing DSS files are incorporated in software such as the WRAP programs by linking during compilation to routines from a HEC-DSS library of computer code developed by the HEC (Wurbs, 2015).

HEC-DSS and HEC-DSSVue are designed for efficiently working with large datasets of time series data. The HEC-DSS Visual Utility Engine (HEC-DSSVue) is a graphical user interface program for managing, viewing, editing and graphing data in DSS files and performing statistical analyses and arithmetic operations. Data can be conveniently exchanged between HEC-DSSVue and Microsoft Excel. HEC-DSSVue directly accesses the U.S. Geological Survey (USGS) National Water Information System (NWIS) website and other online data sources. HEC-DSSVue is explained in detail by a user's manual (Hydrologic Engineering Center, 2009) available at the HEC website along with the software.

The WRAP programs are applied in combination with HEC-DSSVue to create and employ DSS files. The WRAP programs include optional features for reading hydrology input data from DSS files or writing simulation results to DSS files. HEC-DSS and HEC-DSSVue were used with WRAP in the past primarily for plotting simulation results generated with the WRAP programs. However, additional DSS features have been added to the WRAP programs during 2016-207. HEC-DSS and HEC-DSSVue are fully integrated components of the current version of WRAP that will be publically released later in 2017. HEC-DSSVue was employed extensively in compiling and analyzing the stream flow datasets discussed in this thesis.

2.4 Hydrology Update and Refinement Studies for the Daily WAMs

Development of daily modeling capabilities to supplement the monthly WRAP/WAM System has been motivated by the Texas Instream Flow Program created by the 2001 Senate Bill 2 and establishment of environmental flow standards pursuant to the 2007 Senate Bill 3. Daily features of WRAP are documented by Wurbs and Hoffauir (2015). Daily versions of the WRAP input datasets for the Brazos, Colorado, Trinity, Neches, Sabine, and Guadalupe and San Antonio (GSA) River Basins were created under the sponsorship of the TCEQ during 2012-2014 at TAMU. The six daily WAMs are documented by a series of TCEQ contract reports (Wurbs, Hoffpauir, and Schnier, 2012; Wurbs and Hoffpauir, 2013; Hoffpauir, Pauls, and Wurbs, 2013; Hoffpauir, Pauls, and

Wurbs, 2014; Wurbs, Hoffpauir, Pauls, Ryu, and Bista, 2014; Wurbs, Ryu, Pauls, and Hoffpauir, 2014; Wurbs, 2015).

Continued improvements to WRAP modeling capabilities during 2015-2017 are being documented by the next edition of the WRAP manuals to be completed later in 2017. The six case study daily WAM datasets are also being updated and expanded. A new DSS-based strategy for updating and improving monthly and daily WAM hydrology has been applied to the Trinity, Brazos, and Neches and Sabine WAMs (Wurbs, 2017a; Wurbs, 2017b; Wurbs and Verma, 2017). The same general strategy is currently being applied to the other three daily WAMs. The hydrology updates of the WRAP simulation input datasets include (1) extending the monthly naturalized flows through December 2015, (2) extending the monthly net evaporation-precipitation rates through 2015; and (3) developing datasets of daily pattern hydrographs. The work also includes compilation of other related datasets in the process of creating the updated/refined WAM hydrology input datasets for the WRAP simulation model. The compilation, analysis, selection, and management of the datasets are accomplished using DSS files and HEC-DSSVue.

The comparative analyses of stream flows presented in the following chapters of this thesis are based upon the datasets described in the preceding paragraphs. The following four of the six daily WAMs are investigated in the thesis research: Brazos, Trinity, Neches, and Sabine. These river basins are described in Chapter III by replicating information from the daily WAM reports cited in the first paragraph of this section (Section 2.4).

General information regarding the hydrology datasets for the four daily WAMs adopted as case studies for the thesis is provided in Table 2. For example, the following information regarding the Brazos WAM is provided in Table 2. The hydrologic period-of-analysis of 1940-1997 in the TCEQ WAM System has been recently updated at TAMU to cover 1940-2015. The Brazos WAM has a total of 3,852 control points. 1940-2015 naturalized monthly flows at 77 primary control provided as simulation input, and flows at the other 3,775 secondary control points are synthesized within the simulation based on flows at the 77 primary control points and input watershed parameters. Sixty-seven 1940-2015 sequences of monthly net evaporation less precipitation depths are input for use in the simulation for computing evaporation-precipitation volumes at 719 reservoirs.

Table 2. Daily WAMs Adopted for the Thesis Research

Water availability model (WAM)	Brazos	Trinity	Neches	Sabine
Original period-of-analysis	1940-1997	1940-1996	1940-1996	1940-1998
Daily WAM period-of-analysis	1940-2012	1940-2012	1940-2013	1940-2013
Updated period-of-analysis	1940-2015	1940-2015	1940-2015	1940-2015
Total number of control points	3,852	1,403	313	387
Primary control points	77	40	20	27
Secondary control points	3,775	1,363	293	360
Daily flow input control points	58	49	17	17
Evaporation-precipitation rates	67	50	12	20
Number of reservoirs	719	697	180	212
	Number of Sites with Daily Flow Data			
USGS observed flow sites	74	38	16	17
USACE unregulated flow sites	37	49	none	none
(period covered by daily flows)	(1940-1997)	(1940-2009)	-	-
SWAT synthesized flow sites	none	none	20	21
(period covered by daily flows)	-	-	(1940-2013)	(1940-2013)

Information regarding the datasets of daily flows investigated in the thesis research is provided in the bottom part of Table 2. Observed daily flows are compiled at 74, 38, 16, and 17 USGS gaging stations in the Brazos, Trinity, Neches, and Sabine River Basins. The periods-of-record vary between the gaging stations. Unregulated daily flows from the USACE modeling system extending from January 1940 through December 1997 are available for 35 locations in the Brazos River Basin, for 1940-2009 at 20 sites in the Trinity, and for 1929-2011 at five sites in the Neches Basin. Daily flows extending from January 1940 through December 2013 for natural undeveloped watershed conditions at 20 locations in the Neches and 21 locations in the Sabine River Basin were developed in previous studies (Ryu, 2015). Most of the sites of SWAT and USACE daily flows are at USGS gages.

CHAPTER III

CASE STUDY WAMS

The 15 major river basins and eight coastal basins of Texas are delineated by the Texas Water Development Board (TWDB) in Figure 2 and modeled in the Water Availability Modeling (WAM) System maintained by the Texas Commission on Environmental Quality (TCEQ).

Figure 2 Major River Basins of Texas by TWDB

This research thesis deals with the Brazos, Trinity, Neches and Sabine River Basins and associated water availability models (WAMs). Reports, datasets, software, manuals and related input files for the WAMs can be accessed from https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm.

3.1 Neches River Basin

Neches River Basin is located in the east of Texas as shown in Figure 3. It is the fourth largest river basin by average flow volume. October 2012 Authorized use scenario consisted of 313 control points with only 20 primary control points at USGS gaging station as tabulated in Table 3 and illustrated in Figure 4. Furthermore, the latest Neches WAM consists of 180 reservoirs, out of which 13 reservoirs have the storage capacity greater than 5,000 acre-feet constituting 98.7% of total storage volume as illustrated in Figure 5.

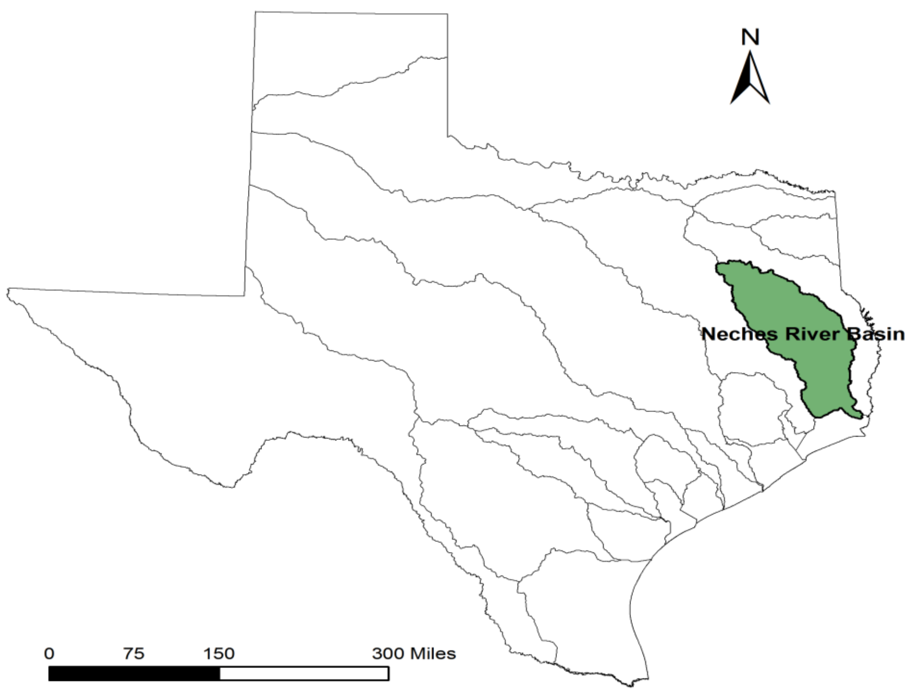

Figure 3 Neches River Basin (Wurbs et al., 2014)

Table 3 System Components in Neches WAM (Wurbs and Verma, 2016)

Latest Update of Datasets	Oct 2012	Sep 2012
Water Use Scenario	Authorized	Current
Filename	Neches3	Neches8
total number of control points	313	395
number of primary control points	20	20
control points with evaporation-precip rates	12	12
number of reservoirs as counted by *SIM*	180	203
number of *WR* record water rights	362	385
number of instream flow *IF* record rights	25	78
number of *FD* records in DIS file	273	289

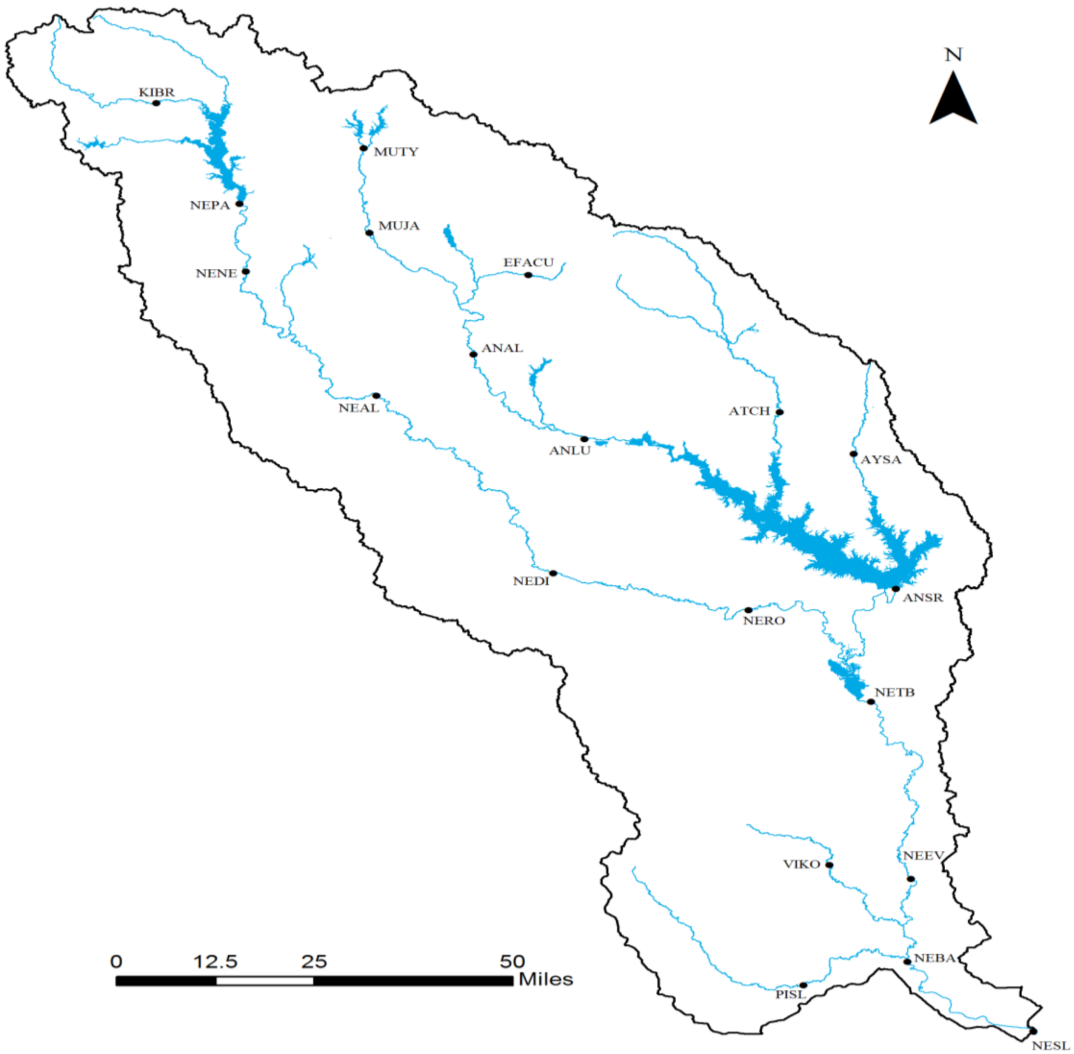

Figure 4 Control points in the Neches River Basin (Wurbs et al., 2014)

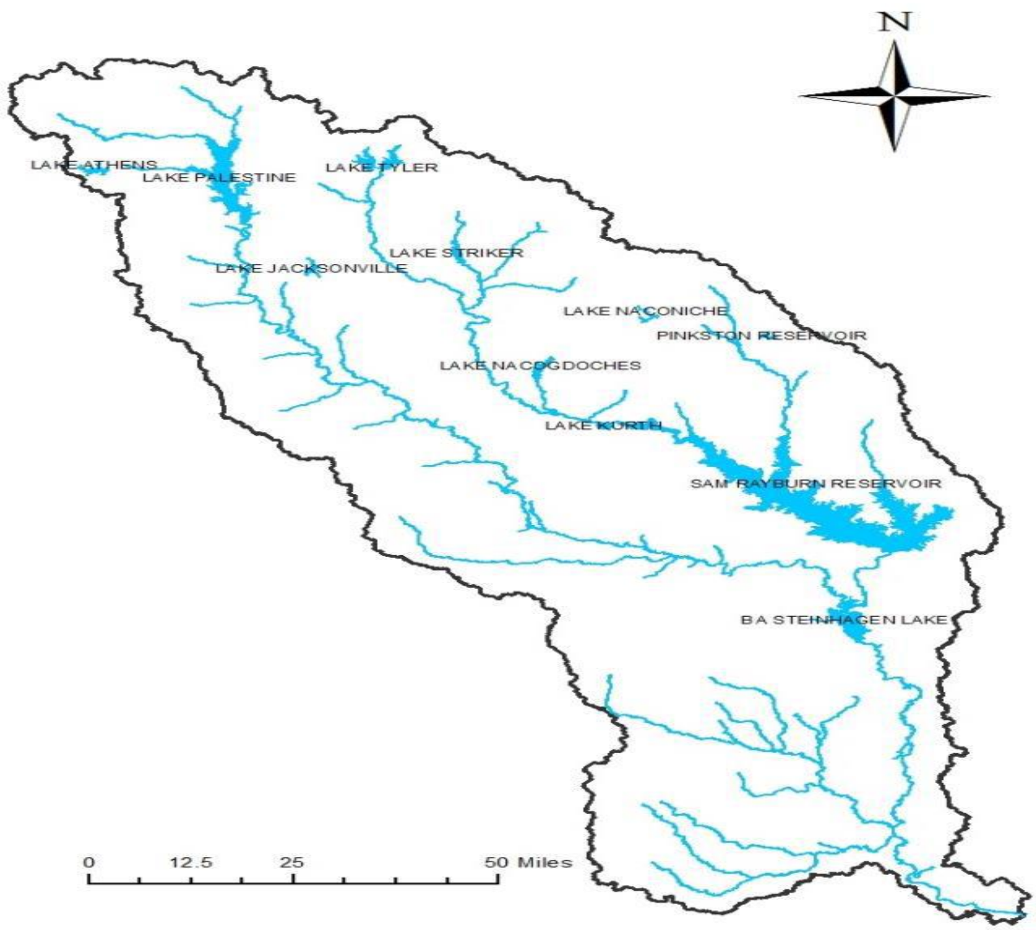

Figure 5 Major tributaries and Reservoirs in Neches River Basin (Ryu, 2015)

3.2 Sabine River Basin

Sabine River Basin is also located in the east of Texas as shown in Figure 6. It has the second largest average flow volume in Texas. June 2004 Authorized use scenario consisted of 376 control points with only 17 primary control points at USGS gaging station as tabulated in Table 4 and illustrated in Figure 7. Furthermore, the latest Sabine WAM consists of 207 reservoirs, out of which 13 reservoirs have the storage capacity greater than 5,000 acre-feet constituting 99% of total storage volume as shown in Figure 8.

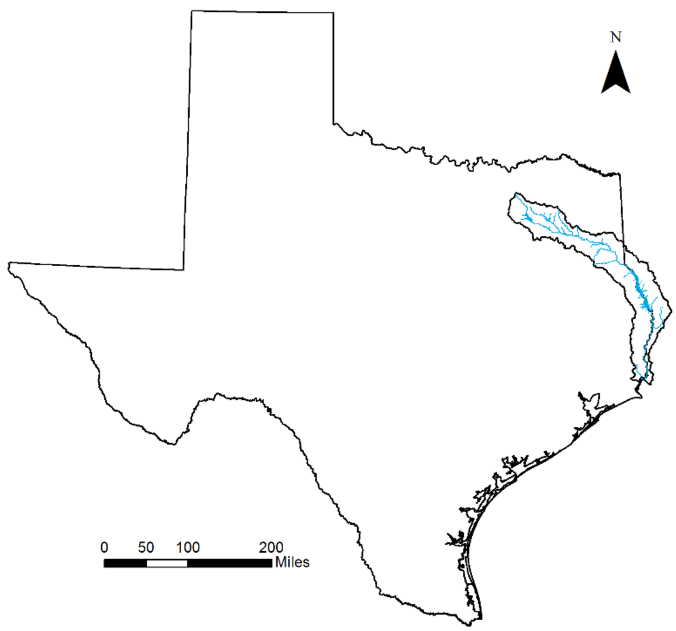

Figure 6 Sabine River Basin (Wurbs et al., 2014)

Table 4 Number of System Components in Sabine WAM Datasets (Wurbs et al., 2014a)

Latest Update of Datasets Water Use Scenario Filename	June 2004 Authorized sabine3	June 2004 Current sabine8
total number of control points	376	375
number of primary control points	27	27
control points with evaporation-precip rates	20	20
number of reservoirs as counted by *SIM*	207	206
number of *WR* record water rights	310	314
number of instream flow *IF* record rights	21	21
number of system water rights	18	18
number of drought index *FA* records	0	0
number of *FD* records in DIS file	347	346

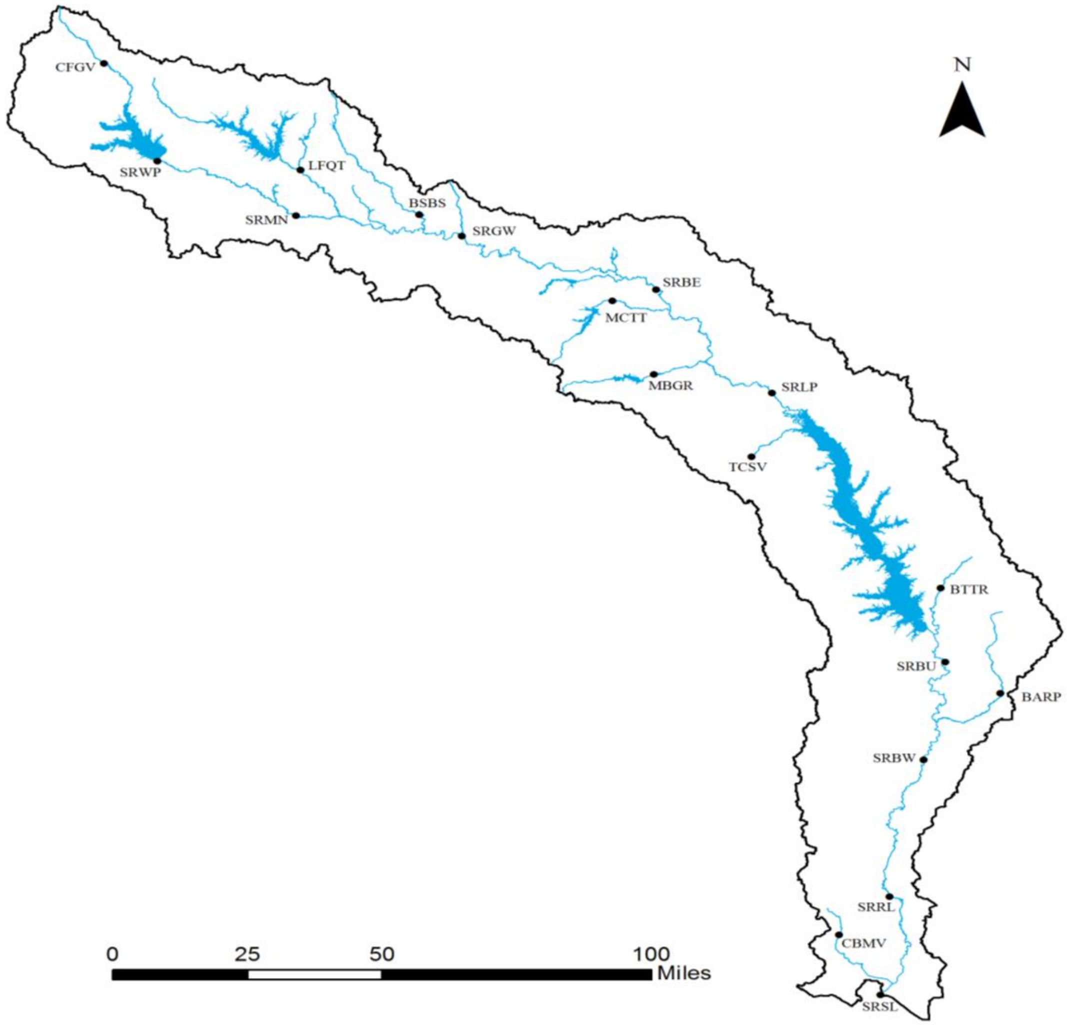

Figure 7 Control points in the Sabine River Basin (Wurbs and Verma, 2016)

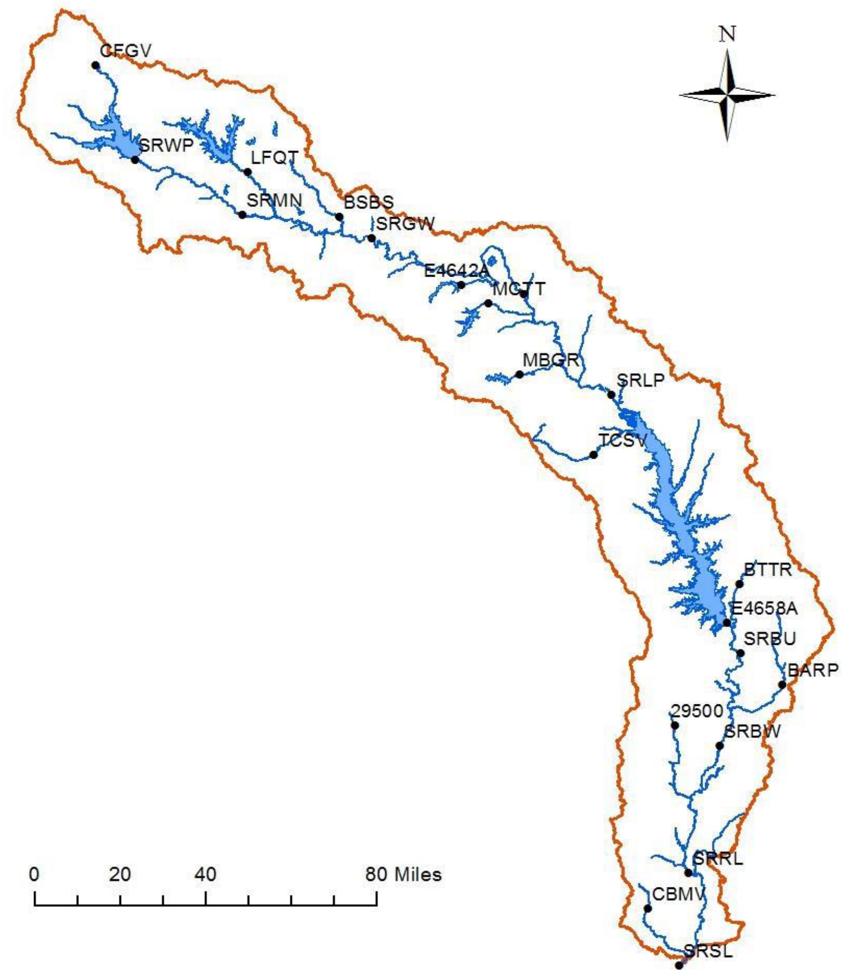

Figure 8 Major tributaries and Reservoirs in Sabine River Basin (Ryu, 2015)

3.3 Trinity River Basin

Trinity River Basin is located in the north-eastern side of Texas as shown in Figure 9. It has the third largest average flow volume in Texas. October 2012 Authorized use scenario consisted of 1403 control points with only 39 primary control points at USGS gaging station as tabulated in Table 5 and illustrated in Figure 10. Additionally, the latest Trinity WAM consists of 697 reservoirs, out of which 32 reservoirs have the storage capacity greater than 5,000 acre-feet constituting 98% of total storage volume as illustrated in Figure 11.

