Daily Water Availability Model for the Brazos River Basin and Brazos-San Jacinto Coastal Basin

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make every drop count

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ABSTRACT

The monthly Brazos WAM consists of the generalized Water Rights Analysis Package (WRAP) and input data for the Brazos River Basin and adjoining coastal basin from the statewide TCEQ Water Availability Modeling (WAM) System. The Brazos WAM simulates water resources development, allocation, management and use in accordance with the over 1,200 water rights permits in effect for the basin. Operations of 680 reservoirs are simulated. The daily version of the Brazos WAM documented by this report was created by converting the monthly WAM to daily, adding routing parameters for 67 selected river reaches, flood control operations of 19 Corps of Engineers reservoirs, and SB3 environmental flow standards at 19 gage sites. The hydrologic period-of-analysis was updated to extend from January 1940 through December 2017. Monthly naturalized stream flows at 77 primary gaged control points are distributed to over 3,000 ungauged control points within the simulation. Monthly naturalized flows are disaggregated to daily based on daily pattern hydrographs at 58 gaging stations. This report accompanies the WRAP simulation input files for daily and monthly versions of the Brazos WAM and relevant auxiliary data files.

The Brazos WAM represents the inaugural application of the expanded daily modeling capabilities incorporated in the July 2018 and May 2019 versions of WRAP. The Brazos case study development and application of a daily WAM contributed to improvements in the generalized WRAP modeling system. The first half of this report focuses on development of the daily Brazos WAM. Latter chapters explore case study comparative analyses of the various features of the simulation model and alternative options for performing different tasks. Monthly WRAP/WAM modeling is complex, and daily modeling is much more complex. This report provides guidelines and sets of recommended optional methods for developing manageable and effective strategies for employing the daily modeling system that are generally applicable for any river basin.

Daily WRAP/WAM modeling and analysis capabilities can significantly contribute to various types water management endeavors. The work documented by this report focuses on improving capabilities for incorporating Senate Bill 3 (SB3) environmental flow standards (EFS) in the TCEQ WAM System. A strategy is demonstrated in which daily instream flow targets for SB3 EFS are computed and summed to monthly quantities within the daily *SIMD* simulation for input to the monthly *SIM* simulation model. The monthly *SIM* simulation model is applied with the SB3 EFS modeled as instream flow *IF* record water rights with targets defined as target series *TS* records stored in an input file. Both a daily WAM dataset and a monthly WAM dataset with SB3 EFS added in this manner accompany this report.

Different strategies for employing the expanded WAM will be useful for different types of applications. With the strategy explored in this report, after SB3 EFS targets are established with the daily WAM, routine modeling applications employ the monthly WAM. SB3 EFS set-asides are incorporated in the monthly WAM, appropriately reducing the quantities of stream flow available for further appropriation by junior water users. The daily WAM can be employed directly in many other types of studies with input data varied in alternative daily *SIMD* simulations to explore various water management strategies and issues. For example, the daily model can be applied directly in the formulation, evaluation, and improvement of environmental flow standards to assess capabilities (reliabilities) of satisfying proposed alternative sets of flow standards. The daily simulation modeling capabilities can also support various types of studies in which operation of reservoirs during and after floods is a significant concern.

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CHAPTER 1
INTRODUCTION

The Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System consists of the Water Rights Analysis Package (WRAP), WRAP input datasets for all of the river basins of Texas, and related information. The TCEQ WAM System input dataset for a particular river basin combined with the generalized WRAP modeling system is called a water availability model or WAM. The water availability model for the Brazos River Basin and adjoining coastal basin lying between the Brazos and San Jacinto River Basins is called the Brazos WAM. This report documents the following additions to the authorized use scenario Brazos WAM.

- Available data are compiled to update the original 1940-1997 hydrologic period-of-analysis to extend through December 2017.
- The Hydrologic Engineering Center (HEC) Data Storage System (DSS) is fully integrated in the WRAP/WAM modeling system and the Brazos WAM.
- A daily WAM is created by expanding the monthly WAM to include flow disaggregation, routing, and forecasting.
- Daily *SIMD* features for simulating flood control reservoir operations are employed to simulate flood control operations of nine U.S. Army Corps of Engineers reservoirs.
- New expanded WRAP capabilities for simulating SB3 environmental flow standards are implemented in the daily *SIMD* simulation model.
- Daily instream flow targets computed in the daily simulation for SB3 environmental flow standards are summed to monthly targets that are incorporated in the input dataset for the monthly WAM.