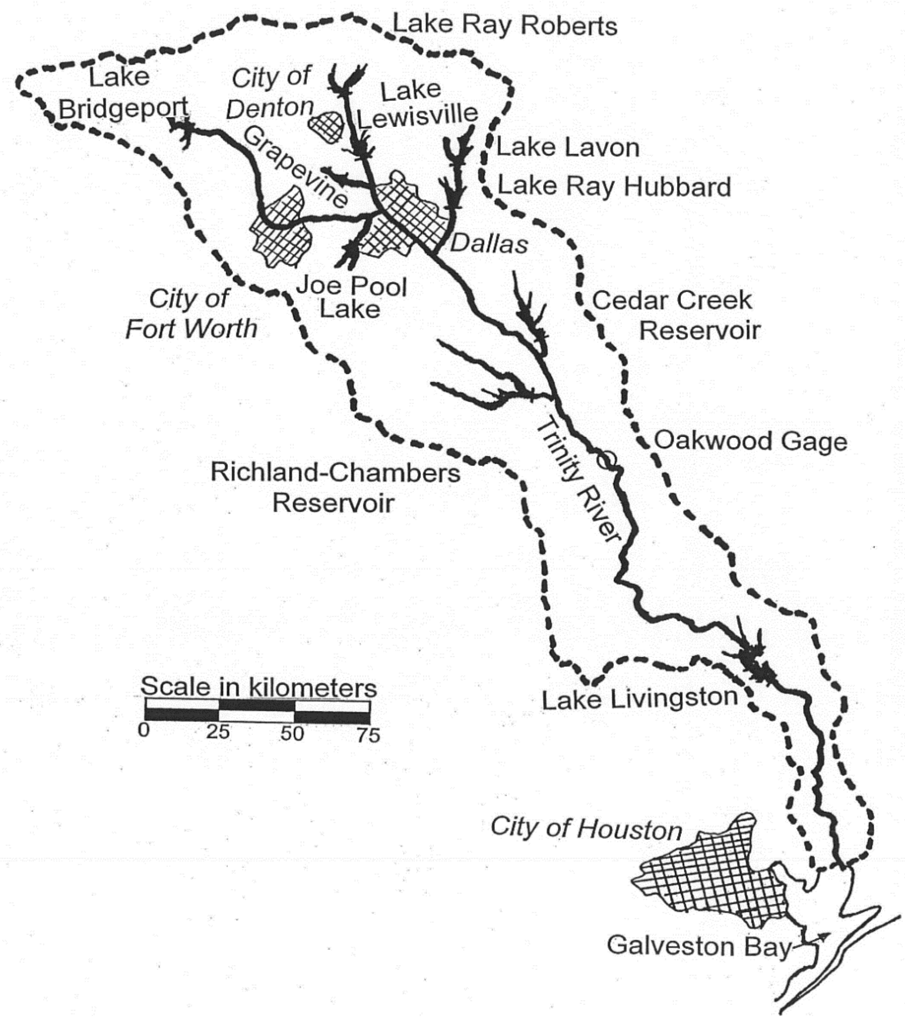

Figure 9 Trinity River Basin (Wurbs, 2016)

Table 5 Number of System Components in Trinity WAM (Wurbs, 2016)

Latest Update of Datasets Water Use Scenario Filename	Oct 2012 Authorized trin3	Oct 2012 Current trin8	Oct 2014 Authorized trin3
total number of control points	1,398	1,418	1,403
number of primary control points	40	40	40
control points with evaporation-precip rates	50	50	50
number of reservoirs as counted by *SIM*	697	700	697
number of *WR* record water rights	1,061	1,067	1,057
number of instream flow *IF* record rights	71	89	71
number of *FD* records in DIS file	1,246	1,247	1,251

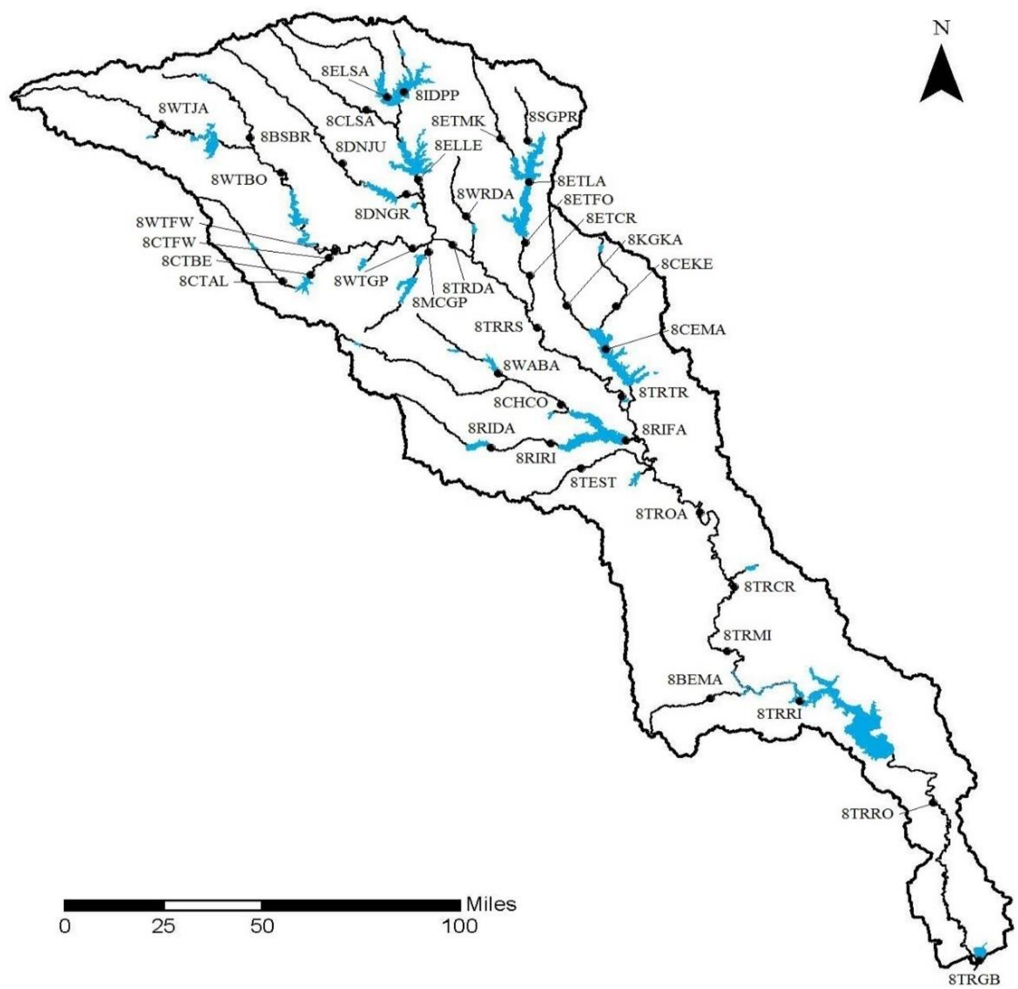

Figure 10 Control points in the Trinity River Basin (Hoffpauir et al., 2014)

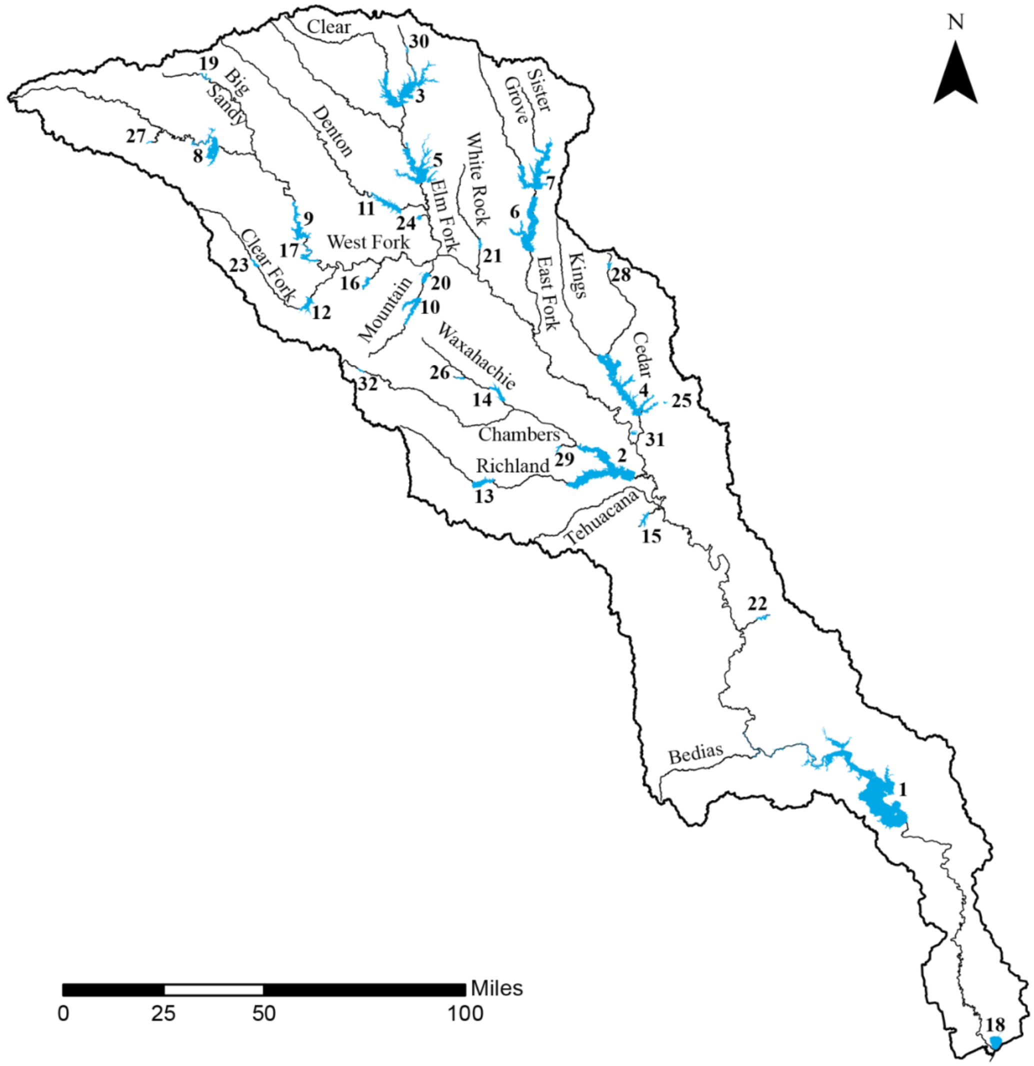

Figure 11 Major tributaries and Reservoirs in Trinity River Basin (Hoffpauir et al., 2014)

3.4 Brazos River Basin

Brazos River Basin, as shown in Figure 12, is the second largest river basin by area in Texas. September 2008 Authorized use scenario consist of 3,842 control points with other system components as tabulated in Table 6. Brazos control points are illustrated schematically in Figure 13. Furthermore, the latest Brazos WAM consists of 678 reservoirs, out of which 16 largest reservoirs are depicted in Figure 14.

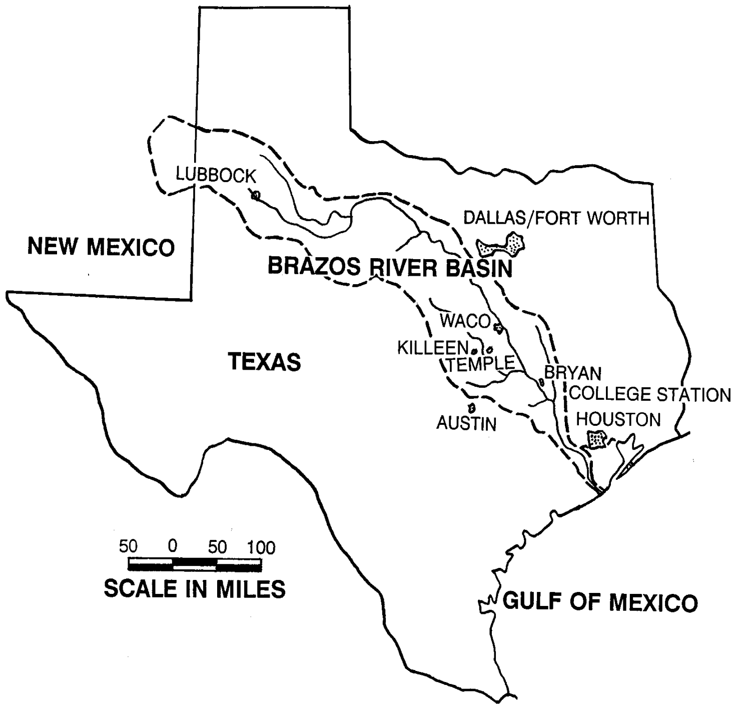

Figure 12 Brazos River Basin and San Jacinto-Brazos Coastal Basin (Wurbs, 2016)

Table 6 Number of System Components in Brazos WAM (Wurbs, 2016)

Latest Update of Datasets Water Use Scenario Filename	Sep 2008 Authorized Bwam3	Sep 2008 Current Bwam8
total number of control points	3,842	3,852
number of primary control points	77	77
control points with evaporation-precip rates	67	67
number of reservoirs as counted by *SIM*	678	719
number of water right *WR* records	1,643	1,734
number of instream flow *IF* records	122	145
number of *FD* records in DIS file	3,152	3,157

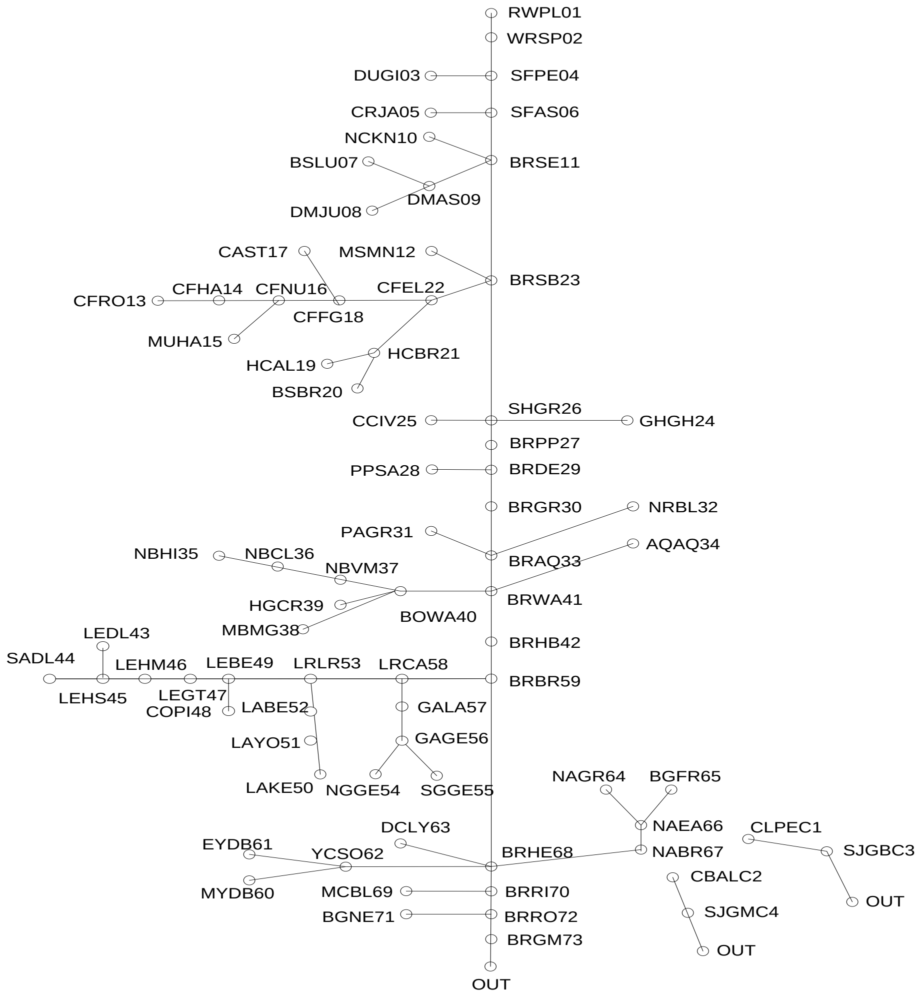

Figure 13 Schematic representation of Control Points in the Brazos River Basin

(Wurbs et al., 2012)

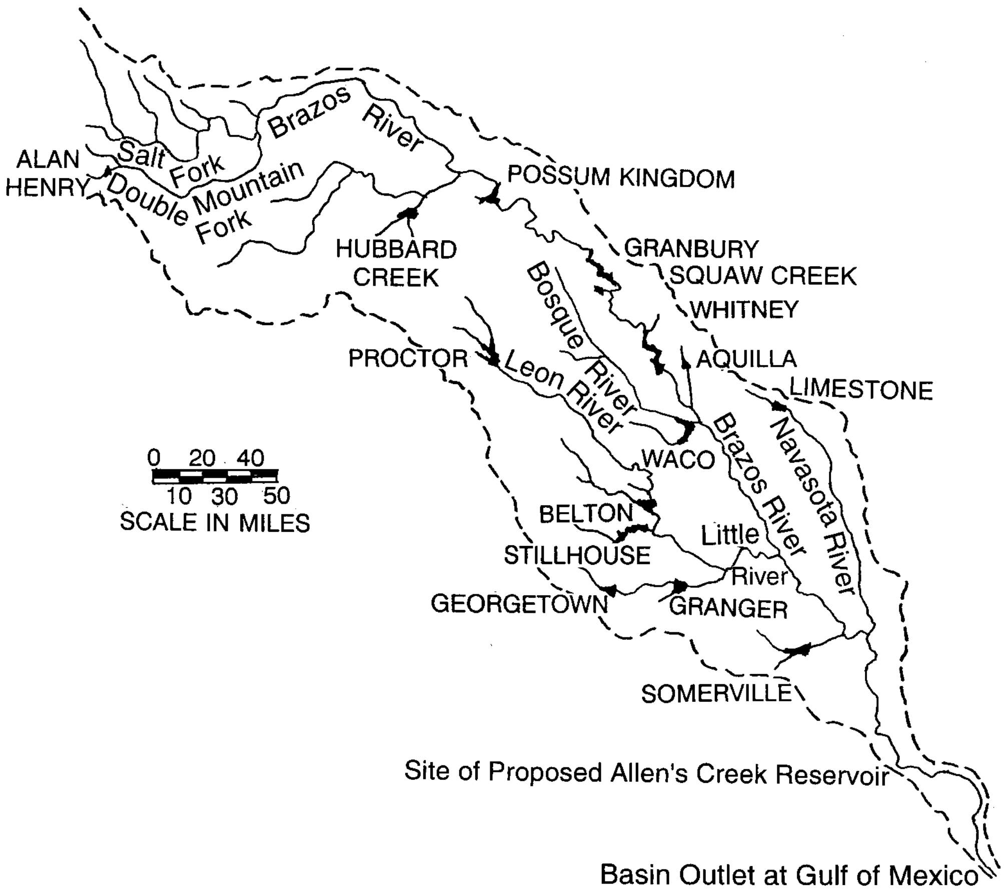

Figure 14 Major tributaries and largest reservoirs in the Brazos River Basin (Wurbs et al. 2012)

CHAPTER IV

ALTERNATIVE FLOW DATASETS

This chapter explores the availability of different datasets with sequences of stream flows for all the river basins of Texas, which includes unregulated flows from U.S. Army Corps of Engineers (USACE), Soil and Water Assessment Tool (SWAT) and Hydrologic and Water Quality System (HAWQS) generated simulated flows from rainfall-runoff modeling system, gaged flows from U.S. Geological System (USGS) and monthly naturalized flow volumes from Water Availability Modeling (WAM) system.

4.1 U.S. Army Corps of Engineers (USACE) Daily Unregulated Flows

The U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) developed a modeling system on a daily time step especially for operating flood control operations in multiple-purpose reservoirs. Earlier SUPER, a river/reservoir simulation model, was used now replaced with RiverWare and ResSim. The total regulated flows at a control point are calculated by accumulating incremental unregulated streams. The unregulated flows computed by USACE are developed by similarly adjusting gaged flows like that of WAM naturalized flows. Therefore, USACE unregulated flow is similar to WAM naturalized flow and used interchangeably. The only difference is in computational method involved in adjusting gaged flows. Unregulated daily naturalized flows are aggregated within HEC-DSSVue for synthesizing unregulated monthly naturalized flows. Earlier, daily unregulated flows were only used as pattern flow hydrographs (Wurbs and Hoffpauir, 2013).

Brazos and Trinity River Basin comprises nine and eight reservoirs respectively, which is owned and operated by USACE Fort Worth District. In total, there are twenty-four reservoirs in whole Texas which are owned and operated by USACE Fort Worth District.

The daily unregulated flows for the Brazos, Trinity, and Neches covers the period of analysis from 1940-1997, 1940-2009 and 1929-2011 respectively. These streamflows are available at 37 sites for Brazos, at 30 primary and 19 secondary points for Trinity and at 5 control points for Neches River Basin.

4.2 Soil and Water Assessment Tool (SWAT) Flows

SWAT is a generalized, physical based, semi-distributed rainfall-runoff model used for simulating hydrologic processes (Arnold et al., 2012a, 2012b; Neitsch et al., 2011). It is a public domain software which is jointly developed, maintained and updated by the U.S. Department of Agriculture - Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research, which is also a part of Texas A&M University. The input and output documentation (Arnold et al., 2012a), user manual covers in depth about the software. The other relevant information is available at SWAT website: http://swat.tamu.edu/.

SWAT simulates hydrologic processes which calculate runoff in stream flows based on rainfall (Singh and Frevert, 2006). It can also simulate erosion, sedimentation, and water quality for any type, size, and kind of watersheds. Land use, agricultural and management practices, water quantity and quality of river basins can be analyzed using SWAT.

The input data for SWAT are rainfall, land use land cover (LU/LC), soil type, digital elevation models (DEMs), climatic conditions and other watershed parameters. SWAT simulates river basin hydrology on a daily, monthly and annual time scale based on above inputs. SWAT divides a watershed into subbasins and further divide subbasins into homogeneous spatial units known as Hydrological response units (HRUs) based on the similar characteristics of soil, land cover and other topographical conditions. HRUs are the basic computation unit in SWAT.

Digital Elevation Models (DEMs) are used by SWAT to delineate watersheds and for estimating hydraulics parameters like channel length, slope, etc. DEM data are available at different resolutions such as 1m, 2m, 5m, 10m, 30m and so on. The SWAT flows were generated by using 30m resolution data.

SWAT uses STATSGO for estimating Natural Resource Conservation Service (NRCS) curve number (CN), and other geological characteristics of the selected basin. Originally, STATSGO was developed at 1995, updated in 2006 and further updated in 2010 by NRCS. Land cover and DEMs are also obtained from NRCS website.

The SWAT weather generator automatically generates daily rainfall, temperature, humidity and other weather data. The model uses nearest centroid of each subbasin for calculating the missing values of rainfall and other weather station values. SWAT calculates surface runoff by the Natural Resource Conservation Service (NRCS) curve number method. It also computes base flow, ground water flow, sub-surface flows. Manning's equation is used for calculating surface runoff and Muskingum method for routing purposes.

SWAT incorporates various losses such as evaporation, transpiration, infiltration and transmission losses. One of the advantages of this model is it separately calculates evaporation and transpiration. Evaporation is calculated from the soil using exponential functions of soil depth and water content and transpiration from plants using the linear function of potential evapotranspiration and leaf index area. For calibrating and validating the hydrologic model, certain standard statistics which are widely used such as regression correlation coefficients (R^2) and the Nash-Sutcliffe model efficiency (NSE) coefficient (Nash and Stucliff, 1970) is applied.

The SWAT rainfall-runoff model is used for developing daily Neches, Sabine and Guadalupe and San Antonio (GSA) WAM which were used as daily pattern hydrograph for disaggregating monthly naturalized flows into daily. The sequences of daily stream flow consist of a 1940-2013 period of analysis at 20 sites for Neches and 21 sites for Sabine River and their tributaries. The daily flows are aggregated to monthly using HEC-DSSVue.

4.3 Hydrologic and Water Quality System (HAWQS)

The Hydrologic and Water Quality System (HAWQS) is water quantity, and quality modeling system developed and maintained at Texas A&M University Spatial Sciences Laboratory under the sponsorship of the U.S. Environmental Protection Agency. Its Beta version was launched in June 2016. Its user's guide, documentation, brochure, software and other relevant information can be found at https://epahawqs.tamu.edu/.

The HAWQS is a web-based interactive tool with Soil and Water Assessment Tool (SWAT), a physically based, semi-distributed model, employed as the core modeling component in HAWQS. It enables the use of SWAT to simulate the effects of management practices on the basis of crops, soils, natural vegetation types, land uses, and climate change scenarios for hydrology and various water quality parameters such as sediments, pathogens, nutrients, and pesticides.

The main advantage of HAWQS lies in its web interaction with the user, expansion of rainfall-runoff model including climate models, rainfall/temperature sensitivity analysis and calibration of a large number of parameters quickly. The output generated consumes less time as all its input (Table 7) are uploaded in the databases which significantly reduces processing time.

The HAWQS generated daily naturalized flows are available for six river basins of Texas namely Trinity, Brazos, Neches, Sabine, Guadalupe and San Antonio (GSA) and Colorado for the hydrologic period of record from January 1, 1966, through December 31, 2010. The daily synthesized flows can be summed to monthly volumes using HEC-DSSVue. These synthesized flows provide an alternative dataset for daily and monthly naturalized flows.

4.4 U.S. Geological Survey (USGS) Gage Flows

The U.S. Geological Survey's (USGS) National Water Information System (NWIS) is a disperse and in-depth application that obtains, maintain and store the long-term sequences of water data. The Water Data for the Nation is publicly available and is maintained within NWIS.

There are more than 850,000 stations installed at the national level providing information about stream flow, reservoirs, surface-water quality, rainfall and stream levels. These data are collected automatically with the help of recorders and manual field measurements at the installed sites.

The data collection is done either through telephones or satellites such as Geostationary Operational Environmental Satellite (GOES) or by seasoned field personnel. With the advancement of technology, satellite data are processed within a short interval of time and made available online immediately. Daily summary data are generated at the end of the day when all set of readings are received and processed from a site.

Primary control points are the locations for which monthly naturalized flows are provided in SIM or SIMD input dataset. The USGS gage flow is available at primary control points with daily time step which can be aggregated into monthly observed streamflows. The flows are downloaded from the U.S. Geological Survey (USGS) National Water Information System (NWIS) website using HEC-DSSVue with unit cubic feet per second (cfs).

The Brazos WAM consists of 77 primary control; Trinity WAM consists of 40 primary control; Neches WAM consists of 20 primary control and Sabine WAM consists of 27 primary controls.

4.5 WAM Monthly Naturalized Flow Volume

Naturalized flow represents natural hydrology eliminating effects of anthropogenic activities, reservoirs, adjusting flows like return flows, water supply diversion i.e. water management activities which might influence the flows in the past (Wurbs, 2013a). The methodology adopted for developing naturalized flow is expressed by the equation (TCEQ, 2014).

$$NF = GF + \sum D - \sum RF + \sum E + \sum \Delta S \qquad (1)$$

where NF is the naturalized flow, GF is the gaged flow, D is all diversions upstream of the gage, RF is all return flows upstream of the gage, E is the net reservoir evaporation for all reservoirs upstream of the gage, and ΔS is the change in content for all reservoirs upstream of the gage.

Historical gaged flow is obtained from USGS website. There were many missing flow records, and some USGS control points have stopped been operating. Missing flow records and extension of stopped gages were completed with the help of standard hydrological and statistical techniques such as double mass curve, linear regression equations, logarithmic least square analysis, using flows from nearby gages, etc.

Upstream diversions and return flows were estimated from variously available water rights such as municipal, industrial and agricultural. Previous water use historical data from Texas Natural Resource Conservation Commission (TNRCC) is used to determine historical diversions for municipal water rights. Gaps were filled by making estimates on per capita basis using total population data at that time, by contacting individual water right holders. Historical water pattern use was utilized for determining industrial and agricultural water rights.

Historical changes in the reservoir content were determined using historical USGS data, estimates of storage content or with other available information. The net evaporation is determined by subtracting precipitation from evaporation and when it is multiplied by the average surface area of the reservoir results in historical reservoir evaporation. For each reservoir evaporation and precipitation was computed using sum weighted averages from adjacent TWDB quadrangles.

The HYD is a physically relevant, rainfall-streamflow model used for extending monthly naturalized flows based on monthly precipitation and evaporation rates. The TWDB maintains monthly dataset of precipitation and evaporation rates for 92 one degree latitude by one-degree longitude quadrangles. The HYD methodology is described in detail in chapter 4 and 7 of the *Hydrology Manual*.

The HYD model is calibrated (regressed) with many parameters for various control points. The convoluted distinct optimization algorithm is performed within HYD for computing optimal parameter values. Calibration of individual control point is complicated and require significant time and effort. However, after the model has been calibrated extension of naturalized flows and net evaporation-precipitation rates can be quickly performed. Naturalized flows in the future can be further extended after TWDB updates precipitation and evaporation datasets. The HYD model is used to extend naturalized flows for above-mentioned river basins covering 2015-2016.

CHAPTER V

HAWQS METHODOLOGY

As previously discussed in Chapter IV, HAWQS is a web-based interactive tool used for assessing water quantity and water quality with SWAT employed as its core modeling component. HAWQS naturalized flows are generated for all six river basins, Brazos, Trinity, Neches, Sabine, Guadalupe and San Antonio (GSA) and Colorado extending from January 1, 1966 through December 31, 2010.

This chapter discusses HAWQS modeling process, input datasets employed by HAWQS for the perspective of generating naturalized flows, comparative evaluation and analysis of HAWQS synthesized flow with other available flow datasets by using statistical frequency and parameters analysis.

5.1 HAWQS Modeling Process

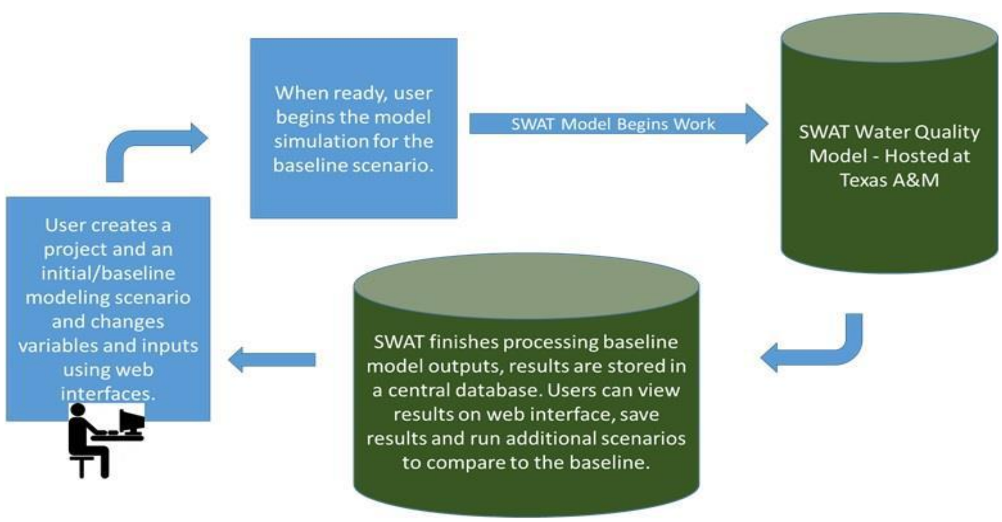

Figure 15 Overview of the HAWQS Modelling Process (https://epahawqs.tamu.edu)

HAWQS modeling process is cyclic in nature as depicted above in Figure 15. It is initiated by creating a project with inputs feed by a user. Distinct scenarios can be created, depending upon requirements, for assessing water quality and quantity. SWAT modeling system, hosted at Texas A&M University, then begin synthesizing naturalized flows. Results are saved automatically and stored in the central database of Texas A&M University, which can be viewed and downloaded anytime for further modification.

5.2 HAWQS Input

The HAWQS input along with its sources, notes, and data accessed are tabulated below in Table 7. The description of these input datasets is provided afterward. All these inputs were already fed, by default, at the server of Texas A&M University for simulating the rainfall-runoff model.

Table 7 HAWQS Inputs (https://epahawqs.tamu.edu)

Input	Source	Notes	Date Accessed
Weather*	NCDC corrected for PRISM[1]	1967-2010	October 2010
Soil	USDA-NRCS[2]	STATSGO	October 2010
Land Use	MRLC (Fry)[3]	NLCD (2006) and CDL (2011-2012)	October 2010 and January 2015
Aerial Deposition	NADP[4]	(1980-2010) monthly	October 2010
Watershed Boundaries	USGS[5]	HUCS 8, 10, and 12	October 2010
Stream Networks	NHDPlus[6]	Reduced form	October 2010
Elevation	NED[7]	30 meter DEM	October 2010
Point Sources	USGS[8]	Regression of population and SPARROW model outputs	October 2010
Management Data	NRCS[9]	CDL (tillage, fertilizer/manure, crop yields)(NRCS field database)	January 2015
Reservoirs	USACE[10]	National Inventory of Dams	October 2010
Livestock and Crops	USDA-NASS[11]		October 2010
Model	USDA-ARS and Texas A&M	Soil Water Assessment Tool	January 2015

*weather: Working on NEXRAD (2000-2015) and PRISM (1980-2015)

1. United States Department of Agriculture, Natural Resources Conservation Practices, Climate—Parameter-elevation Regressions on Independent Slopes Model (PRISM). Available online: http://www.wcc.nrcs.usda.gov/climate/prism.html (Accessed on 1 October 2010)

2. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2). Available online at http://sdmdataaccess.nrcs.usda.gov/. (Accessed on 1 October 2010)

3. Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J., 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

4. University of Illinois at Urbana-Champaign, Atmosphere Deposition—National Atmospheric Deposition Program (NADP). Available online: http://nadp.sws.uiuc.edu/ (Accessed on 1 October 2010)

5. Coordinated effort between the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS), the United States Geological Survey (USGS), and the Environmental Protection Agency (EPA). The Watershed Boundary Dataset (WBD) was created from a variety of sources from each state and aggregated into a standard national layer for use in strategic planning and accountability. Watershed Boundary Dataset for {county, state, or HUC#}, State [Online WWW]. Available URL: "http://datagateway.nrcs.usda.gov" [Accessed 1 October 2010].

6. United States Environmental Protection Agency and United States Geological Survey, National Hydrography Dataset Plus-NHDPlus. Available online: http://epa.gov/waters (Accessed on 1 October 2010)

7. United States Geological Survey, National Elevation Dataset-NED, Available online: http://nationalmap.gov/elevation.html (Accessed on 1 October 2010)

8. Schwarz, G.E., Hoos, A.B., Alexander, R.B., and Smith, R.A., 2006, The SPARROW surface water-quality model: Theory, application and user documentation: U.S. Geological Survey Techniques and Methods, section B, chapter 6-B3, 248 p., available only online at http://pubs.usgs.gov/tm/2006/tm6b3/.

9. United States Department of Agriculture, National Agricultural Statistics Service (NASS). Land Use - Cropland Data Layer (agricultural). Available online: http://nassgeodata.gmu.edu/CropScape/ (Accessed on 1 January 2015)

10. United States Corps pf Engineers, Reservoirs—National Inventory of Dams (NID). Available online: http://nid.usace.army.mil/cm_apex/f?p=838:5:0::NO (Accessed on 1 October 2010)

11. United States Department of Agriculture, National Agricultural Statistics Service (NASS). Land Use - Cropland Data Layer (agricultural). Available online: http://nassgeodata.gmu.edu/CropScape/ (Accessed on 1 October 2010).

5.3 Comparative Analysis of HAWQS generated flows

This section explores the feasibility of employing HAWQS flows to synthesize daily flow pattern hydrographs, comparative analyses of streamflow generated with HAWQS versus SWAT flows. Quantitative statistics is used for model evaluation, along with statistical frequency analysis it is applied to analyze daily flow characteristics, the impacts of water resources development on daily flow characteristics and model evaluation.

Nash-Sutcliffe coefficient of efficiency (NSE), percent bias (PBIAS) and coefficient of determination (r^2) are the statistical parameters employed along with frequency analysis for evaluating HAWQS and SWAT stream flows. In general, model simulation outcomes can be considered satisfactory for NSE > 0.50 and PBIAS + 25% (Moriasi et. Al, 2007). These are discussed below:

Coefficient of determination (r^2):

The coefficient of determination (r^2) describes the strength of collinearity between the measured and simulated data. The coefficient of determination (r^2) ranges from 0 to 1. As the magnitude increases from 0 to 1, it signifies minor error variance. It describes the proportion of variance of measured data when compared with the observed one. In general, when the coefficient of determination (r^2) is greater than 0.5 it is considered acceptable (Santhi et al., 2001, Van Liew et al., 2003). Usually, this statistical parameter is widely accepted for model evaluation. However, r^2 is highly sensitive to extreme values and very less sensitive to additive and the proportional difference between measured and observed values (Legates and McCabe, 1999).

Nash-Sutcliffe coefficient of efficiency (NSE):

According to Nash and Sutcliffe in 1970, NSE is defined as a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared to the measured data variance (“information”). The equation for computing NSE is

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(y_i^{obs} - y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(y_i^{obs} - \bar{y} \right)^2} \right] \tag{2}$$

where y_i^{obs} is the i^{th} observation for the constituent being evaluated, y_i^{sim} is the i^{th} simulated value for the constituent being evaluated, $\bar{y}$ is the mean of observed data for the component being evaluated, and *n* is the total number of observations.

NSE provides an indication of data fitting between simulated and observed data in the 1:1 line. The range of NSE lies between -∞ to 1.0 (1 inclusive). The accepted range for NSE is between 0 and 1, NSE was highly recommended by ASCE in 1993 and by Legates and McCabe in 1999, and thus it is widely used and popularly accepted among scholars.

Percent bias (PBIAS):

Percent bias (PBIAS) measures the common tendency between the simulated and observed data. This simulated average may be greater or smaller when compared to their observed counterparts (Gupta et al., 1999). The PBIAS is computed with the following equation:

$$PBIAS = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right) * 100}{\sum_{i=1}^{n} \left(Y_i^{obs} \right)} \right] \tag{3}$$

Where Y_i^{obs} is the i^{th} observation for the constituent being evaluated, Y_i^{sim} is the i^{th} simulated value for the component being evaluated. PBIAS is the deviation of data being evaluated and is expressed as a percentage. The optimum value of PBIAS is 0.0, and thus low value suggests accurate and precise model simulations. According to Gupta et al. in 1999, positive values indicate model underestimation bias, and negative values indicate model overestimation bias.

Statistical Frequency Analysis:

Exceedance Frequency (P) is defined as number of times some critical value exceeds in a given time period. Usually, this critical value is significantly far away from its mean. It is also known as annual rate of exceedance.

It is a procedure used for estimating the probability (or the frequency) of occurrence of an event. It is seen that more severe events are inversely proportional to its frequency i.e. they occur less frequently. The objective of frequency analysis is to relate these events to their frequency of occurrence with the help of probability distributions. Exceedance Frequency is calculated by Weibull formula as shown below–

$$P = \frac{m}{N+1} * 100\% \tag{4}$$

where P = Exceedance frequencies

m = rank

N = sample size

This section explores similarity between HAWQS and SWAT synthesized flows. The outcomes of statistical parameters for Neches and Sabine River Basin for control points NERO, NEEV, SRGW and SRBE respectively are tabulated below from Table 8 to 11. The Brazos and Trinity River Basin doesn't have any SWAT generated flows, as already discussed in Chapter IV and tabulated in Chapter II, and hence cannot be analyzed. The comparative analysis of daily plots between HAWQS and SWAT stream flows is illustrated from Figure 16 through Figure 19. The statistical frequency analysis for January 1, 1966 to December 31, 2010 is depicted through Table 12 and 13 which is developed within HEC-DSSVue.

Table 8 Statistical parameter result for control point NERO

Flows	NSE	PB	r^2
HAWQS	0.1323	-9.190	0.1739

Table 9 Statistical parameter result for control point NEEV

Flows	NSE	PB	r^2
HAWQS	0.0372	60.94	0.2206

Table 10 Statistical parameter result for control point SRGW

Flows	NSE	PB	r^2
HAWQS	0.1486	64.03	0.2803

Table 11 Statistical parameter result for control point SRBE

Flows	NSE	PB	r^2
HAWQS	-0.2927	76.03	0.0444

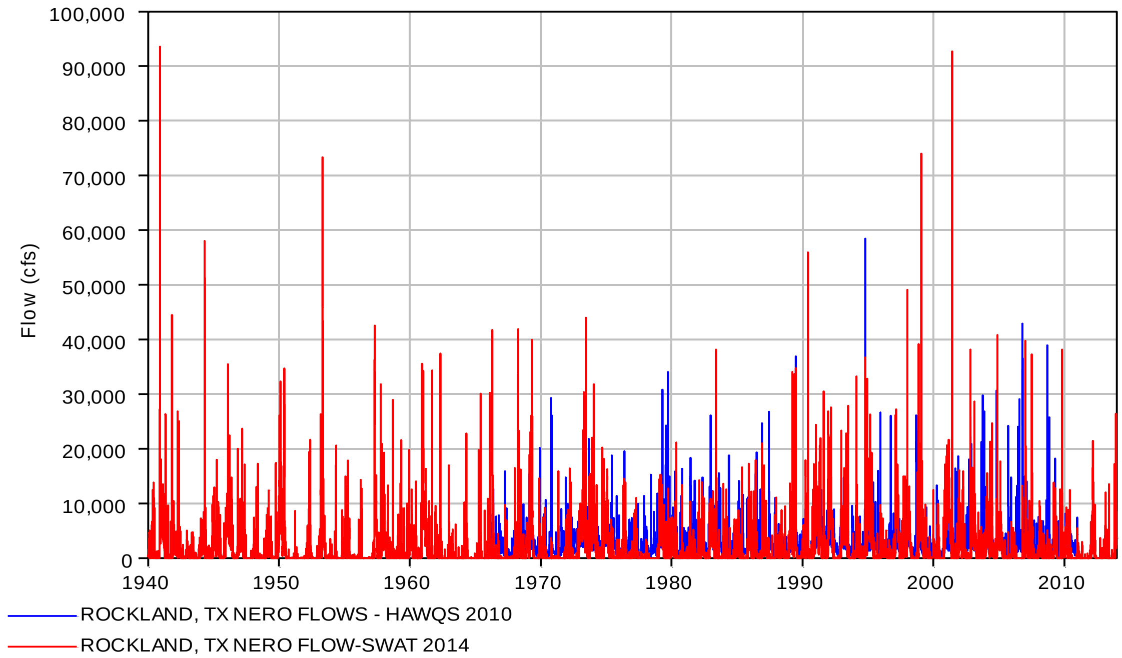

Figure 16 HAWQS & SWAT daily flows for the control point NERO

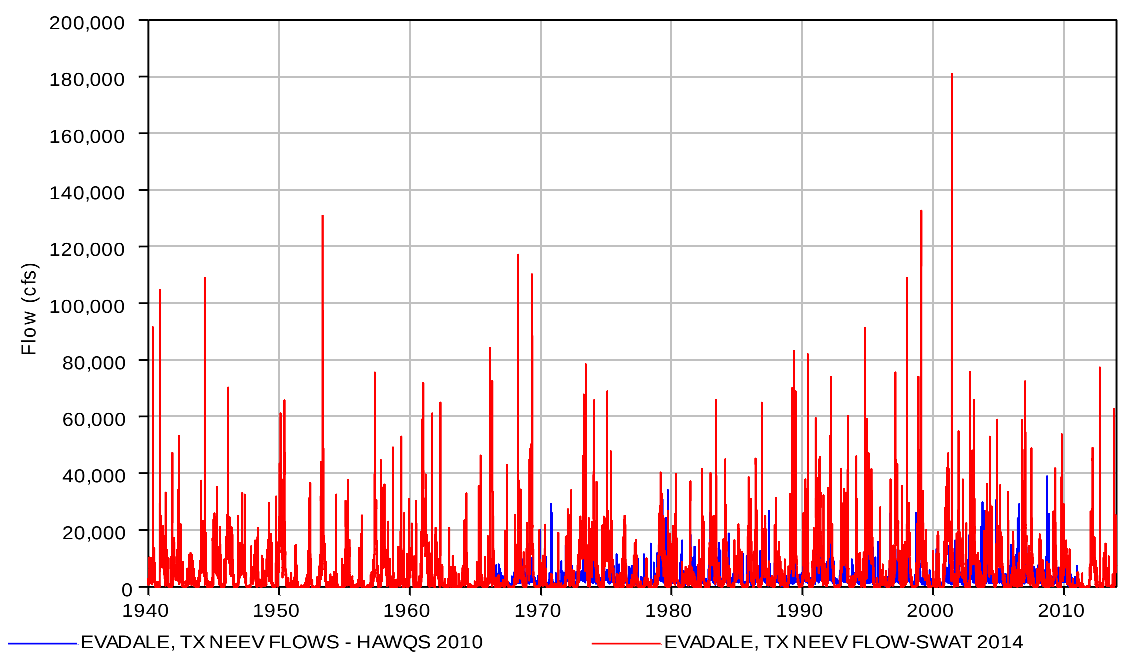

Figure 17 HAWQS & SWAT daily flows for the control point NEEV

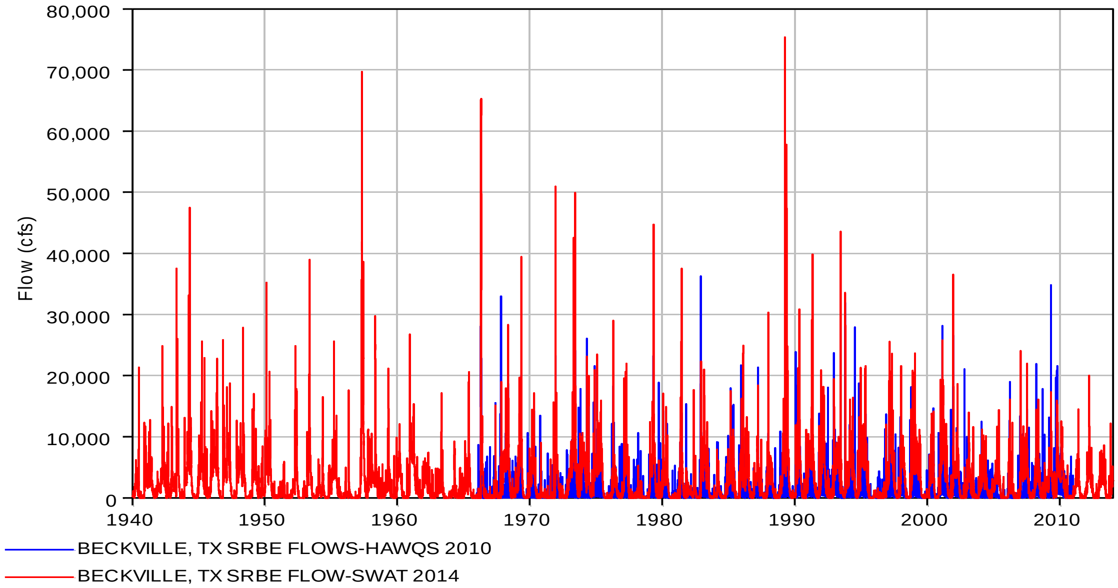

Figure 18 HAWQS & SWAT daily flows for the control point SRBE

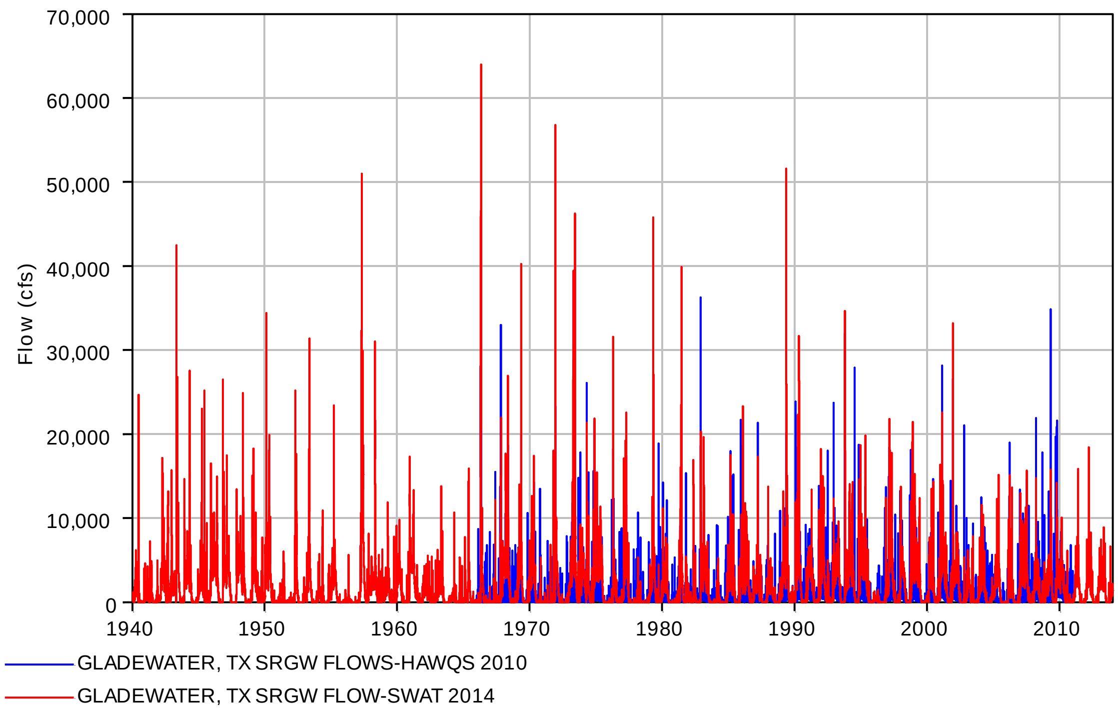

Figure 19 HAWQS & SWAT daily flows for the control point SRGW

Table 12 Flow Frequency Metrics for Control Point NEEV and NERO

	Neches River Basin			
	Control point NEEV		Control Point NERO	
	SWAT Daily (cfs)	HAWQS Daily (cfs)	SWAT Daily (cfs)	HAWQS Daily (cfs)
Mean	5573	2177	1993	2177
Std Dev	8907	2447	3974	2447
Min	0.0	79.7	0.0	79.7
Max	181023	58445	92701	58445
0.2%	70157.5	24044.1	34546.3	24044.1
0.5%	53299.1	16691.9	22810.6	16691.9
1%	40117.5	12672.7	17481.6	12672.7
2%	30594.3	9187.3	13173.7	9187.3
5%	20679.4	5585.9	8518.4	5585.9
10%	15095.6	3747.9	5888.0	3747.9
15%	11985.8	3028.3	4500.7	3028.3
20%	9778.6	2655.3	3448.8	2655.3
30%	6331.9	2211.7	1885.8	2211.7
40%	3775.8	1891.1	819.3	1891.1
50%	2073.0	1642.5	257.8	1642.5
60%	1002.2	1404.7	31.8	1404.7
70%	328.4	1175.3	0.0	1175.3
80%	24.7	954.7	0.0	954.7
85%	0.0	796.3	0.0	796.3
90%	0.0	636.4	0.0	636.4
95%	0.0	473.2	0.0	473.2
98%	0.0	344.1	0.0	344.1
99%	0.0	292.0	0.0	292.0
99.5%	0.0	247.8	0.0	247.8
99.8%	0.0	168.2	0.0	168.2

Table 13 Flow Frequency Metrics for Control Point SRBE and SRGW

	Sabine River Basin			
	Control point SRBE		Control Point SRGW	
	SWAT Daily	HAWQS Daily	SWAT Daily	HAWQS Daily
	(cfs)	(cfs)	(cfs)	(cfs)
Mean	2716	632	1756	632
Std Dev	4075	1798	3123	1798
Min	0.0	0.0	0.0	0.0
Max	75361	36268	63954	36268
0.2%	33213.8	18598.5	28715.2	18598.5
0.5%	22302.0	12331.5	18015.6	12331.5
1%	17525.8	8688.3	13626.6	8688.3
2%	13513.5	5719.3	9740.7	5719.3
5%	9172.3	2793.8	6233.0	2793.8
10%	6918.1	1276.7	4488.5	1276.7
15%	5750.8	801.3	3665.7	801.3
20%	4921.4	579.9	3128.0	579.9
30%	3478.5	376.1	2155.1	376.1
40%	2159.4	251.6	1255.4	251.6
50%	1182.5	166.6	555.7	166.6
60%	544.4	103.5	160.4	103.5
70%	216.3	56.1	0.0	56.1
80%	41.6	24.2	0.0	24.2
85%	0.0	12.4	0.0	12.4
90%	0.0	0.9	0.0	0.9
95%	0.0	0.0	0.0	0.0
98%	0.0	0.0	0.0	0.0
99%	0.0	0.0	0.0	0.0
99.5%	0.0	0.0	0.0	0.0
99.8%	0.0	0.0	0.0	0.0

The simulation results of the HAWQS streamflow are not under acceptable range as illustrated through Table 8 to 11 and thus unable to satisfy statistical parameters NSE, PBIAS, and r^2 as per Moriasi et. al. The flow frequency metrics as depicted in Table 12 and 13 illustrates exactly same flow metrics for control points NERO and NEEV as well as for SRBE and SRGW, indicating that HAWQS is unable to capture flow characteristics for nearby control points. Moreover, both HAWQS and SWAT were unable to reproduce low flows as depicted through Figure 16 to 19.

SWAT flows are more precise as compared to HAWQS flows. The accuracy exhibited by SWAT is probably because of its capability to set the parameters for individual control points separately. Whereas, for analysis by HAWQS inbuilt pre-calibrated parameters are employed implicitly for all the control points. Therefore, for the selection of the final set of daily flow pattern hydrographs, HAWQS flows are not used instead SWAT flows are used. Thus, SWAT, USGS, and USACE flows may be used for synthesizing the entire period of analyses which is discussed in the next chapter.

Poor performance is observed while capturing low flows by HAWQS and SWAT. The most probable reason for this problem may be that both HAWQS and SWAT are unable to quantify accurately and precisely the groundwater flows computations. HAWQS is in beta (trial) version and therefore might be encountering such issues. The alternate solution to this problem may be by modeling groundwater flow computations separately. Later on, the results can be used as input for HAWQS and SWAT for calculation of surface runoff. In addition to this following improvement can be made:

- Improvement in water temperature model.
- Uncertainty analysis can be enhanced on the basis of model input parameters.
- Certain agricultural inputs such as SSURGO soils, crop management, point sources data, etc. can be further improved and updated.
- Several updated climate change models and scenarios such as CMIP5 can be included to get more precise and accurate computation.

- As of now, flows can be generated till 2010. Thus, input parameters must frequently be updated so that one can get updated streamflows every year.

HAWQS is expected to improve as it is still in beta (trial) version. The results may get enhanced by altering inbuilt pre-calibrated parameters in the HAWQS. Additionally, pre-calibrated flows can be further calibrated using calibration/uncertainty analysis programs like SWAT-CUP.

CHAPTER VI

COMPARATIVE ANALYSIS OF DAILY FLOWS

As previously discussed in Chapter IV, USGS gaged flows, SWAT and HAWQS synthesized naturalized flows, and USACE unregulated flows provide alternative sets of daily flows. Chapter V concludes, HAWQS flows should not be employed due to its inability to replicate low flows as well as unable to satisfy statistical parameters for model evaluation. Thus, USGS, SWAT, and USACE daily flows are used for the formulation of daily flow pattern hydrograph. Therefore, this section deals with comparative analysis and evaluation of these daily flows on the Brazos, Trinity, Neches and Sabine River basin.

Four control points from Brazos River Basin, SFAO06, BRSE11, BRWA41 and BRRI70, three from Trinity, 8CTFW, 8TRDA and 8TROA, two from Neches and Sabine River Basin, NERO and NEEV, SRGW and SRBE respectively are selected. The reason for the inclusion of these control points is the availability of relatively very extended period of USGS gaged flow records and establishment of environmental instream flow standard in accordance with Senate Bill 3 (SB3).

The parameters employed for comparative analysis of daily flows are flow frequency metrics or duration curve and daily flow plots for an entire 1940-2015 hydrologic period of study. The frequency metrics is particularly useful for analyzing low flows. Streamflow plots provide a general understanding of flow characteristics. The plots impart illustration of high flows, the possible location of dams, and long-term trends.

Flow frequency metrics is divided into two subperiods for purposes of computing and comparing frequency parameters. It covers a hydrologic period of analyses from 1940-97 and 1998-2015 in the case of Brazos, 1940-2009, and 2010-15 for Trinity, 1940-2011 and 2012-15 in the case of Neches and 1940-2013 for Sabine River basin as depicted in Table from Table 14 to 24. The following statistical metrics are provided in Tables illustrated below. All quantities are in the unit of cfs.

- Minimum value of daily flow.
- Average of mean daily flows.
- Maximum value of daily flow.
- Standard deviation (SD) of daily flows.
- Daily flows corresponding to the exceedance frequencies based on the Weibull formula.

The exceedance frequencies in percent represent the number of days that the mean flow during the day exceeded the indicated magnitudes. This information can be viewed as either flow frequency, probability, or duration relationships. From a duration analysis perspective, the percentages are the percent of time that the flow exceeds the indicated magnitudes.

Daily flow plots for all above-mentioned control points are depicted through Figure 20 to 30, flow frequency metrics from Table 14 to 24 and flow frequency or duration curves through Figure 31 to 50.

Comparative analysis of daily streamflow plots and frequency metrics illustrates randomness and variability in all the river basins of Texas. Higher and lower flow percentage exceedance frequency is particularly useful for analyzing high and low flow respectively. Higher flows were almost similar for differently available datasets with slight variations. Replication of low flows is a critical issue for maintaining environmental instream flow standards as per SB3. Therefore, a general strategy is developed and employed from the perspective of accurately and precisely replicating low flows as discussed in the next paragraph.

It is observed from daily streamflow plots that USACE and USGS flows were almost identical with slight variation in numerous cases. However, it is evident from flow frequency metrics that USACE flow patterns are much more accurate and precise as compared to USGS. SWAT flows are unable to capture low flows and replicate frequency metrics and thus not used. Therefore, USACE unregulated flows are employed wherever available followed by USGS gaged flows representing actual river basin characteristics for synthesizing the daily flow pattern hydrograph for complete 1940-2015 hydrologic period of analysis.