Background and Motivation for the Daily WAM

The TCEQ WAM System is based on performing simulation computations using a time step of a month, which is the generally optimal time step for water availability modeling. However, daily computations are needed to model reservoir operations during floods and to incorporate Senate Bill 3 (SB3) environmental flow standards, particularly high flow pulse components, in the WAMs. Creating a daily WAM by expanding an existing monthly WAM includes adding daily pattern flow hydrographs for disaggregating monthly naturalized flows to daily, adding forecasting and routing parameters, and setting other input parameters. The daily *SIMD* simulation model includes features for simulating flood control operations of flood control reservoirs and/or modeling the effects of water supply reservoirs on downstream flows during high flows or floods.

The daily WAM may be employed in a broad range of applications including drought management decision support, environmental flow studies, reservoir system operational planning studies, and regional planning. This report focuses specifically on employing the daily WAM to incorporate SB3 environmental flow standards in the monthly TCEQ WAM System. Daily instream flow targets computed in the daily simulation are summed to monthly targets and inserted in the monthly WAM dataset. The daily WAM can be executed once to develop SB3 environmental flow targets for the monthly WAM used routinely for applications of interest.

The monthly WAMs have been routinely applied in administration of the water rights permit system and in regional and statewide planning since 2002. The TCEQ has sponsored research at Texas A&M University (TAMU) over the past several years that has included development of a daily WRAP modeling system and daily versions of selected WAM datasets, including the Brazos WAM. TCEQ sponsored research and development at TAMU has also included expanding capabilities for compiling and updating WAM hydrology input datasets.

Developmental test status daily modeling features introduced in the August 2015 WRAP are greatly improved in the July 2018 and May 2019 versions of the daily modeling system. The Brazos WAM served as a case study in developing these expanded modeling capabilities, contributing to improvements reflected in the May 2019 WRAP [1, 2, 3, 4, 5, 6]. Numbers in brackets refer to the list of references at the end of this report.

The Hydrologic Engineering Center (HEC) Data Storage System (DSS) and the *HEC-DSSVue* [7] component of DSS have been fully integrated into the May 2019 version of the WRAP computer programs and manuals, as summarized in Chapter 6 of the WRAP *Users Manual* [2]. DSS is designed for efficient compilation, analysis, manipulation, and management of time series data, including datasets that may be extremely large. The DSS and its *HEC-DSSVue* user interface are employed extensively in the work documented by this report.

The WRAP programs *HYD* [5] and *DAY* [4] also provide capabilities for compiling, synthesizing, and updating monthly and daily, respectively, hydrology input data for the WRAP *SIM* and *SIMD* simulation models. *HYD* and *DAY* methods have been significantly expanded and improved since the August 2015 WRAP and are employed in the work documented by this report.

Compilation of the original monthly Brazos WAM is documented by reports [8, 9] completed in 2001 during the initial development of the TCEQ WAM System, which have been updated in conjunction with a Brazos River Authority (BRA) system operation permit [10, 11, 12, 13, 14]. The Brazos WAM served as the inaugural case study for initial research and development in developing a daily WRAP modeling system [15, 16, 17] and improving capabilities for updating WRAP hydrology datasets [18, 19].

Brazos WAM Hydrology

The original Brazos WAM in the TCEQ WAM System has a hydrologic period-of-analysis extending from January 1940 through December 1997. The validity and accuracy of frequency and reliability estimates derived from the WAMs can be significantly enhanced by periodically updating the hydrologic periods-of-analysis to extend to near the present. The updated hydrology also facilitates comparisons of more recent periods of drought such as 2010-2012 with the 1950-1957 drought, which is the most hydrologically severe drought-of-record for most of the state.

Primary control points are defined as sites for which monthly naturalized flows are provided in a *SIM/SIMD* input dataset as *IN* records in a FLO or DSS file. Naturalized monthly flows at secondary control points are synthesized during the simulation performed by the WRAP programs *SIM* or *SIMD* using parameters read from a flow distribution DIS input file. Monthly net evaporation less precipitation rates used by *SIM* and *SIMD* for computing reservoir surface net evaporation-precipitation volumes are stored on *EV* input records in an EVA file or DSS file. Other time series of hydrologic data include monthly hydrologic index *HI* and daily flow *DF* records.

The monthly 1940-1997 Brazos WAM hydrology includes naturalized flows (*IN* records) at 77 control points and net reservoir surface evaporation less precipitation depths (*EV* records) assigned to 67 control points. The monthly 1940-1997 naturalized flows and net evaporation-precipitation rates in the latest TCEQ WAM dataset are adopted without revision in the development of the new daily WAM presented in this report. These time series input data are updated to extend through December 2017 as described in Chapters 7 and 8.