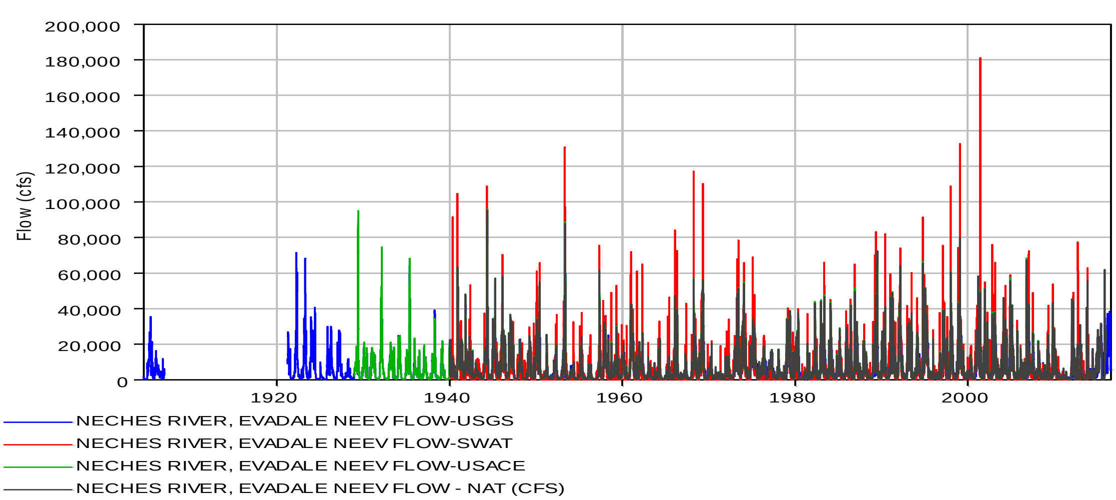

Figure 20 Daily flows at USGS gage on Neches River at Evadale (NEEV)

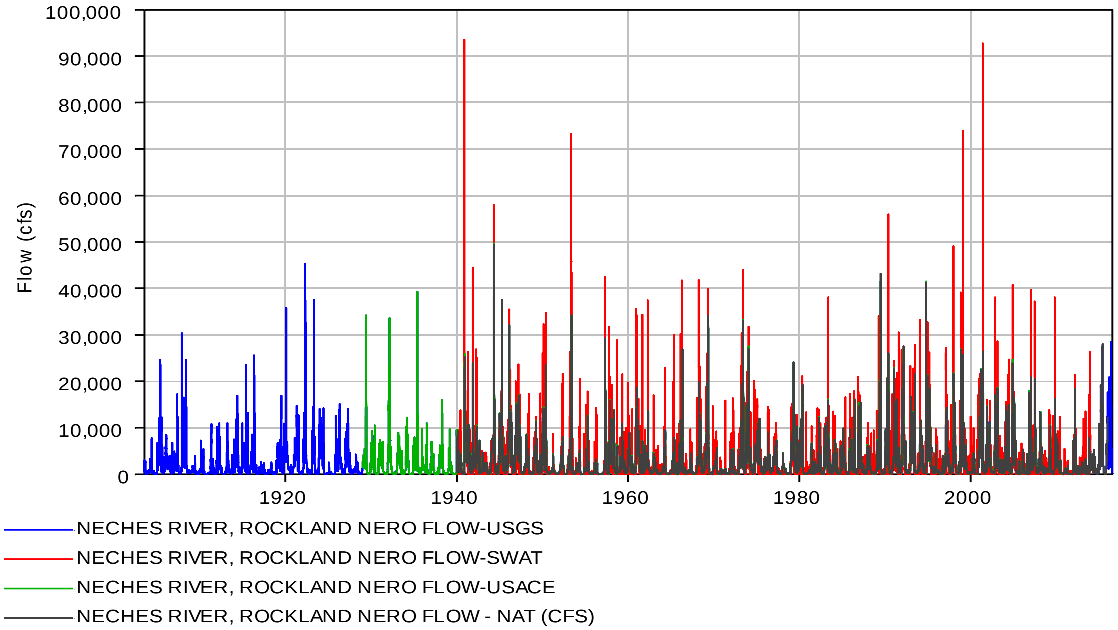

Figure 21 Daily flows at USGS gage on Neches River near Rockland (NERO)

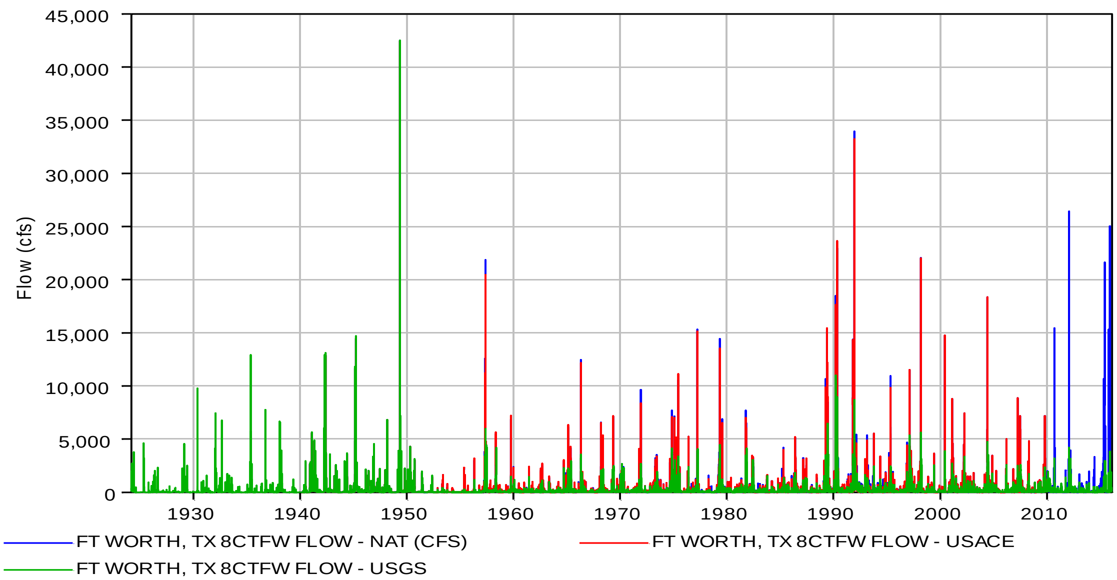

Figure 22 Daily flows at USGS gage on Clear Fork Trinity River at Fort Worth (8CTFW)

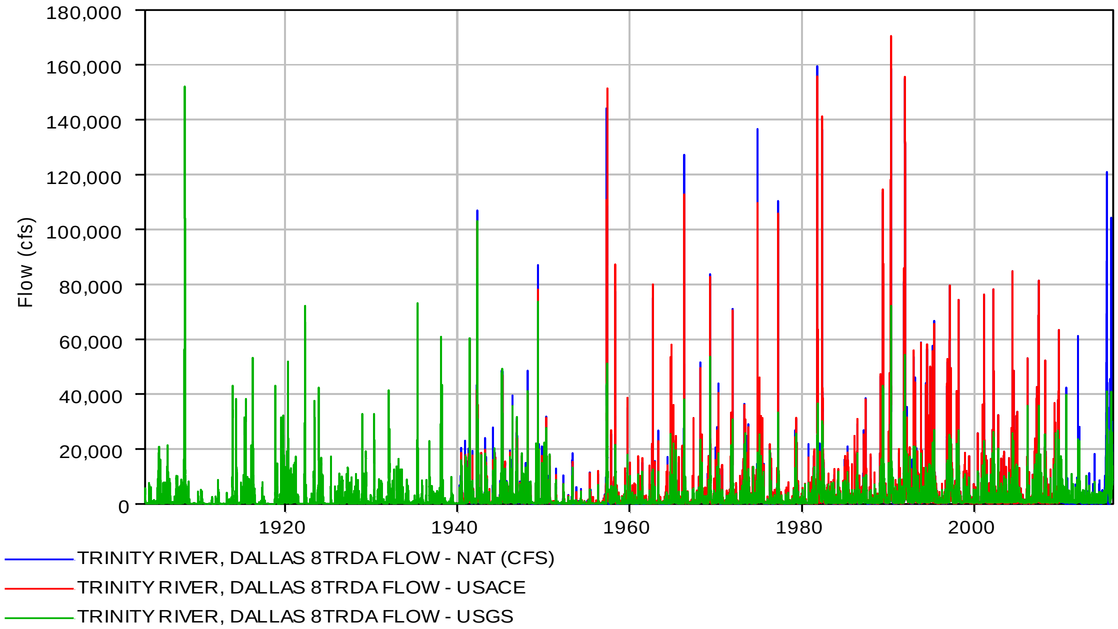

Figure 23 Daily flows at the USGS gage on Trinity River at Dallas (8TRDA)

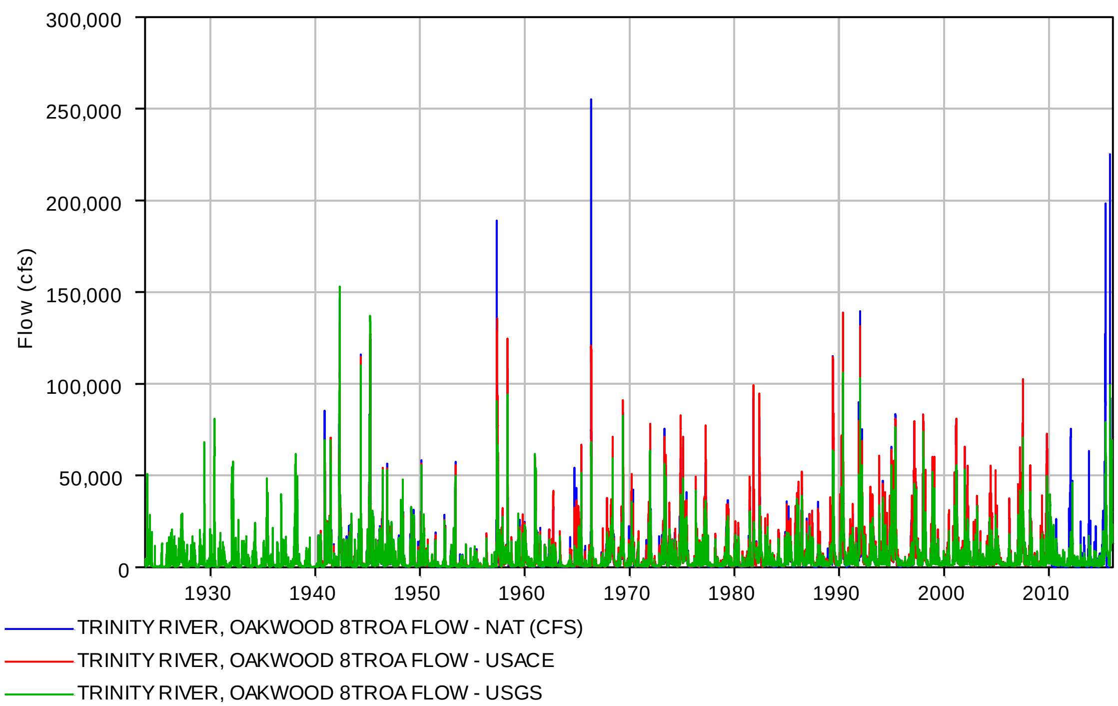

Figure 24 Daily flows at the USGS gage on Trinity River near Oakwood (8TROA)

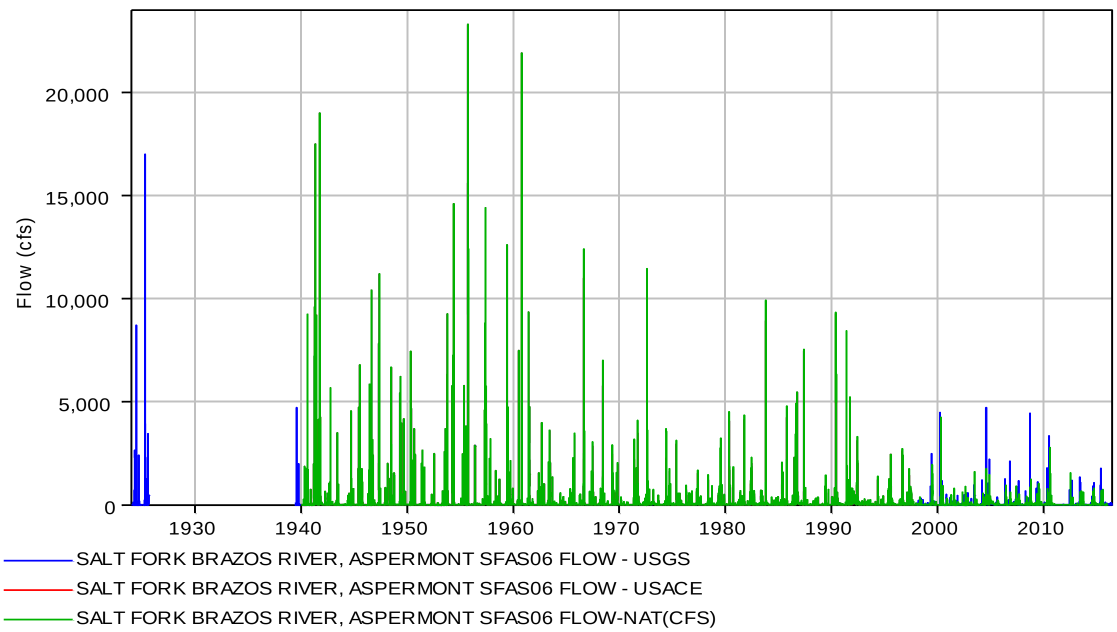

Figure 25 Daily flows at the USGS gage on Salt Fork Brazos River (SFAS06)

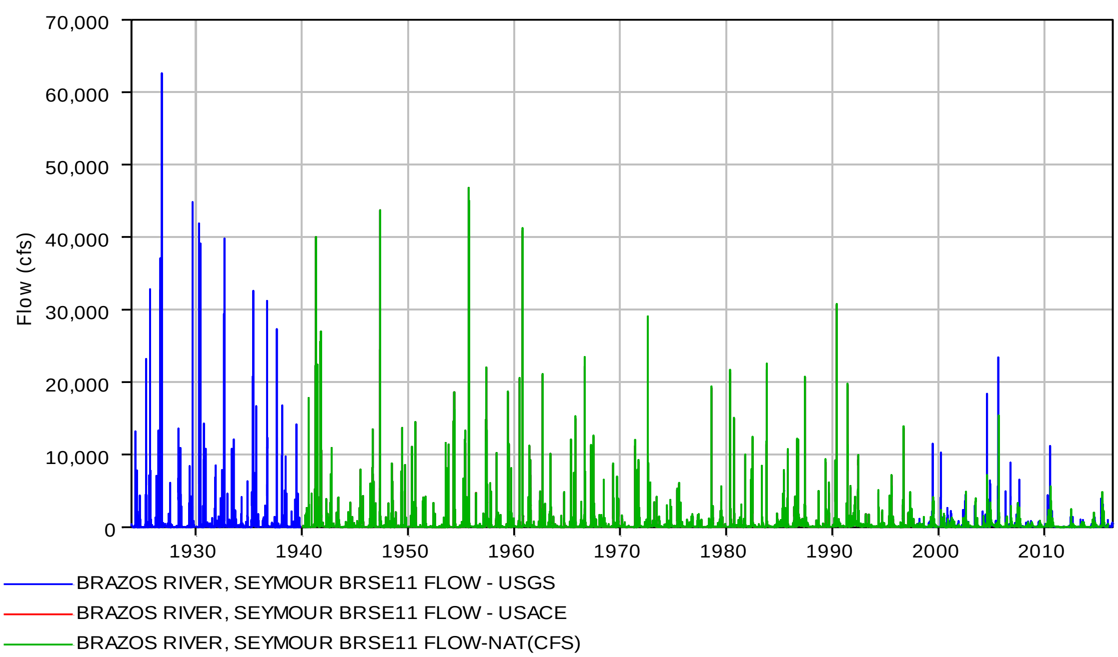

Figure 26 Daily flows at the USGS gage on Brazos River at Seymour (BRSE11)

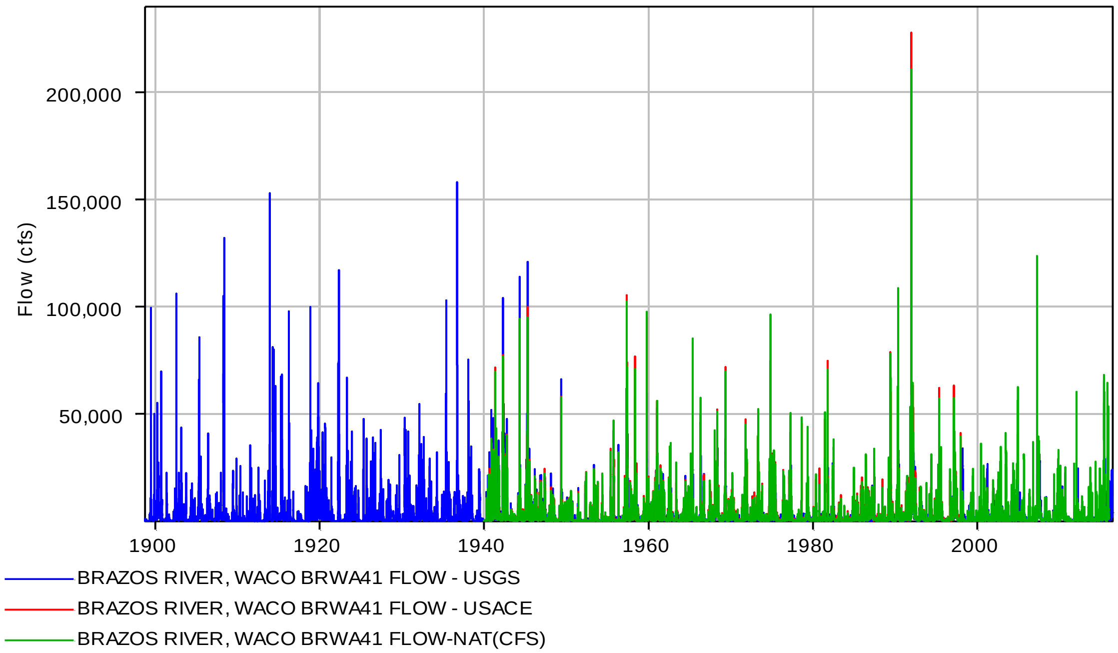

Figure 27 Daily flows at the USGS gage on Brazos River at Waco (BRWA41)

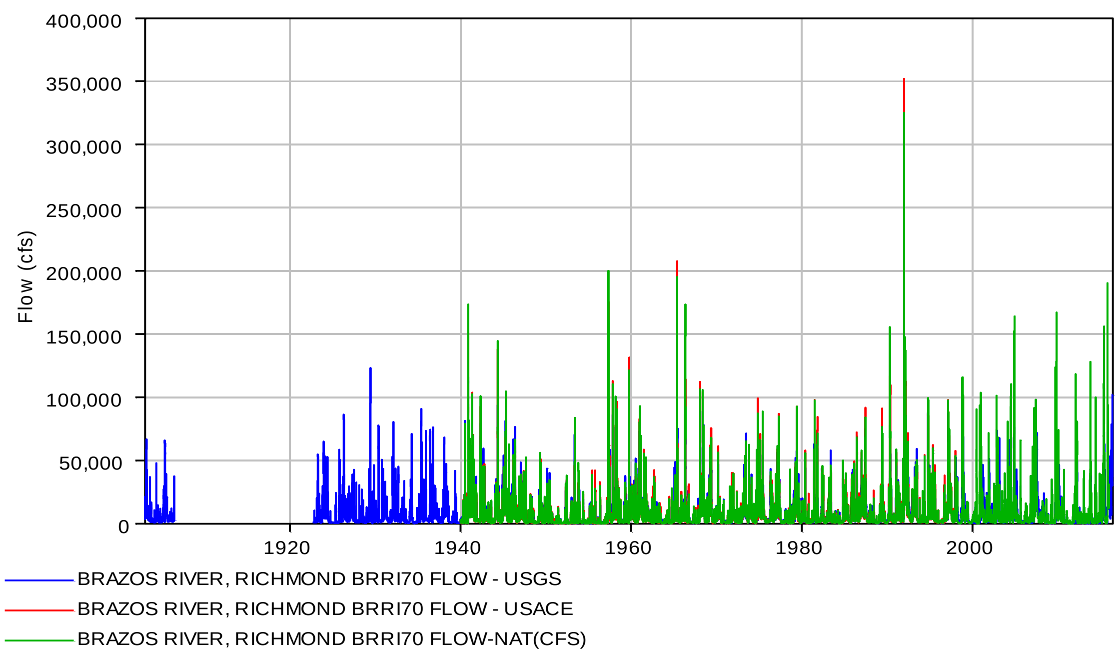

Figure 28 Daily flows at the USGS gage on Brazos River at Richmond (BRRI70)

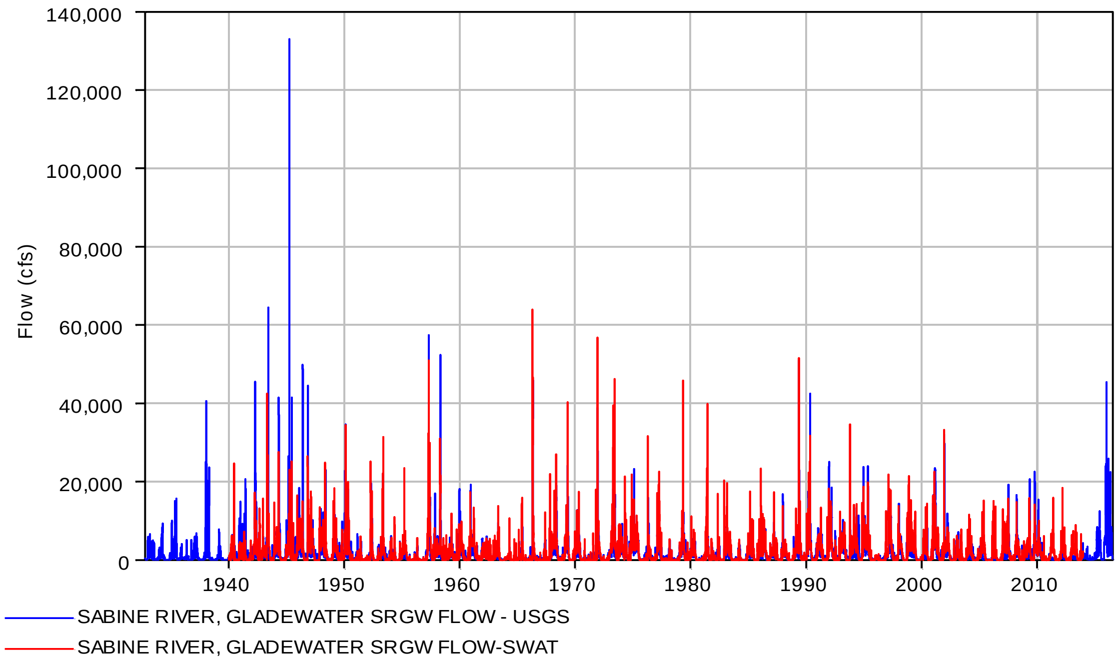

Figure 29 Daily flows at the USGS gage on Sabine River at Gladewater (SRGW)

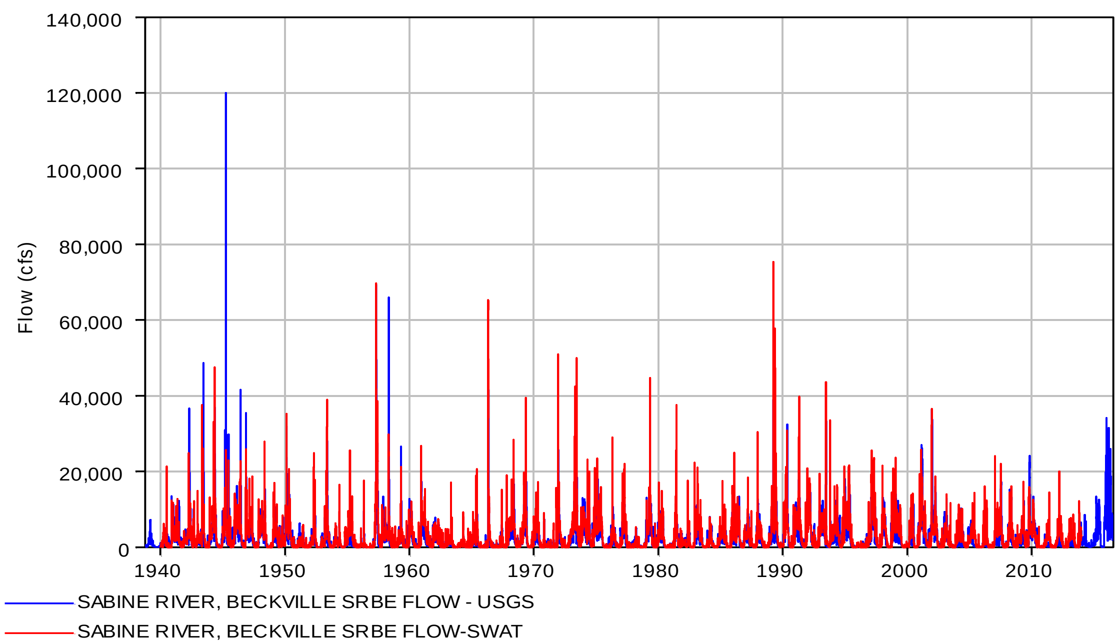

Figure 30 Daily flows at the USGS gage on Sabine River at Beckville (SRBE)

Table 14 Flow Frequency Metrics for Control Point NEEV

	NEEV Neches River at Evadale					
	Frequency Metrics 1940-2011				Frequency Metrics 2012-2015	
	SWAT Daily	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	5026	6207	6599	6599	5034	7236
Std Dev	8547	7137	8755	8743	5519	9061
Min	0.0	63	46	45	467	14
Max	181023	92100	96187	95287	31000	61823
0.2%	70369	47800	57977	57913	30076	55929
0.5%	52286	37301	48679	48393	25676	44409
1%	38670	30302	41249	41063	24614	40085
2%	29058	24800	33692	33571	21152	31547
5%	19431	20500	24329	24320	19490	24404
10%	13889	17000	17595	17617	14780	20719
15%	10785	13200	13409	13444	8874	17599
20%	8624	10100	10655	10663	6540	15239
30%	5364	6580	7102	7112	4428	9418
40%	3106	4340	4711	4707	3318	5734
50%	1692	3300	3082	3078	2690	3080
60%	742	2740	2022	2018	2340	1518
70%	194	2080	1340	1339	1906	638
80%	0	1370	886	887	1700	163
85%	0	1060	668	670	1560	137
90%	0	720	489	488	1420	99
95%	0	445	306	308	1180	64
98%	0	261	211	212	968	55
99%	0	190	173	174	817	42
99.5%	0	144	139	138	738	21
99.8%	0	107	103	100	495	16

Table 15 Flow Frequency Metrics for Control Point NERO

	NERO Neches River near Rockland					
	Frequency Metrics 1940-2011				Frequency Metrics 2012-2015	
	SWAT Daily	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	1822	2430	2429	2430	2294	2294
Std Dev	3925	3728	3727	3725	3955	3955
Min	0.0	1.6	1.6	1.6	33	33
Max	93583	49700	49700	49353	28000	27999
0.2%	34121	26940	26940	26907	27415	27415
0.5%	23657	21750	21750	21727	25004	25004
1%	17435	17901	17901	17876	19038	19038
2%	12671	14000	14000	13980	17376	17376
5%	8133	9610	9600	9630	10700	10700
10%	5463	6580	6580	6577	6390	6390
15%	4058	4920	4920	4917	4507	4507
20%	3030	3830	3832	3840	3362	3362
30%	1519	2510	2510	2509	1810	1810
40%	569	1550	1550	1546	1254	1254
50%	138	926	926	925	648	648
60%	0	541	543	545	409	409
70%	0	335	335	335	249	249
80%	0	203	203	203	136	136
85%	0	154	154	153	114	114
90%	0	109	109	109	90	90
95%	0	70	70	69	67	67
98%	0	40	40	39	42	42
99%	0	22	22	22	38	38
99.5%	0	8	8	9	36	36
99.8%	0	5	5	5	35	35

Table 16 Flow Frequency Metrics for Control Point 8CTFW

	8CTFW Clear Fork Trinity River at Fort Worth				
	Frequency Metrics 1940-2009			Frequency Metrics 2010-2015	
	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	139	162	163	118	236
Std Dev	533	740	750	352	1341
Min	0.0	0.0	0.0	0.0	0.0
Max	42500	42472	42473	4180	26407
0.2%	3910.0	7081	7165	3180.8	19261
0.5%	3034.6	3735	3725	1762.4	8488
1%	2253.1	2223	2234	1600.0	4022
2%	1460.0	1345	1356	1440.0	1982
5%	640.0	596	605	731.4	906
10%	288.0	300	304	259.8	314
15%	166.0	192	196	121.4	182
20%	100.0	137	140	64.0	105
30%	47.0	79	80	34.0	49
40%	29.0	46	46	22.0	25
50%	19.0	28	27	17.0	17
60%	13.0	17	16	13.0	12
70%	8.4	10	8	9.8	6
80%	4.2	4	3	6.7	0
85%	2.6	2	1	5.0	0
90%	0.8	1	0	3.2	0
95%	0.0	0	0	1.4	0
98%	0.0	0	0	0.3	0
99%	0.0	0	0	0.0	0
99.5%	0.0	0	0	0.0	0
99.8%	0.0	0	0	0.0	0

Table 17 Flow Frequency Metrics for Control Point 8TRDA

	8TRDA Trinity River at Dallas				
	Frequency Metrics 1940-2009			Frequency Metrics 2010-2015	
	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	1918	2516	2377	2241	2812
Std Dev	3946	7195	7181	4431	9278
Min	10	12	0.0	295	0.0
Max	103000	170408	159494	41000	120902
0.2%	33000	74724	74279	39493	108331
0.5%	23816	48556	48485	28848	67860
1%	18100	33091	32822	24372	45561
2%	12900	21058	20848	17316	32189
5%	8380	10704	10433	9470	12786
10%	5500	5380	5132	6446	4977
15%	4010	3360	3160	4362	2784
20%	2540	2324	2150	2512	1971
30%	1100	1322	1193	1124	1153
40%	656	875	763	722	717
50%	482	625	522	567	480
60%	396	466	372	486	326
70%	306	352	250	443	246
80%	227	264	147	408	100
85%	191	225	102	390	0
90%	149	180	51	370	0
95%	91	135	0	350	0
98%	66	98	0	332	0
99%	58	76	0	320	0
99.5%	51	58	0	311	0
99.8%	0	40	0	301	0

Table 18 Flow Frequency Metrics for Control Point 8TROA

	8TROA Trinity River near Oakwood				
	Frequency Metrics 1940-2009			Frequency Metrics 2010-2015	
	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	5505	6640	6261	5507	6466
Std Dev	9356	12386	11953	10731	17710
Min	85	0.0	0.0	425	0.0
Max	153000	138734	254947	99200	225017
0.2%	76148	111434	98468	76423	191881
0.5%	56831	80787	76131	62804	123781
1%	44531	64308	60467	56588	95449
2%	33162	47023	44999	42332	58767
5%	21700	27715	26567	30300	31801
10%	15600	16604	16066	16680	13997
15%	11900	12101	11539	8496	7872
20%	8600	8873	8489	5876	5374
30%	4643	5168	4958	2914	3190
40%	2590	3335	3101	1780	1900
50%	1640	2255	2032	1290	1339
60%	1140	1534	1346	1060	966
70%	884	1086	915	940	521
80%	670	737	539	794	275
85%	560	582	383	746	0
90%	441	432	227	692	0
95%	305	307	74	631	0
98%	186	221	0	569	0
99%	150	181	0	527	0
99.5%	123	149	0	508	0
99.8%	105	123	0	481	0

Table 19 Flow Frequency Metrics for Control Point SFAS06

	SFAS06 Salt Fork Brazos River				
	Frequency Metrics 1940-1997			Frequency Metrics 1998-2015	
	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	101	101	106	40	40
Std Dev	626	626	635	180	138
Min	0.0	0.0	0.0	0.0	0.0
Max	23300	23300	23299	4710	4244
0.2%	6811.4	6811.4	6924.1	1997.0	1461.3
0.5%	3600.7	3600.7	3679.9	1160.0	910.1
1%	1931.4	1931.4	1974.3	676.2	591.6
2%	918.6	918.6	974.8	362.5	413.5
5%	328.7	328.7	350.3	147.0	202.6
10%	131.0	131.0	140.8	73.0	85.1
15%	70.0	70.0	75.0	45.0	51.3
20%	42.0	42.0	45.3	30.0	32.3
30%	19.0	19.0	21.0	15.0	15.0
40%	11.0	11.0	12.0	7.9	8.6
50%	6.2	6.2	7.1	4.3	4.2
60%	3.4	3.4	4.1	1.8	2.0
70%	1.4	1.4	1.8	0.4	0.7
80%	0.4	0.4	0.6	0.1	0.2
85%	0.3	0.3	0.4	0.1	0.1
90%	0.2	0.2	0.2	0.1	0.0
95%	0.1	0.1	0.1	0.0	0.0
98%	0.0	0.0	0.0	0.0	0.0
99%	0.0	0.0	0.0	0.0	0.0
99.5%	0.0	0.0	0.0	0.0	0.0
99.8%	0.0	0.0	0.0	0.0	0.0

Table 20 Flow Frequency Metrics for Control Point BRSE11

	BRSE11 Brazos River at Seymour				
	Frequency Metrics 1940-1997			Frequency Metrics 1998-2015	
	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	339	339	345	185	184
Std Dev	1528	1528	1538	713	486
Min	0.0	0.0	0.0	0.0	0.0
Max	46800	46800	46798	23400	15398
0.2%	16451	16451	16451	7442	4016.9
0.5%	9297	9297	9378	4129	3075.9
1%	5737	5737	5790	2428	2395.4
2%	3113	3113	3202	1490	1649.9
5%	1310	1310	1333	688	880.0
10%	601	601	609	354	431.1
15%	331	331	340	238	275.2
20%	216	216	222	172	194.0
30%	114	114	118	100	109.7
40%	68	68	71	64	65.7
50%	42	42	45	45	44.5
60%	27	27	29	31	27.3
70%	17	17	18	14	12.6
80%	8	8	9	5	4.8
85%	4	4	5	3	2.2
90%	1	1	1	0	0.4
95%	0	0	0	0	0.0
98%	0	0	0	0	0.0
99%	0	0	0	0	0.0
99.5%	0	0	0	0	0.0
99.8%	0	0	0	0	0.0

Table 21 Flow Frequency Metrics for Control Point BRWA41

	BRWA41 Brazos River at Waco				
	Frequency Metrics 1940-1997			Frequency Metrics 1998-2015	
	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	2382	2726	2680	1730	2467
Std Dev	5285	6924	6842	4024	5816
Min	0.0	0.0	0.0	2.7	0.0
Max	121000	227752	210539	35800	123681
0.2%	40751	63980	66994	29570	53942
0.5%	34600	47451	45751	27825	37448
1%	28214	33889	33389	24150	30286
2%	22100	22748	22240	17400	21668
5%	10100	11861	11538	8428	10175
10%	4940	6270	6169	3785	5752
15%	3340	3999	3939	2440	3733
20%	2500	2806	2807	1800	2658
30%	1540	1665	1648	1070	1647
40%	1120	1057	1040	683	1122
50%	842	726	703	418	735
60%	628	512	479	261	473
70%	434	358	326	170	296
80%	266	240	206	104	176
85%	196	191	157	74	126
90%	137	140	111	54	86
95%	73	85	63	37	42
98%	41	43	26	23	21
99%	29	26	8	14	11
99.5%	16	15	0	11	2
99.8%	6	7	0	8	0

Table 22 Flow Frequency Metrics for Control Point BRRI70

	BRRI70 Brazos River at Richmond				
	Frequency Metrics 1940-1997			Frequency Metrics 1998-2015	
	USGS Daily	USACE Daily	WAM Daily	USGS Daily	WAM Daily
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
Mean	7571	7942	8075	7093	8600
Std Dev	11961	14537	14342	11729	16703
Min	55	7.0	0.0	182	0.0
Max	118000	351926	325187	79600	190236
0.2%	86288	113014	115362	73280	155969
0.5%	74007	91455	87723	67600	111169
1%	62800	71602	69656	60900	89210
2%	49800	52993	52281	49150	64508
5%	30200	32278	32274	33450	35964
10%	19100	20568	20535	19700	21024
15%	14200	14281	14520	13600	14320
20%	10800	10630	10906	10100	10409
30%	6750	6612	6947	5780	6466
40%	4410	4274	4527	3520	4466
50%	2920	2860	3013	2195	3116
60%	2020	1951	2092	1470	2140
70%	1500	1394	1489	1050	1350
80%	1110	951	1029	738	895
85%	940	745	822	615	727
90%	777	543	604	514	558
95%	590	364	405	410	372
98%	429	206	253	318	202
99%	339	144	174	271	0
99.5%	266	103	121	240	0
99.8%	218	69	0	209	0

Table 23 Flow Frequency Metrics for Control Point SRGW

	SRGW Sabine River at Gladewater Frequency Metrics 1940-2013	
	USGS Daily (cfs)	SWAT Daily (cfs)
Mean	1863	1685
Std Dev	3850	3041
Min	5.6	0.0
Max	133000	63954
0.2%	36256.8	27871.6
0.5%	22496.0	18386.6
1%	17000.0	13691.8
2%	12400.0	9702.4
5%	7470.0	6007.0
10%	5290.0	4326.0
15%	3860.0	3538.5
20%	2800.0	2930.8
30%	1460.0	1990.0
40%	806.0	1149.5
50%	474.0	542.8
60%	293.0	181.1
70%	175.0	0.3
80%	107.0	0.0
85%	82.0	0.0
90%	56.0	0.0
95%	34.4	0.0
98%	20.0	0.0
99%	14.0	0.0
99.5%	11.0	0.0
99.8%	9.1	0.0

Table 24 Flow Frequency Metrics for Control Point SRBE

	SRBE Sabine River at Beckville Frequency Metrics 1940-2013	
	USGS Daily (cfs)	SWAT Daily (cfs)
Mean	2544	2572
Std Dev	4299	3946
Min	2.4	0.0
Max	120000	75361
0.2%	33133.2	32961.6
0.5%	24200.0	23049.0
1%	18600.0	17425.7
2%	13600.0	13125.0
5%	10300.0	8738.6
10%	7200.0	6589.7
15%	5550.0	5419.0
20%	4260.0	4520.3
30%	2410.0	3138.4
40%	1390.0	1994.9
50%	824.0	1115.6
60%	498.0	544.5
70%	299.0	226.1
80%	169.0	41.4
85%	128.0	0.0
90%	88.0	0.0
95%	50.0	0.0
98%	26.0	0.0
99%	17.2	0.0
99.5%	12.0	0.0
99.8%	10.0	0.0

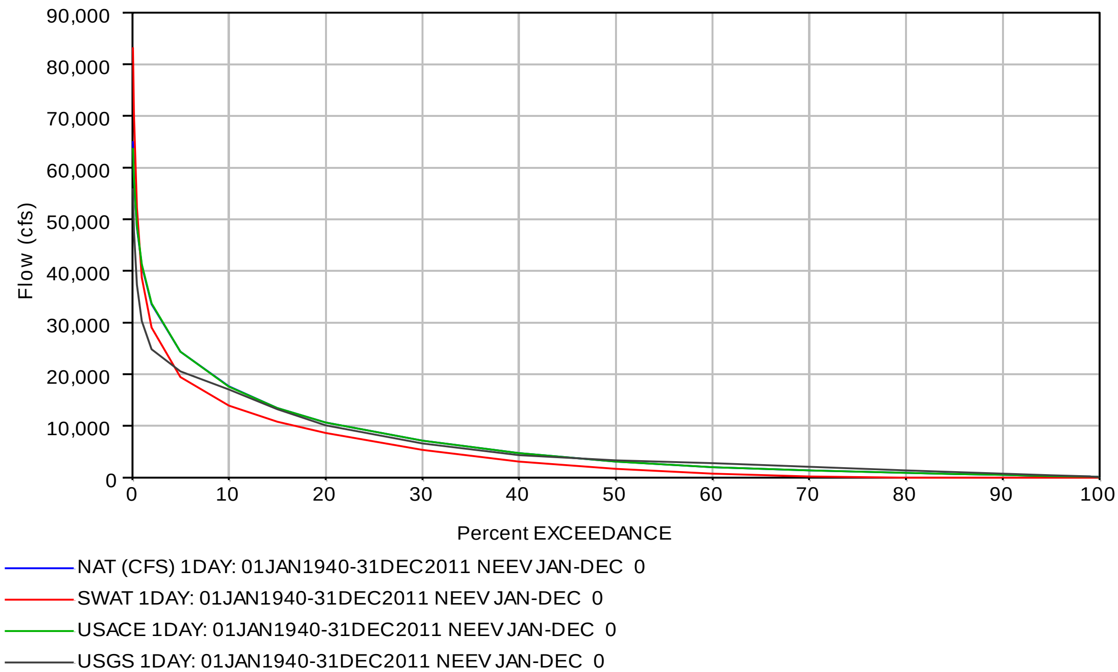

Figure 31 Flow Frequency or Duration Curves on NEEV for 1940-2011

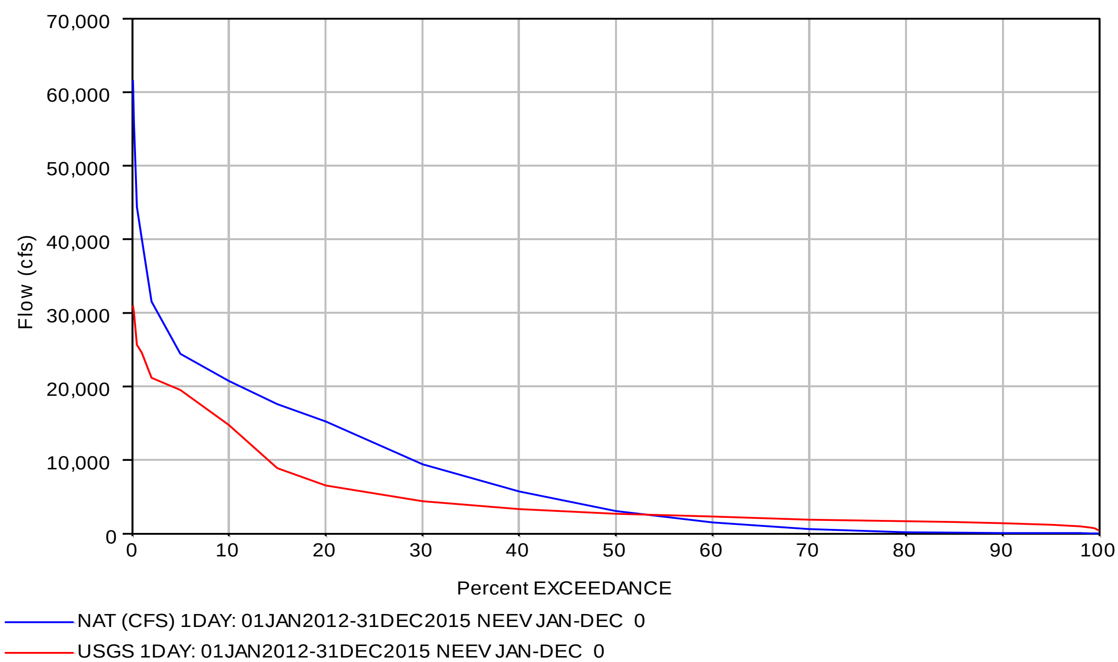

Figure 32 Flow Frequency or Duration Curves on NEEV for 2012-2015

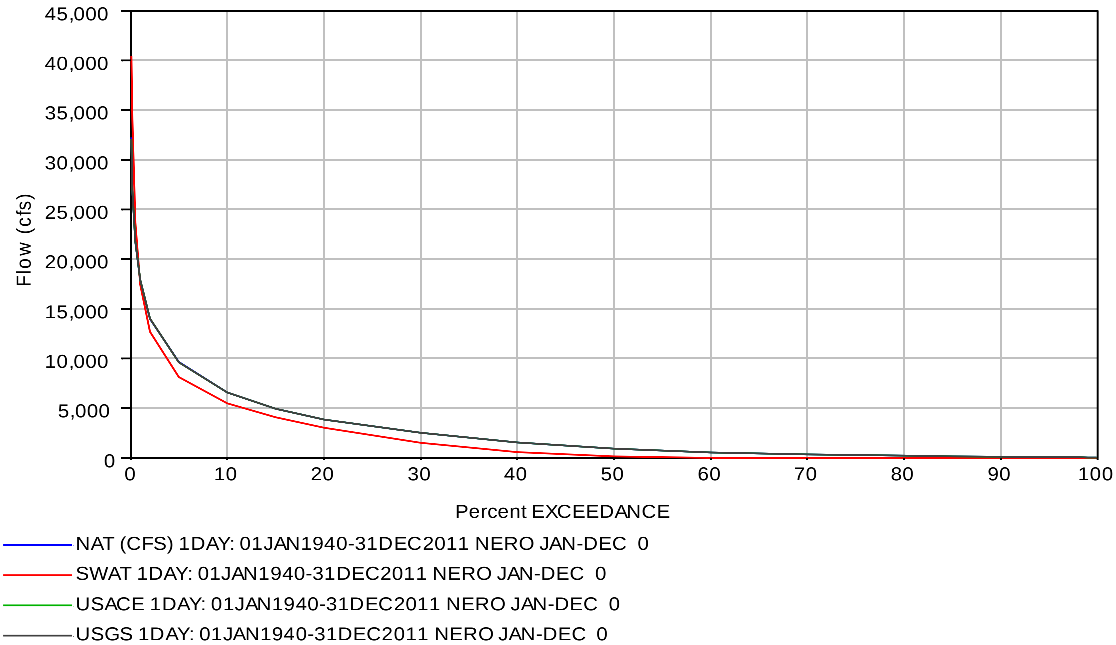

Figure 33 Flow Frequency or Duration Curves on NERO for 1940-2011

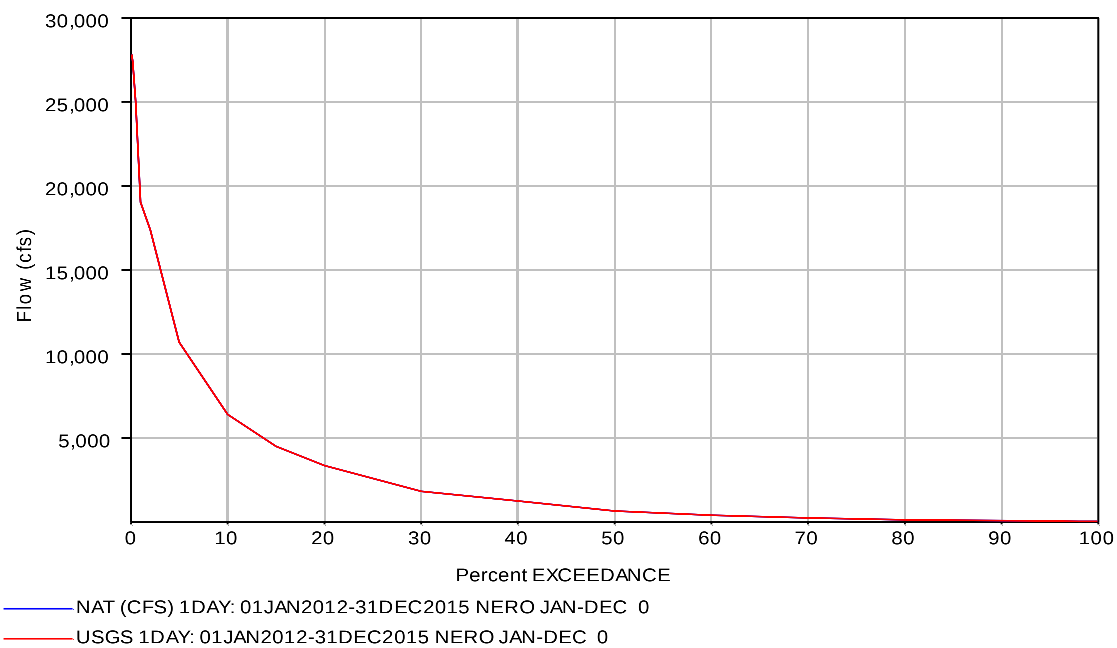

Figure 34 Flow Frequency or Duration Curves on NERO for 2012-2015

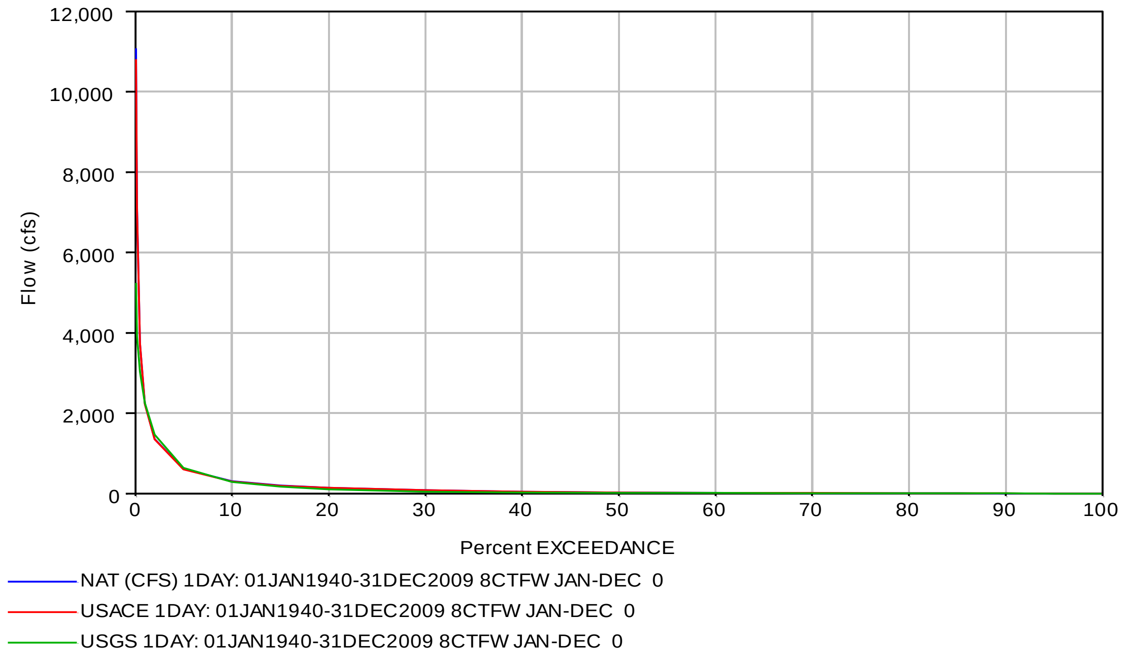

Figure 35 Flow Frequency or Duration Curves on 8CTFW for 1940-2009

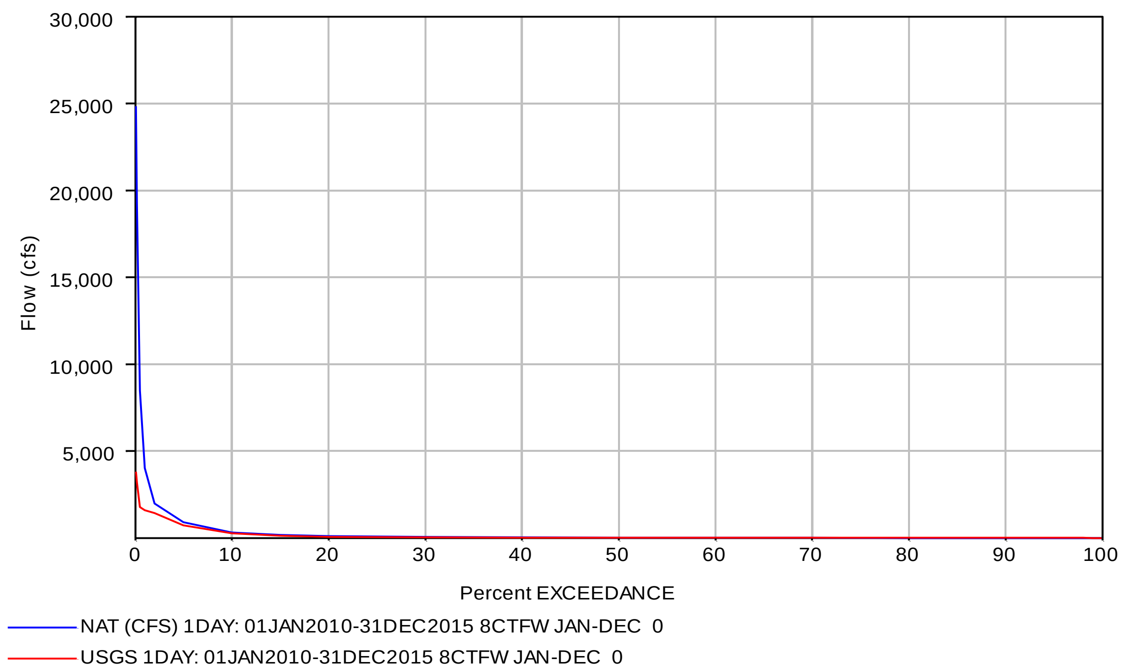

Figure 36 Flow Frequency or Duration Curves on 8CTFW for 2010-2015

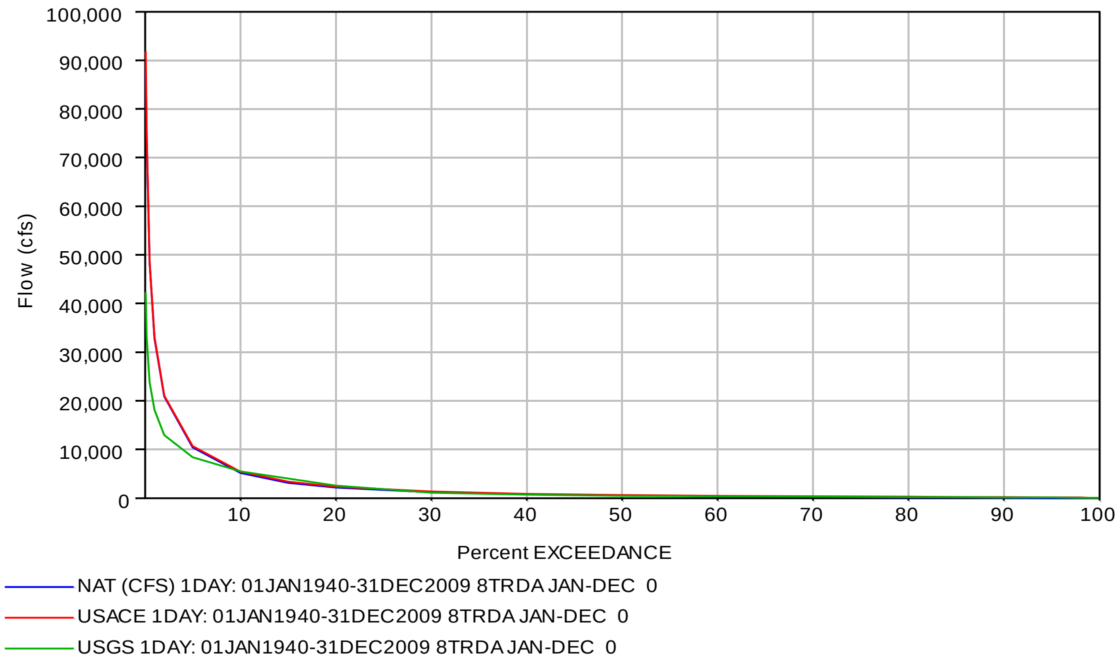

Figure 37 Flow Frequency or Duration Curves on 8TRDA for 1940-2009

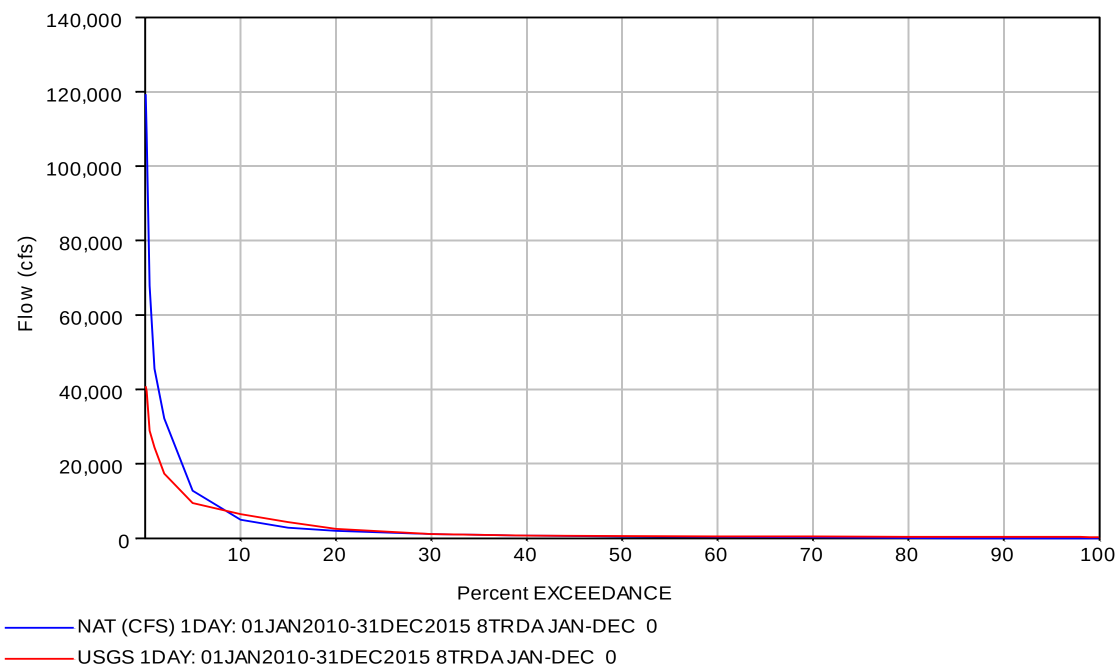

Figure 38 Flow Frequency or Duration Curves on 8TRDA for 2010-2015

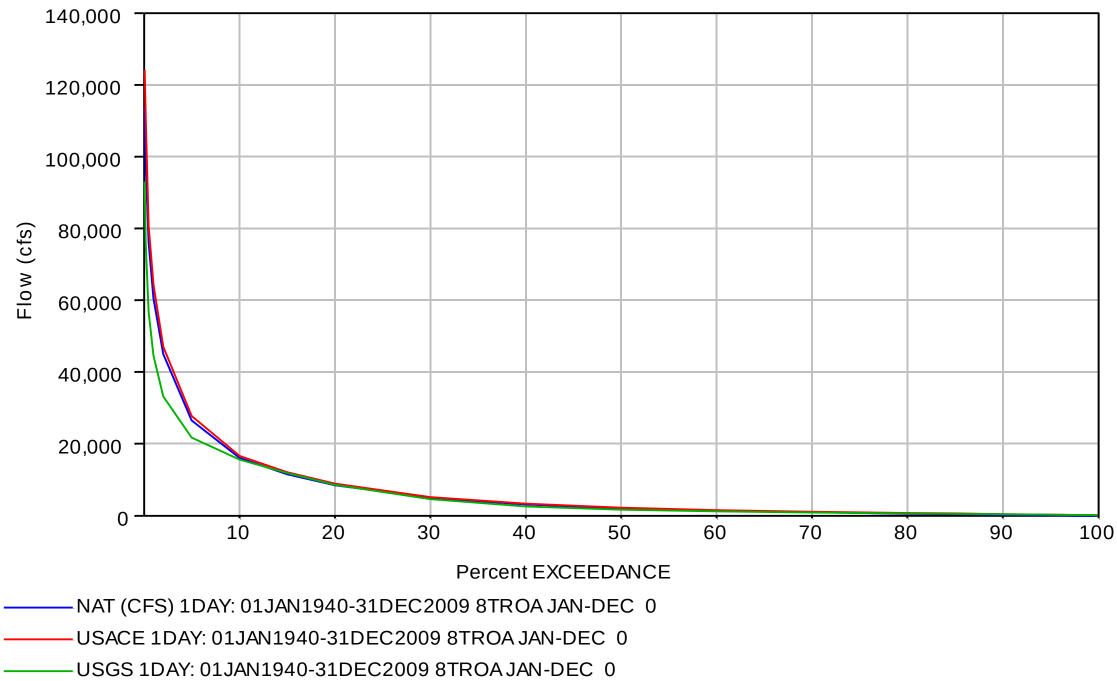

Figure 39 Flow Frequency or Duration Curves on 8TROA for 1940-2009

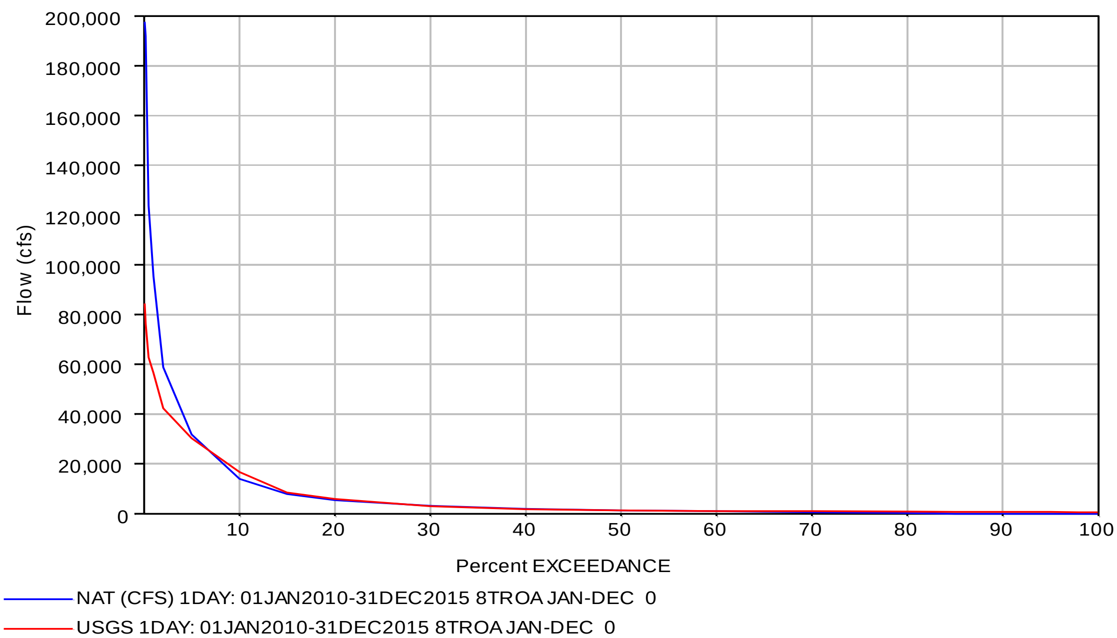

Figure 40 Flow Frequency or Duration Curves on 8TROA for 2010-2015

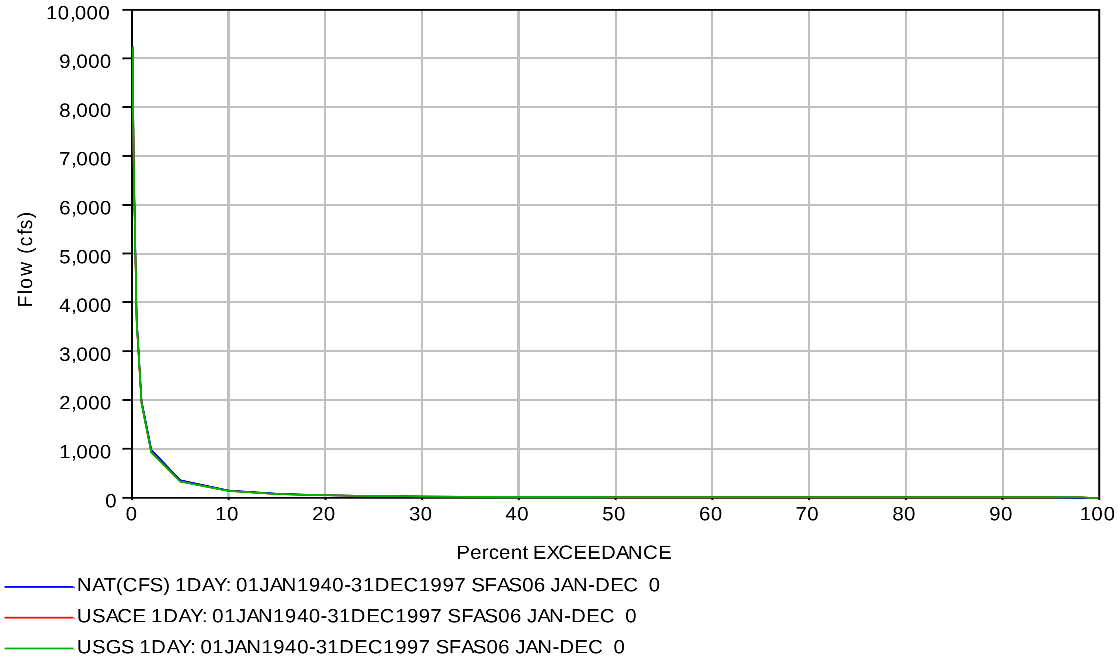

Figure 41 Flow Frequency or Duration Curves on SFAS06 for 1940-1997

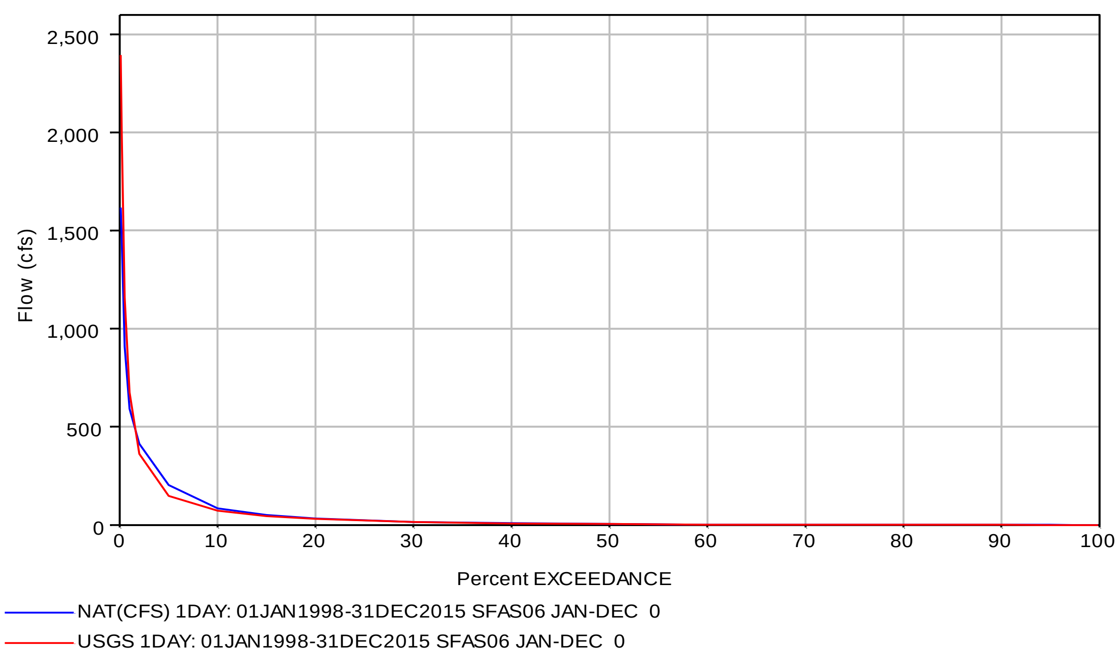

Figure 42 Flow Frequency or Duration Curves on SFAS06 for 1998-2015

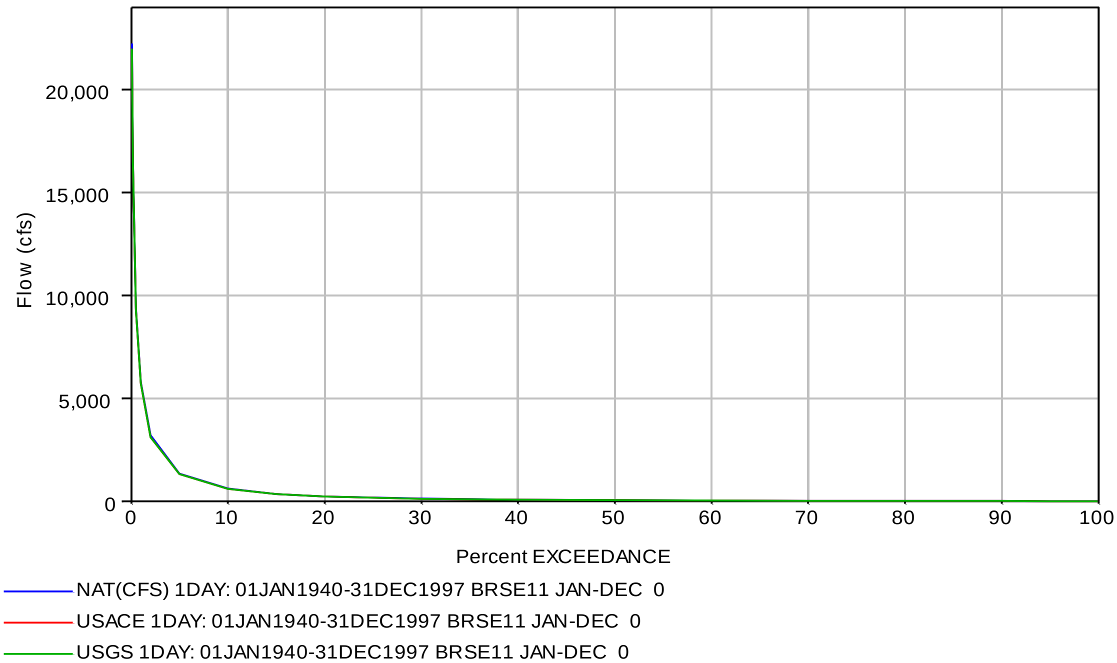

Figure 43 Flow Frequency or Duration Curves on BRSE11 for 1940-1997

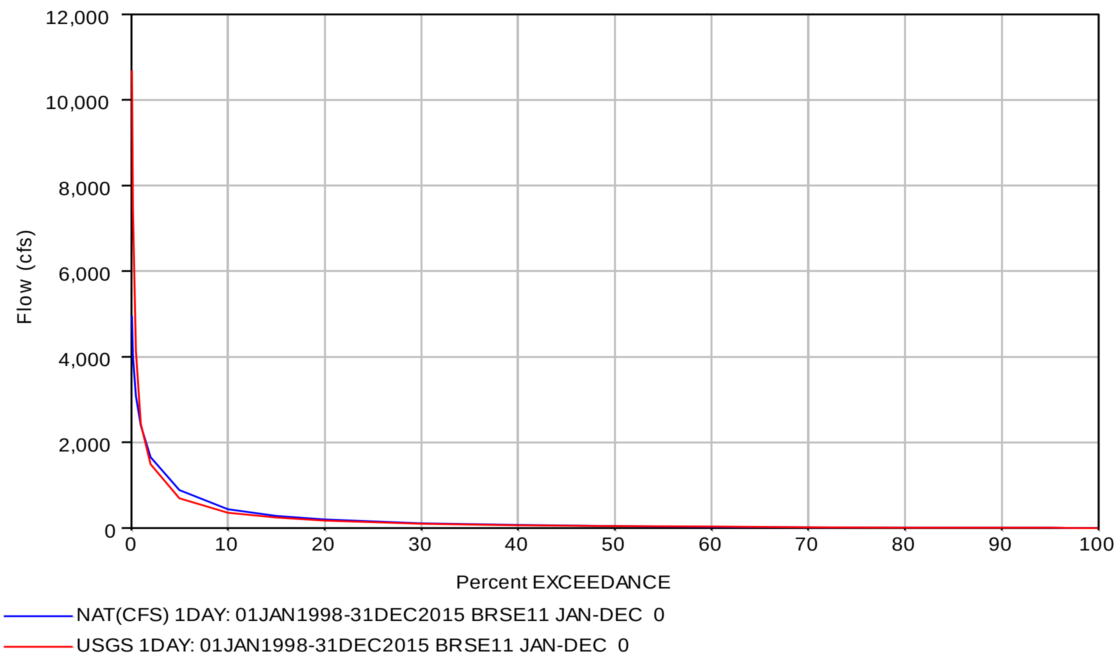

Figure 44 Flow Frequency or Duration Curves on BRSE11 for 1998-2015

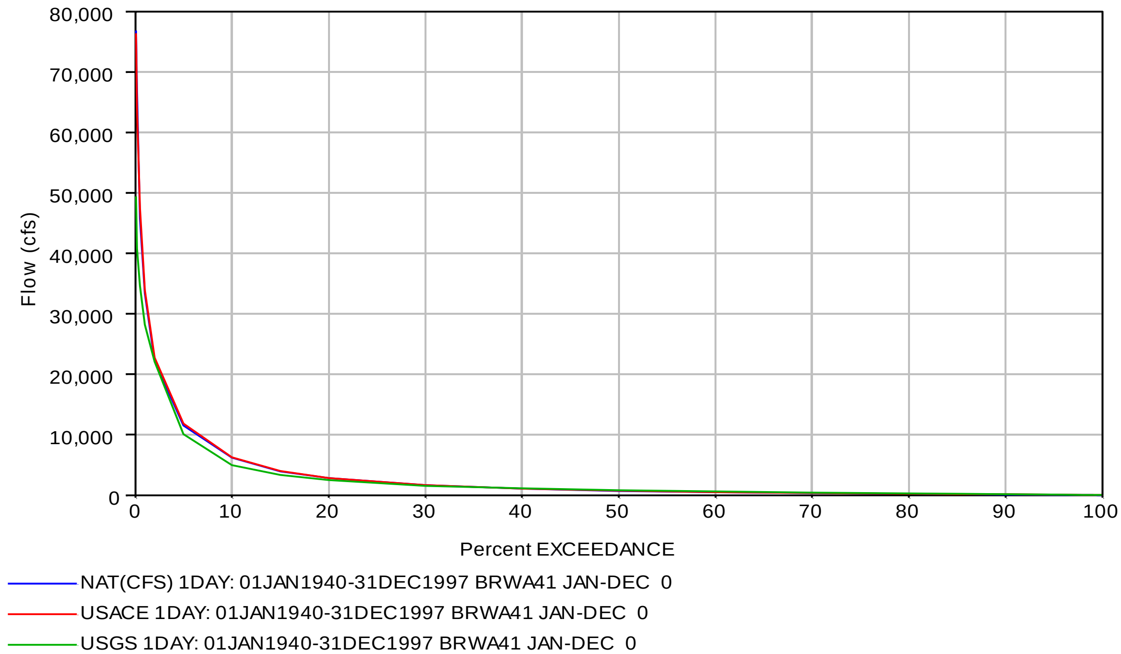

Figure 45 Flow Frequency or Duration Curves on BRWA41 for 1940-1997

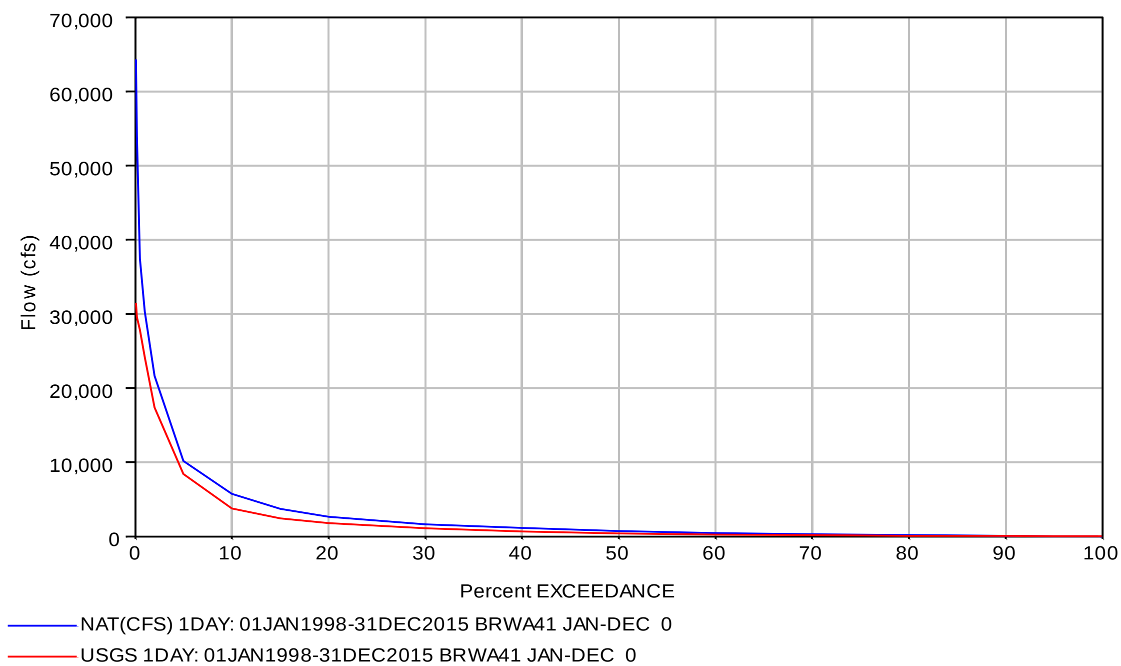

Figure 46 Flow Frequency or Duration Curves on BRWA41 for 1998-2015

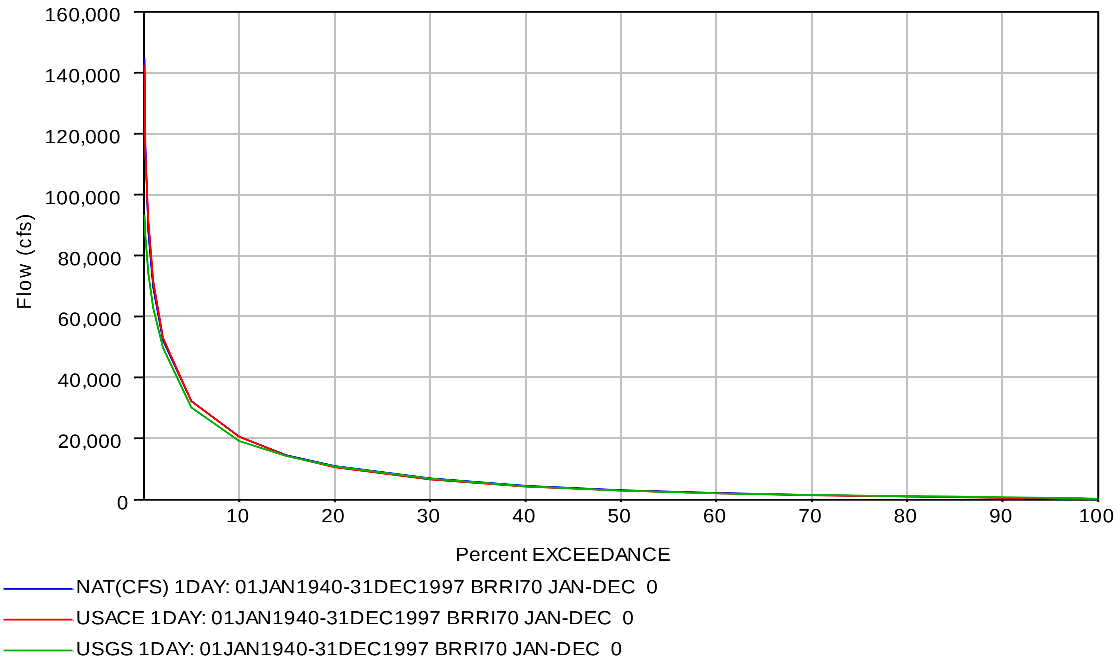

Figure 47 Flow Frequency or Duration Curves on BRRI70 for 1940-1997

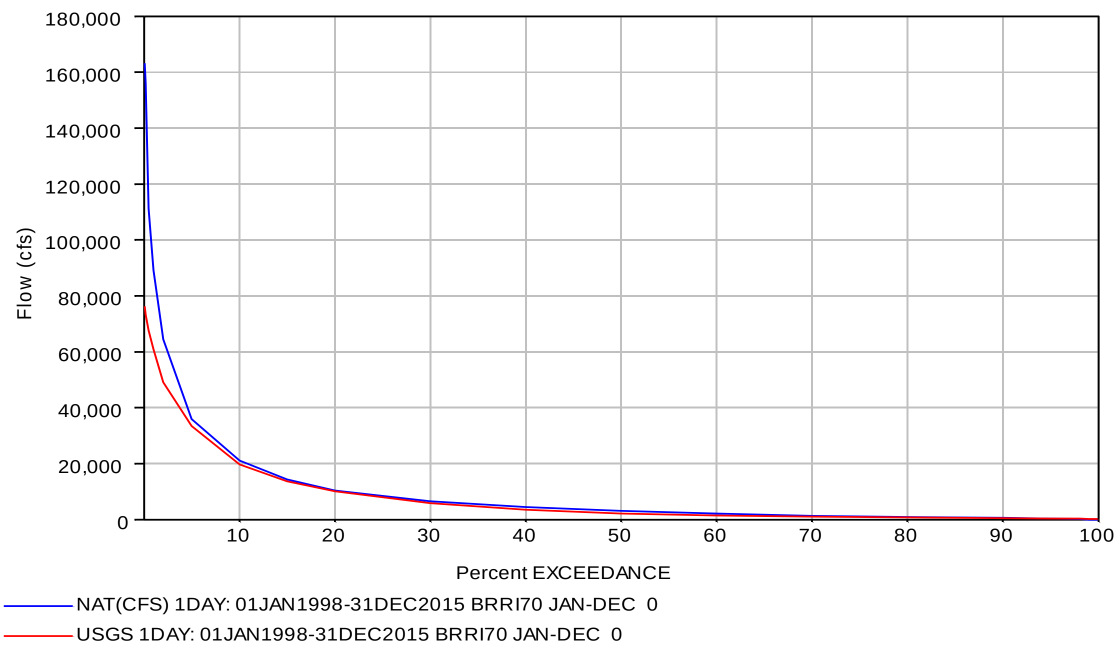

Figure 48 Flow Frequency or Duration Curves on BRRI70 for 1998-2015

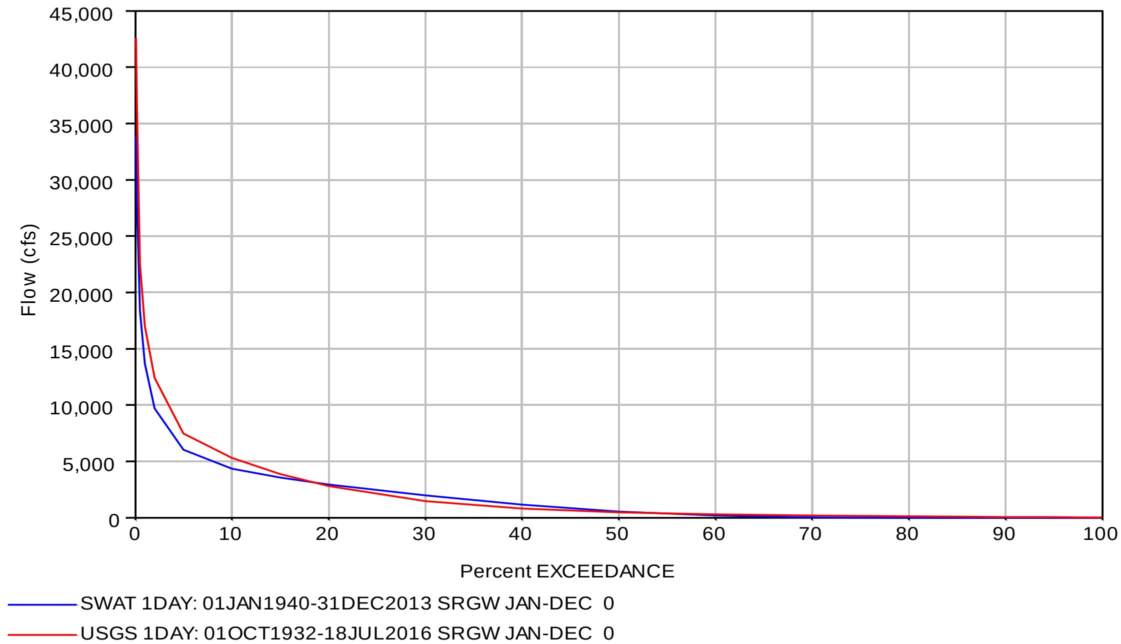

Figure 49 Flow Frequency or Duration Curves on SRGW for 1940-2013

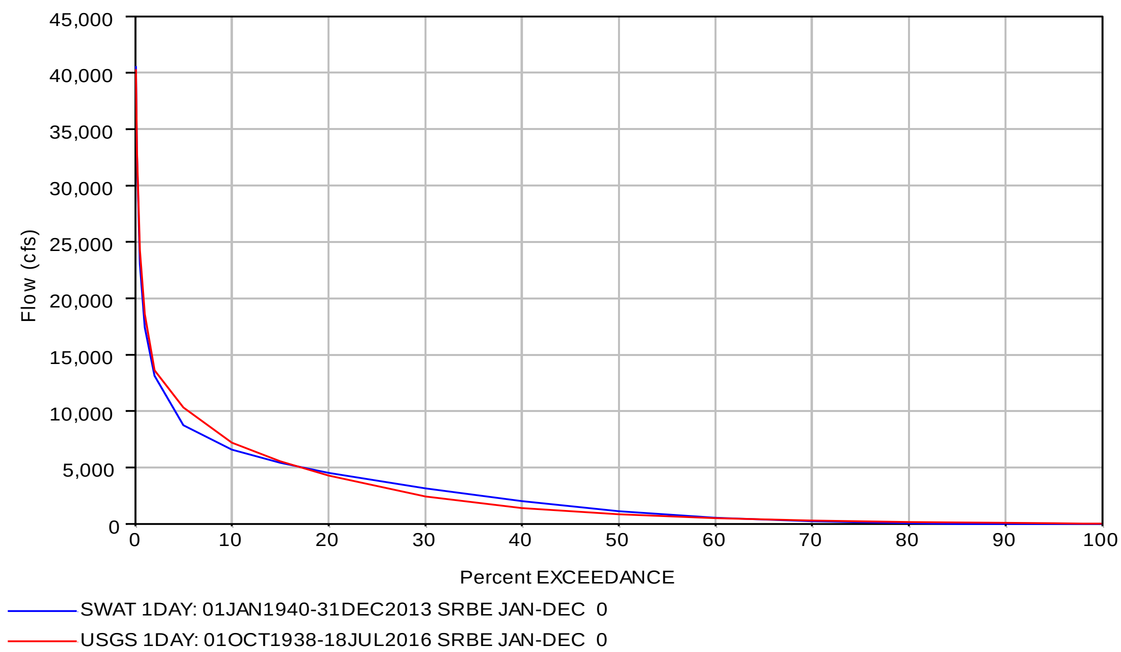

Figure 50 Flow Frequency or Duration Curves on SRBE for 1940-2013

CHAPTER VII

COMPARATIVE ANALYSIS OF WRAP/WAM SIMULATION RESULTS

The previous chapter deals with the comparative analysis of available daily flow datasets for formulating final/actual daily flow pattern hydrograph. This final flow pattern is input to WRAP/WAM simulation modeling system for disaggregating monthly naturalized to daily preserving monthly volumes under authorized use scenario. This chapter discusses the outputs of WRAP/WAM simulation results.

In addition to final flow pattern hydrograph, two other flow patterns were employed for evaluating and analyzing results from these three different simulation studies. The first study deals with actual flow pattern hydrograph, second with linear interpolation technique and third by shifting flow pattern by ten years from the perspective of examining results by repeating subsets within flow pattern hydrograph.

The parameters adopted for comparative analysis of daily stream flows are storage plots and regulated flow metrics for the same record of the hydrologic period of study. Storage plot is a good indicator which provides a general overview of water availability in a whole river basin. Regulated flow metrics and its plot provide general understanding of flow characteristics at individual control points.

Storage flow plots for Neches, Trinity, Brazos and Sabine WAM, are depicted in Figure 51, Figure 52, Figure 53 and Figure 54 respectively. Regulated flow metrics are illustrated from Table 25 to 35 and its plot through Figure 55 to 65. The following statistical parameters are provided for Table 25 to 35. All quantities are in the unit of AC-FT.

- Minimum value of daily flow.
- Average of mean daily flows.
- Maximum value of daily flow.
- Standard deviation (SD) of daily flows.
- Daily flows corresponding to the exceedance frequencies based on the Weibull formula.

The exceedance frequencies in percent represent the number of days that the mean flow during the day exceeded the indicated magnitudes. This information can be viewed as either flow frequency, probability, or duration relationships. From a duration analysis perspective, the percentages are the percent of the time that the flow exceeds the indicated magnitudes.

Regulated flow metrics Table from 25 to 35 depicts three columns for three simulations as already discussed above. The first simulation deals with actual flow WAM input dataset, the second simulation is concerned with linear interpolation, and the third simulation explores shifted flow pattern of 10 years. The outputs of these three simulations studies are written as SIM 1, SIM 2 and SIM 3 respectively.

A general holistic illustration of storage plots of Neches, Trinity, Brazos, and Sabine River Basin depicts similar pattern with slight difference in WRAP/WAM simulation results. Storage plots of Neches and Sabine River basin illustrates, shifted flow pattern and linear interpolation results were unable to match actual final WAM results particularly in the case of high peaks. The linear interpolation simulation results follow the same pattern as that of actual WAM and shifted flow pattern.

In the case of Trinity River basin, shifted flow pattern and actual final WAM results are almost similar with slight variation. In most cases, linear interpolation results follow the same pattern as that of actual WAM and shifted flow pattern. Actual final WAM and linear interpolation results were very close to each other as compared to shifted flow pattern as observed in the Brazos River basin.

The results of storage plots in four simulation studies follows almost the same pattern with slight variation. This similar trend is observed for regulated flow metrics of individual control points. As previously mentioned, objective 3 deals with the sensitivity analysis of WAM results, therefore, it can be concluded from the results of two above-mentioned parameters that WAM simulation outputs were not that much sensitive and basically follows the similar pattern.

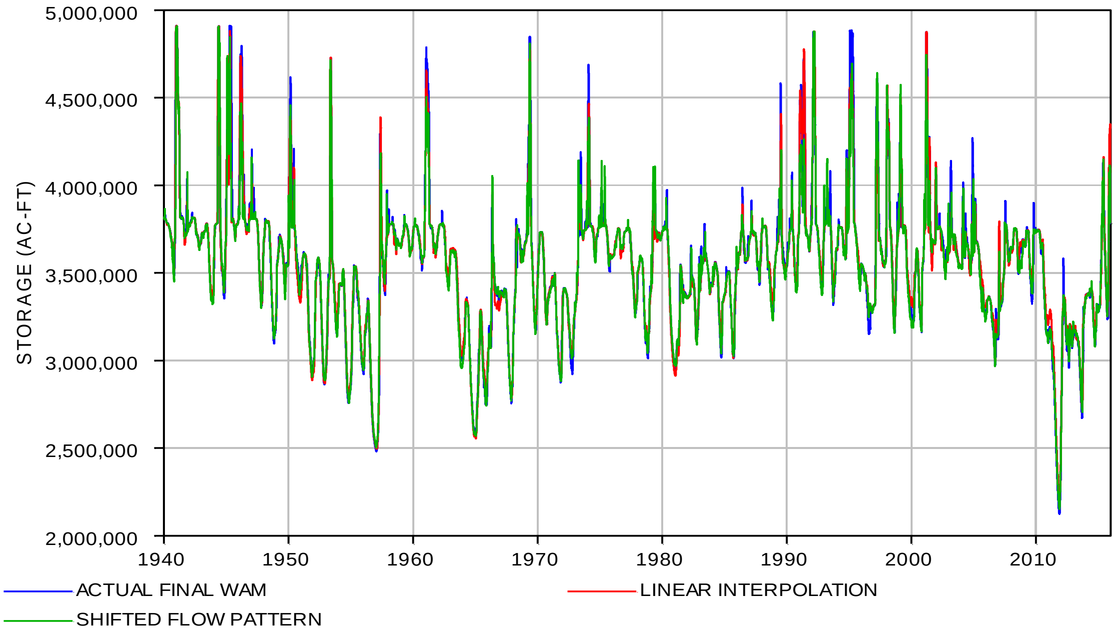

Figure 51 Storage Plots of major reservoir in Neches River Basin

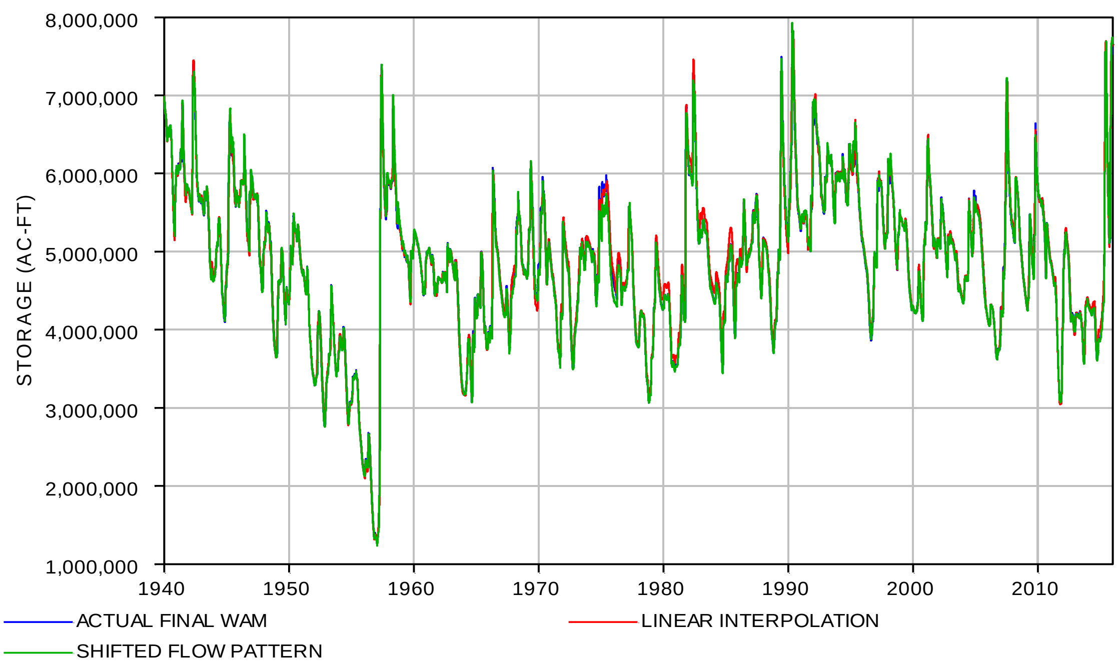

Figure 52 Storage Plots of major reservoir in Trinity River Basin

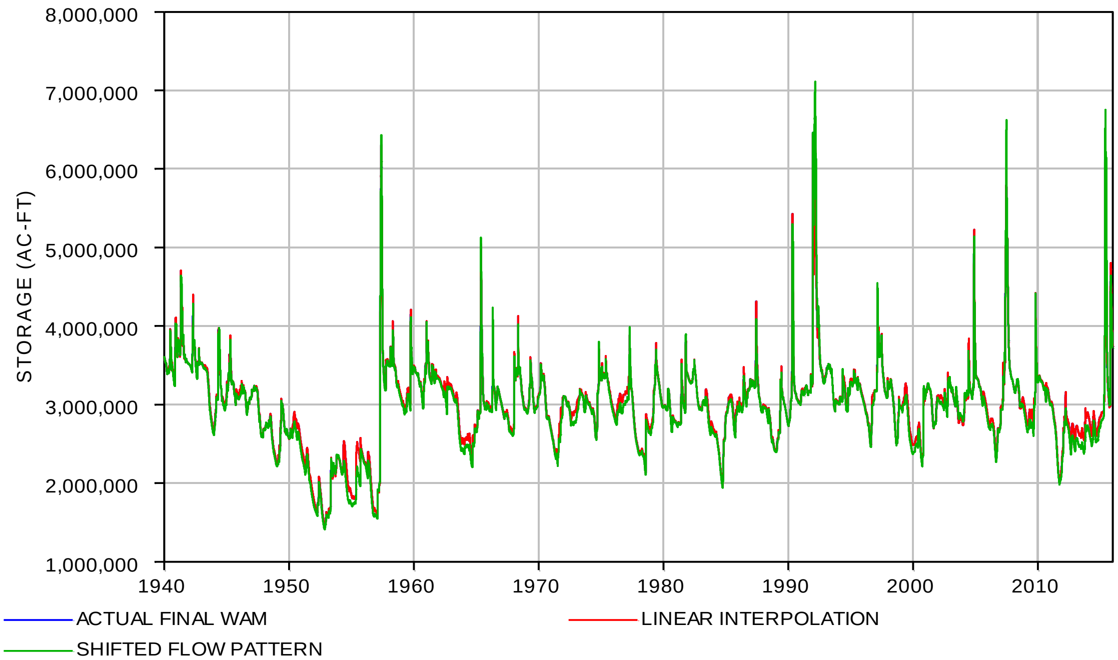

Figure 53 Storage Plots of major reservoir in Brazos River Basin

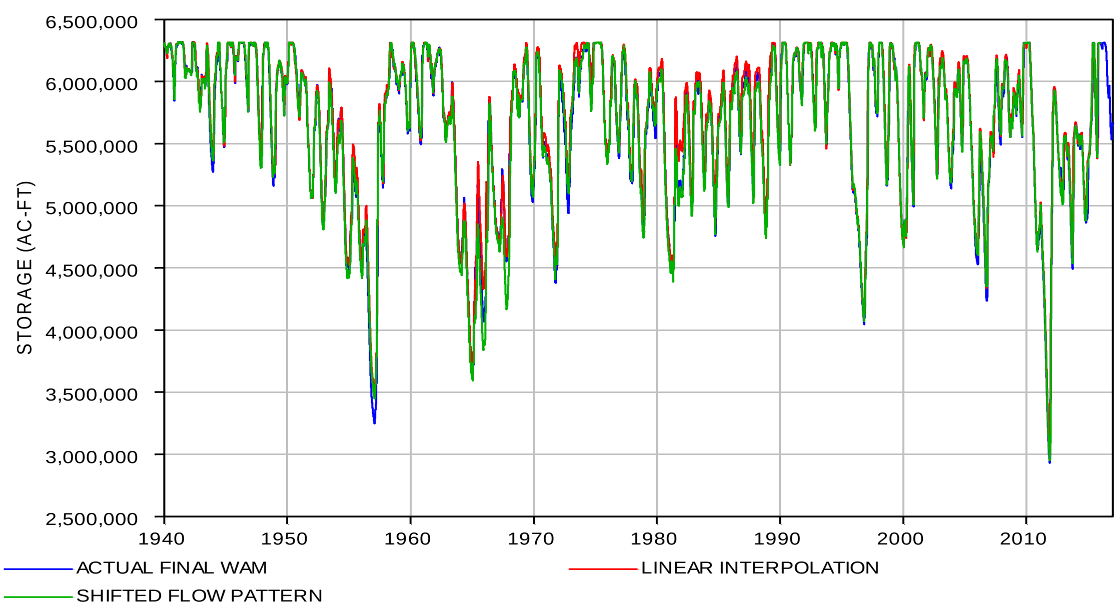

Figure 54 Storage Plots of major reservoir in Sabine River Basin

Table 25 Regulated Flow Metrics for Control Point NEEV

	NEEV Neches River at Evadale		
	Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	13276	13280	13285
Std Dev	16716	15031	18118
Min	0.0	0.0	0.0
Max	338092	606721	546565
0.2%	91121	74887	111618
0.5%	76920	58090	93309
1%	66731	52744	78792
2%	58998	48488	63976
5%	49460	43428	49855
10%	40280	36636	38051
15%	30722	30940	27855
20%	22664	25108	21728
30%	14323	16364	13972
40%	9258	11005	9241
50%	5965	6967	6262
60%	3841	4496	3998
70%	2536	2957	2543
80%	1614	1905	1552
85%	1198	1429	1176
90%	838	919	777
95%	479	510	419
98%	249	190	138
99%	41	87	0
99.5%	0	26	0
99.8%	0	6	0

Table 26 Regulated Flow Metrics for Control Point NERO

	NERO Neches River near Rockland		
	Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	4806	4806	4806
Std Dev	7415	6401	7338
Min	3.1	0.30	2.4
Max	97892	78932	196237
0.2%	53552	40443	50620
0.5%	43209	33264	41872
1%	35695	29033	35091
2%	27979	24197	27808
5%	19162	17649	18732
10%	13025	12911	12832
15%	9713	10528	9637
20%	7563	8524	7589
30%	4931	5400	4892
40%	3008	3352	3151
50%	1812	2243	1983
60%	1063	1294	1184
70%	657	759	729
80%	396	420	404
85%	297	294	290
90%	214	187	193
95%	138	92	105
98%	79	31	49
99%	50	15	29
99.5%	18	8	16
99.8%	10	4	7

Table 27 Regulated Flow Metrics for Control Point 8CTFW

	8CTFW Clear Fork Trinity River at Fort Worth		
	Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	343	343	343
Std Dev	1612	736	1285
Min	0.0	0.0	0.0
Max	84252	12687	60304
0.2%	15774	6369.0	11309
0.5%	7954	5086.3	7091
1%	4594	3804.1	4638
2%	2802	2598.3	2949
5%	1225	1552.2	1492
10%	611	850.3	745
15%	395	546.0	444
20%	281	391.9	299
30%	160	244.7	161
40%	95	159.4	89
50%	59	104.1	55
60%	38	68.8	34
70%	24	44.6	20
80%	14	23.1	11
85%	11	14.1	10
90%	9	10.7	9
95%	8	8.5	8
98%	7	6.5	7
99%	6	6.5	6
99.5%	6	6.0	6
99.8%	6	6.0	6

Table 28 Regulated Flow Metrics for Control Point 8TRDA

	8TRDA Trinity River at Dallas		
	Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	4791	4791	4791
Std Dev	14617	9433	12871
Min	0.0	0.0	0.0
Max	316359	146194	471538
0.2%	151547	84192	120387
0.5%	97988	64730	84031
1%	67844	50702	57873
2%	42564	32373	37922
5%	21011	18740	20118
10%	10169	12071	11365
15%	6224	8826	7572
20%	4230	6532	5345
30%	2366	4018	3006
40%	1514	2627	1854
50%	1039	1633	1170
60%	740	1047	739
70%	502	636	449
80%	293	272	242
85%	204	133	152
90%	98	37	64
95%	11	10	11
98%	9	8	9
99%	7	7	7
99.5%	7	7	7
99.8%	6	6	6

Table 29 Regulated Flow Metrics for Control Point 8TROA

	8TROA Trinity River near Oakwood		
	Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	12459	12459	12459
Std Dev	24801	18993	22517
Min	0.4	5.7	5.3
Max	505686	212125	307011
0.2%	203647	129252	186699
0.5%	158555	113202	142950
1%	125424	96321	114256
2%	91547	77282	83938
5%	53419	49451	52490
10%	31789	32448	32757
15%	22428	24380	23134
20%	16435	19443	17294
30%	9487	12523	10300
40%	5934	8029	6729
50%	3887	5225	4349
60%	2589	3363	2791
70%	1780	1982	1730
80%	1020	1003	945
85%	718	621	621
90%	406	258	335
95%	92	31	67
98%	10	10	10
99%	8	8	8
99.5%	7	7	7
99.8%	6	6	6

Table 30 Regulated Flow Metrics for Control Point BRRI70

	BRRI70 Brazos River at Richmond		
	Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	16882	16836	16871
Std Dev	29509	22194	27866
Min	9.5	9.5	9.5
Max	645126	263129	741526
0.2%	260217	162552	210493
0.5%	184619	132658	167218
1%	146276	109255	134992
2%	110162	85907	102591
5%	65679	60339	64646
10%	41273	41595	41163
15%	29054	32403	30458
20%	21776	25920	23317
30%	14028	17031	15026
40%	9519	11825	10379
50%	6759	8430	7303
60%	4949	6226	5262
70%	3752	4547	3755
80%	2865	3271	2693
85%	2430	2637	2189
90%	1953	2105	1644
95%	1440	1471	1110
98%	1019	898	649
99%	723	538	354
99.5%	473	270	157
99.8%	48	14	10

Table 31 Regulated Flow Metrics for Control Point BRSE11

	BRSE11 Brazos River at Seymour Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	609	609	609
Std Dev	2710	1396	2689
Min	0.0	0.0	0.0
Max	92823	20270	145227
0.2%	27752	12344	22774
0.5%	15581	9098	14185
1%	9311	7083	9406
2%	5395	5224	5703
5%	2384	2818	2522
10%	1107	1630	1178
15%	636	1047	679
20%	424	710	454
30%	229	372	235
40%	139	217	137
50%	89	128	85
60%	57	84	50
70%	34	54	26
80%	15	27	10
85%	8	16	5
90%	2	7	1
95%	0	1	0
98%	0	0	0
99%	0	0	0
99.5%	0	0	0
99.8%	0	0	0

Table 32 Regulated Flow Metrics for Control Point BRWA41

	BRWA41 Brazos River at Waco Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	5793	5739	5782
Std Dev	12981	9010	12273
Min	9.5	10	9.5
Max	417608	145309	292135
0.2%	123663	76716	123073
0.5%	87267	56424	80764
1%	63869	45978	54936
2%	43951	33474	38739
5%	22438	20907	21530
10%	12190	13235	12928
15%	7930	9683	8948
20%	5732	7445	6563
30%	3662	5048	4213
40%	2823	3500	3071
50%	2333	2706	2390
60%	1811	2243	1862
70%	1397	1708	1369
80%	1128	1276	1031
85%	1013	1122	888
90%	910	965	687
95%	744	852	359
98%	329	595	130
99%	183	335	65
99.5%	115	190	35
99.8%	76	71	17

Table 33 Regulated Flow Metrics for Control Point SFAS06

	SFAS06 Salt Fork Brazos River Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	179	179	179
Std Dev	1110	488	1014
Min	0.0	0.0	0.0
Max	46213	6746	55033
0.2%	11434	4359.2	9439
0.5%	6023	3525.3	5310
1%	3149	2718.8	3035
2%	1557	1820.4	1859
5%	617	828.0	672
10%	247	431.3	265
15%	134	265.6	140
20%	83	176.0	88
30%	39	85.3	40
40%	22	45.5	23
50%	13	27.6	13
60%	7	17.3	7
70%	3	9.8	3
80%	1	3.3	1
85%	1	1.6	0
90%	0	0.6	0
95%	0	0.1	0
98%	0	0.0	0
99%	0	0.0	0
99.5%	0	0.0	0
99.8%	0	0.0	0

Table 34 Regulated Flow Metrics for Control Point SRGW

	SRGW Sabine river at Gladewater Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	4268	4270	4270
Std Dev	8226	6139	7729
Min	5.5	0.0	2.3
Max	263817	68576	281686
0.2%	72118	41229	58096
0.5%	49293	35249	45257
1%	36963	29658	36001
2%	27125	23873	27952
5%	16736	16457	17618
10%	11592	11300	11348
15%	8731	8686	8195
20%	6429	6963	6244
30%	3693	4691	3794
40%	2179	3023	2396
50%	1320	1873	1524
60%	822	1085	938
70%	499	612	536
80%	277	292	271
85%	189	172	174
90%	116	81	100
95%	51	31	41
98%	30	7	20
99%	22	2	13
99.5%	19	1	9
99.8%	16	0	7

Table 35 Regulated Flow Metrics for Control Point SRBE

	SRBE Sabine river at Beckville Flow Metrics 1940-2015		
	SIM 1	SIM 2	SIM 3
	(AC-FT)	(AC-FT)	(AC-FT)
Mean	5914	5911	5912
Std Dev	9153	7386	9038
Min	12.9	0.0	7.4
Max	244844	84797	241059
0.2%	72395	51336	63810
0.5%	50965	41753	48377
1%	39630	34418	40513
2%	29468	27077	32637
5%	21781	20073	22845
10%	15999	15220	15263
15%	12444	12319	11551
20%	9794	9991	9023
30%	5893	6733	5856
40%	3716	4792	3945
50%	2378	3127	2671
60%	1610	1984	1790
70%	1118	1284	1176
80%	756	808	768
85%	551	548	538
90%	363	311	332
95%	195	120	156
98%	87	39	62
99%	53	16	33
99.5%	35	8	20
99.8%	26	3	15

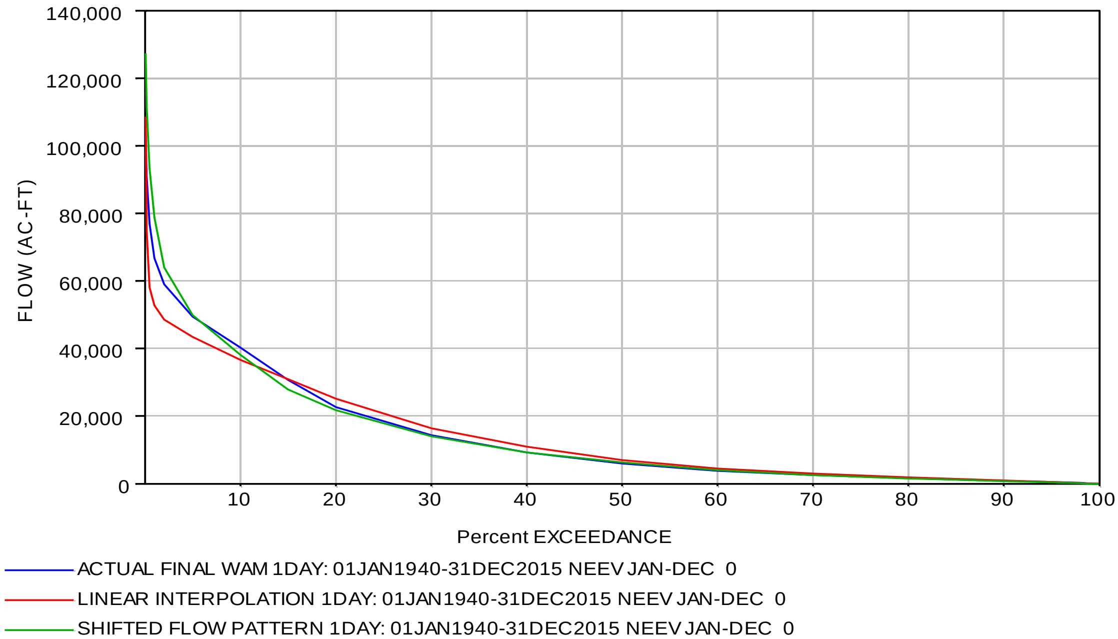

Figure 55 Regulated Flow Frequency plot of NEEV for 1940-2015

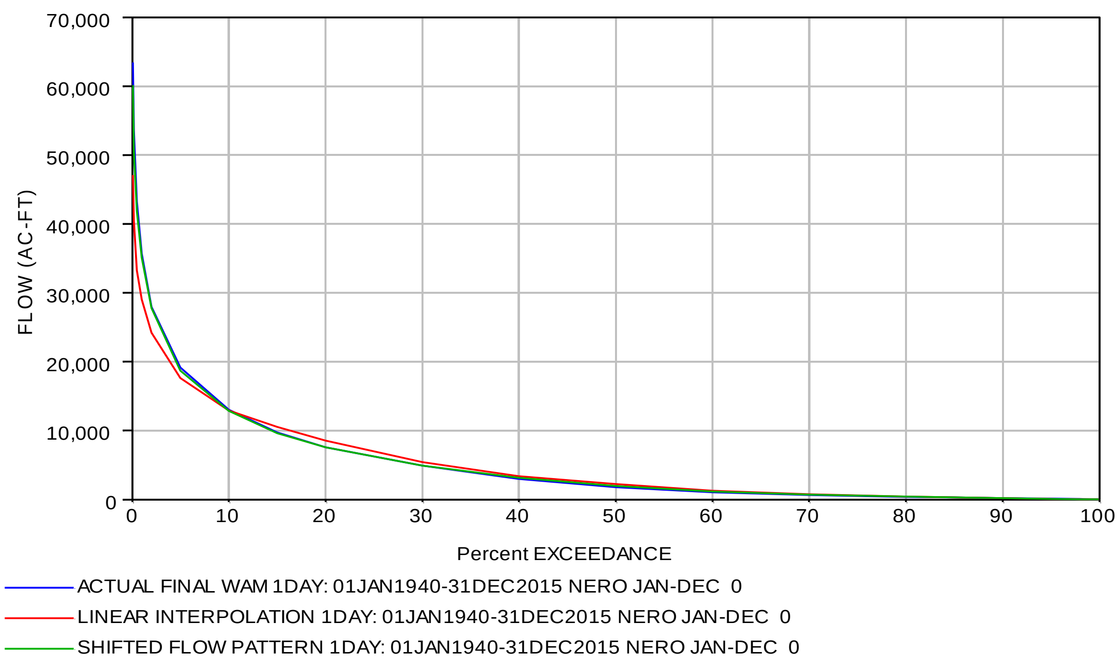

Figure 56 Regulated Flow Frequency plot of NERO for 1940-2015

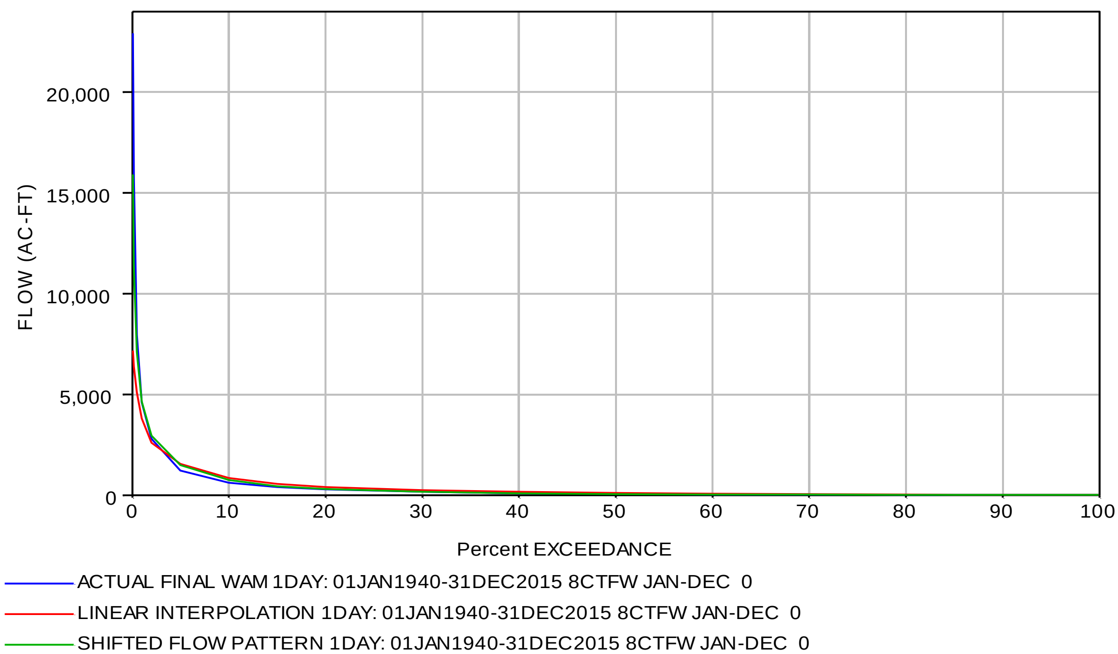

Figure 57 Regulated Flow Frequency plot of 8CTFW for 1940-2015

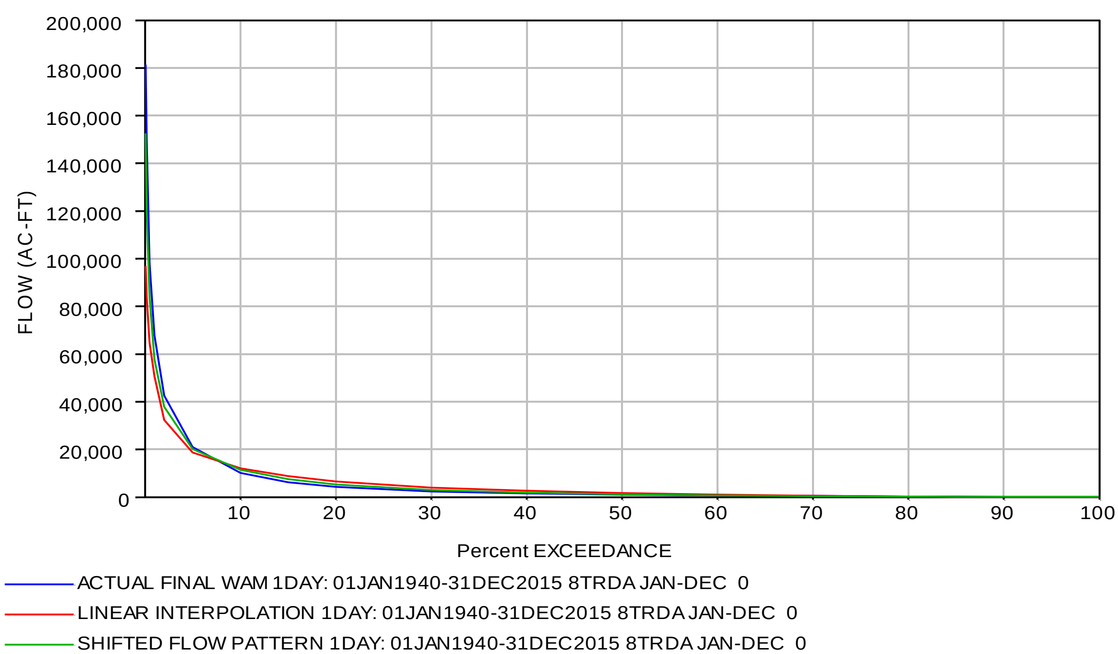

Figure 58 Regulated Flow Frequency plot of 8TRDA for 1940-2015

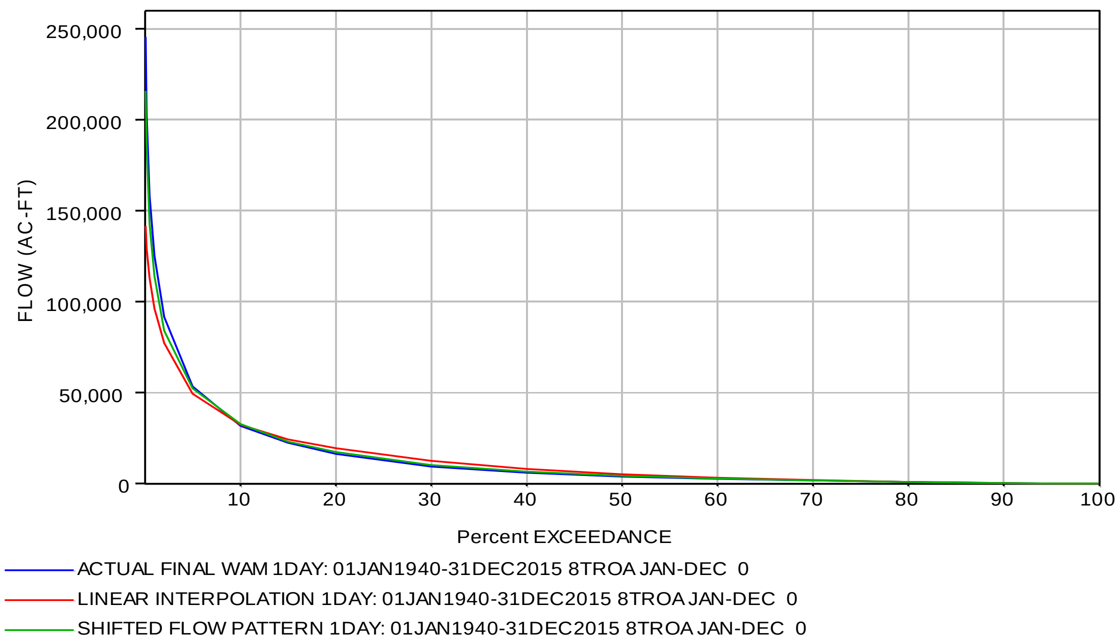

Figure 59 Regulated Flow Frequency plot of 8TROA for 1940-2015

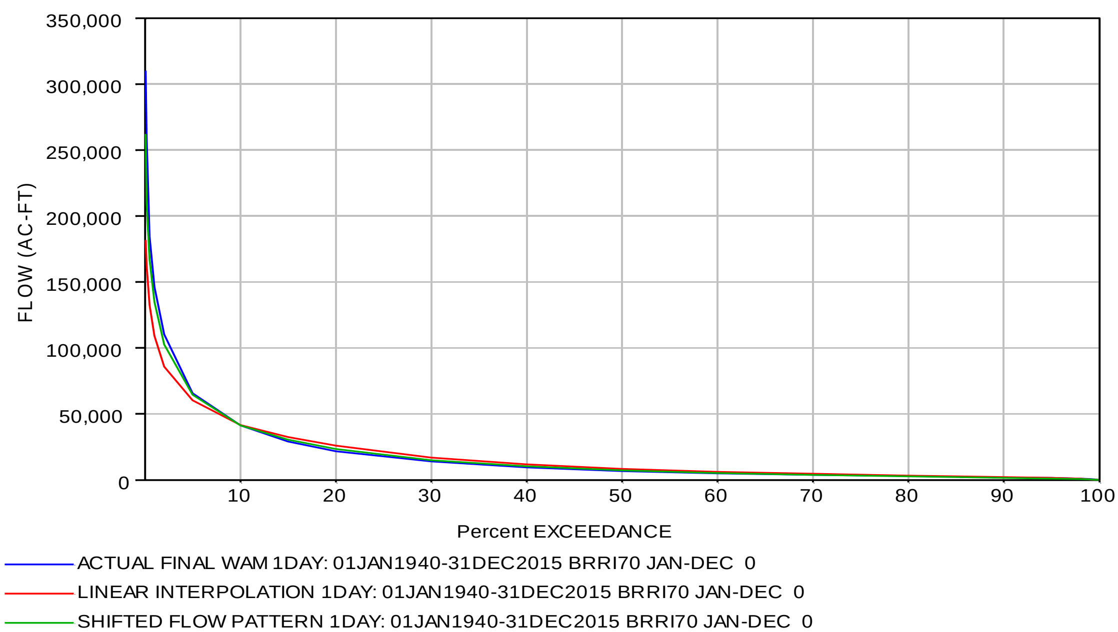

Figure 60 Regulated Flow Frequency plot of BRRI70 for 1940-2015

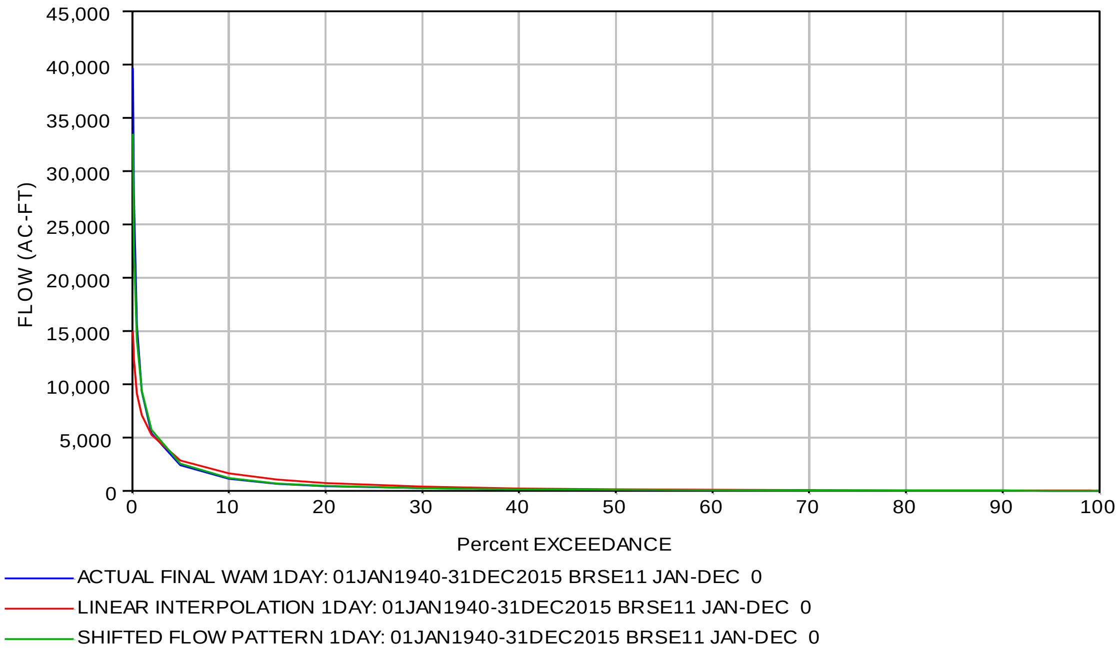

Figure 61 Regulated Flow Frequency plot of BRSE11 for 1940-2015

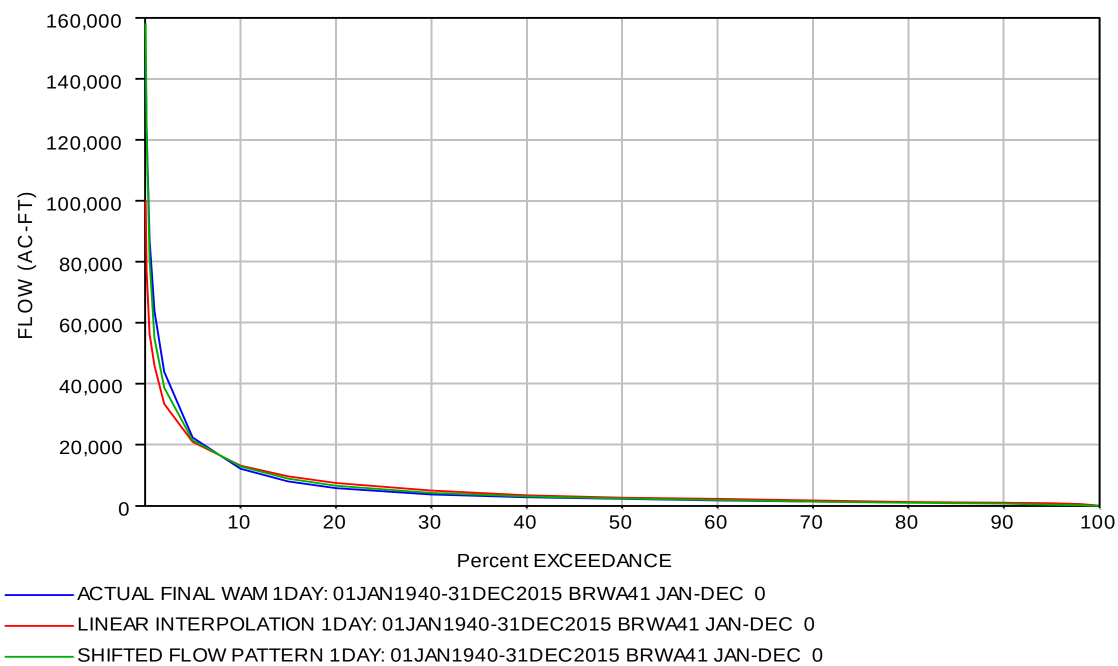

Figure 62 Regulated Flow Frequency plot of BRWA41 for 1940-2015

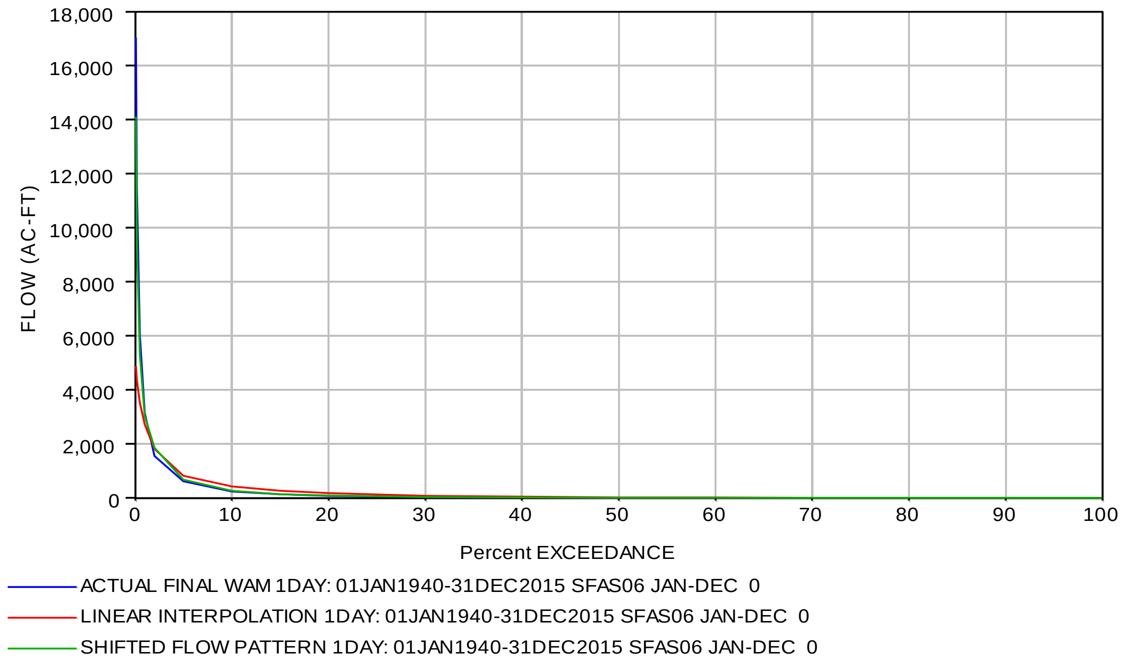

Figure 63 Regulated Flow Frequency plot of SFAS06 for 1940-2015

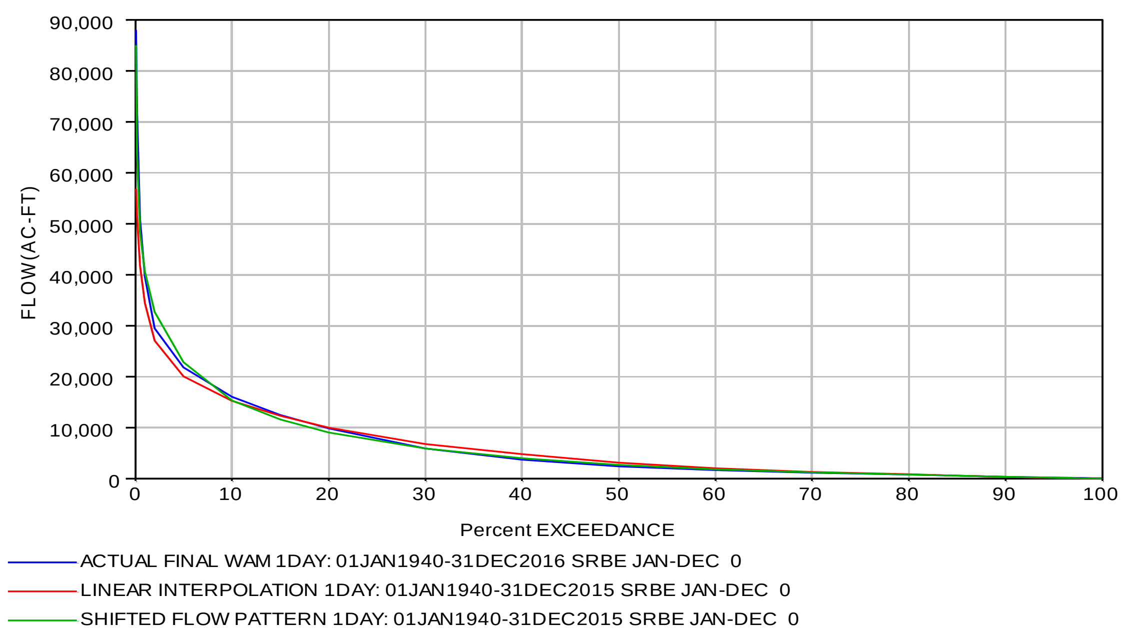

Figure 64 Regulated Flow Frequency plot of SRBE for 1940-2015

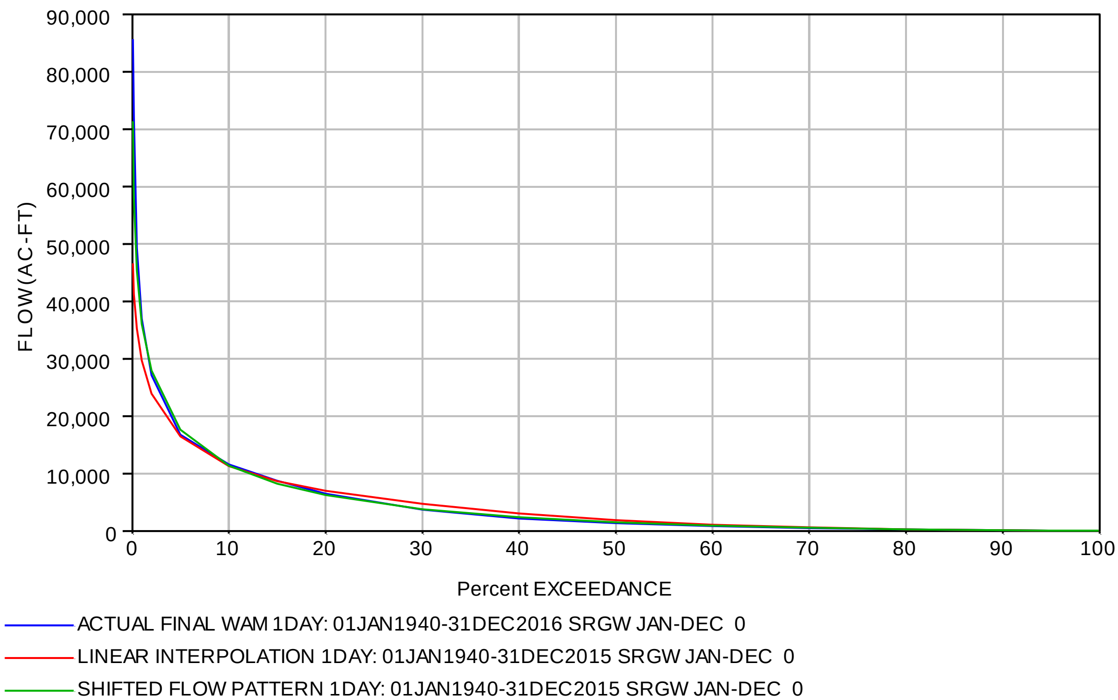

Figure 65 Regulated Flow Frequency plot of SRGW for 1940-2015

CHAPTER VIII

SUMMARY AND CONCLUSION

The WRAP/WAM is one of the generalized river/reservoir simulation modeling system which simulates development, management, control, allocation, regulation and use of water resources of a river basin under prior appropriation water rights permit system. As discussed in Chapter I and II, the Texas Commission on Environmental Quality (TCEQ) Water Availability Model (WAM) System consists of the generalized Water Rights Analysis Package (WRAP) modeling system and monthly WRAP simulation input datasets for all the river basins of Texas. WRAP and an input dataset for a particular river basin are called a WAM.

Daily stream flows particularly environmental flows became a critical issue in the state of Texas after Senate Bill 3 (SB3) enacted by Texas Legislature in the year 2007. SB3 program emphasizes technical research based flow conditions required to maintain and support a sustainable ecological environment for Texas WAM. The environmental study is meaningful on daily time step and thus need arises for the expansion of WRAP to incorporate all necessary changes in accordance with SB3. Therefore, the prime motivation for this research is the recent inclusion of daily modeling capabilities in the TCEQ WAM System to support analyses of environmental instream flow issues.

The research involved in this thesis investigates comparative analysis of different available flows with the objective of disaggregating monthly naturalized flow volumes to daily, along with enhancing its capabilities. The research analyzes flow characteristics of all river basins and its impact due to water resources development. WAM outcomes are resulting from flow pattern hydrographs for three different scenarios and, as already mentioned, expansion of WRAP capabilities from the perspective of improving monthly to daily disaggregation.

Chapter III deals with the Brazos, Trinity, Neches, and Sabine River Basin Water Availability Models (WAMs) serving as case studies for this research. Chapter IV explores different available daily and monthly streamflow datasets incorporating observed daily flows at U.S. Geological Survey (USGS) gaging stations, unregulated daily flows from U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD), daily naturalized synthesized stream flows using SWAT and HAWQS watershed rainfall-runoff modeling systems and recently updated and extended monthly WAM naturalized flows using HYD model.

Chapter V explores HAWQS methodology encompassing HAWQS modeling system, its input datasets and comparative analysis of HAWQS flow vs SWAT flows. The statistical frequency metrics is applied along with Nash-Sutcliffe efficiency (NSE), Percent Bias (PBIAS) and coefficient of determination (r^2) statistical parameters for model evaluation.

Chapter VI analyzes comparative analyses of observed and synthesized flows in daily time step as already discussed in Chapter IV. Daily plots, flow frequency metrics based on Weibull formula and its duration curve are explored for the formulation of daily flow pattern hydrograph.

Chapter VII deals with the comparative analysis of WRAP/WAM simulation results. Three simulation scenarios were created for comparative analysis. The first simulation deals with actual flow pattern hydrograph, the second simulation is concerned with linear interpolation, and the third simulation explores shifted flow pattern of 10 years. Storage plots, regulated flow metrics, and its duration curve are employed to reach the conclusion.

The findings suggest that calibrated SWAT and HAWQS watershed rainfall-runoff modeling systems were not highly accurate. The SWAT and HAWQS daily synthesized flows were not able to capture low flows. Moreover, they were unable to replicate frequency metrics accurately. HAWQS flows were not able to satisfy statistical parameters for model evaluation and hence not employed for the formulation of daily flow pattern hydrograph. The period of flow records can only be generated from 1960-2010 for HAWQS simulation model.

Missing data for longer periods of records were addressed using available stream flows located near target control points, and statistical analysis was applied in case of relatively shorter record of missing data. A new technique is used for transferring stream flows; instead of employing conventional drainage area ratio approach, the ratio of mean naturalized flows is utilized which proves out to be more accurate. The HYD synthesized flows closely replicates the statistical metrics of original WAM naturalized flows for each river basin.

It is evident from daily streamflow plots and flow frequency metrics that USACE unregulated flow patterns were more accurate and precise as compared to other available daily flows. Therefore, USACE flow patterns were employed wherever available followed by USGS gage flows. SWAT generated flows were not used at all due to its inability to capture low flows and replicate frequency metrics. Instead of using SWAT naturalized flows and/or repeating sub-periods of USACE unregulated flows, USGS gaged flows were predominantly used in the formulation of daily flow pattern hydrograph facilitated by expanded use of DSS files and HEC-DSSVue.

The outcomes of storage plots and regulated flow metrics employed in four simulation studies indicate that final flow pattern hydrograph, shifted flow pattern and linear interpolation technique were following the same pattern with slight differences. Therefore, it is meaningful to conclude that WAM simulation results were not significantly sensitive.

Overall, extreme flow variability, both spatially and temporally, is observed in all the river basins of Texas. Long-term trends are tough to detect and quantify due to significant continuous, dramatic variability and randomness including severe multiple-year droughts, major flood events as well as seasonal variations. The impacts of water resources development on flow regime vary substantially between different locations and for different range of flows.

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