The original developmental daily Brazos WAM [15] also used the 1940-1997 hydrologic period-of-analysis which was later [16, 18] extended to 1940-2012 using approximate methods. The original developmental daily *SIMD* input file included daily flows at 34 control points stored in a DCF file used in disaggregating monthly flows to daily. Daily flows for selected sub-periods of 1940-1997 were repeated within *SIMD* to cover 1998-2012. The earlier daily WAM also included calibrated lag and attenuation routing parameters at 34 control points. The daily flows are now expanded and improved and the routing parameters are replaced as documented by this report.

Of the several river systems with SB3 environmental flow standards established to date, the Brazos has the only SB3 standards that use the Palmer hydrologic drought index (PHDI) to define hydrologic conditions. Hydrologic conditions are defined for the SB3 flow standards for the other river systems based on either 12-month preceding stream flow volume or preceding reservoir storage contents. The present study includes compiling new and extended PHDI-based monthly hydrologic indices for the lower, middle, and upper Brazos River Basin.

The hydrologic period-of-analysis of the Brazos WAM has been updated to extend from January 1940 through December 2017. The 1940-2017 hydrology consists of *SIM*/*SIMD* monthly evaporation-precipitation depths assigned to 67 control points, monthly naturalized flows at the 77 primary control points, *SIMD* daily flow pattern hydrographs at 58 control points, and PHDI-based monthly hydrologic indices for the three defined regions of the river basin. The 1940-2017 naturalized monthly flow volumes in acre-feet, 1940-2017 monthly evaporation-precipitation depths in feet, and 1940-2017 monthly dimensionless hydrologic condition indices are input data for both the monthly *SIM* and daily *SIMD* simulation models. The 1940-2017 daily flows used in the disaggregation of monthly naturalized flow volumes to daily are employed only in a daily *SIMD* simulation.

In addition to updating the Brazos WAM hydrology, the hydrology datasets and the data compilation and synthesis strategies employed in developing the datasets have been investigated and improved. Stream flow characteristics were examined in the process of updating the hydrology. The various time series datasets compiled and stored in DSS files can be used in a variety of future studies investigating characteristics of stream flow and other hydrologic variables. Graphical and tabular displays and statistical analyses can be performed with *HEC-DSSVue*.

The preceding paragraphs deal with times series data. *SIM/SIMD* channel loss factors recorded on *CP* records in the DAT file and *SIMD* lag and attenuation routing parameters stored on *RT* records in the DIF file are also related to hydrology. The original channel loss factors continue to be employed without further analysis or modification. A new routing parameter calibration methodology [4] developed during 2016-2017 is employed to develop lag and attenuation parameters for 57 river reaches for the daily *SIMD* input dataset. These new calibrated values for the routing parameters are record on *RT* records in the daily input DIF file.

Scope of Work

The work reported here consists of employing expanded July 2018 and May 2019 WRAP capabilities and *HEC-DSS* to develop updated and expanded daily and monthly versions of the Brazos WAM. Improvements in modeling SB3 environmental flow standards are a central motivating objective, but the expanded WAM capabilities are relevant to a broad range of applications. The tasks accomplished in work documented by this report are outlined in Table 1.1.

Table 1.1
Tasks Performed in Expanding the Brazos WAM

1. Update of 1940-1997 monthly Brazos WAM period-of-analysis to 1940-2017 and conversion of the time series from FLO, EVA, and HIS files to a single DSS file.

   Compilation of monthly naturalized flow volumes on *IN* records for 77 control points.
   Compilation of evaporation-precipitation depths on *EV* records for 67 control points.
   Compilation of monthly hydrologic index stored on *HI* records for three regions.

2. Creation of a new daily Brazos WAM by converting the monthly WAM to daily.

   Selection of options for forecasting, routing, and disaggregation.
   Addition of 1940-2017 sequences of daily flows at 58 control points used as pattern hydrographs for disaggregating monthly naturalized flows to daily at 77 primary and over 3,000 secondary control points.
   Addition of lag and attenuation routing parameters for 67 river reaches.
   Addition of flood control operations for nine federal multiple-purpose reservoirs operated by the U.S. Army Corps of Engineers (USACE) Fort Worth District.

3. Simulation of SB3 environmental flow standards at 19 control points using the new features introduced in the July 2018 and May 2019 versions of *SIMD*.

4. Execution of a daily *SIMD* simulation to compute daily targets for the SB3 flow standards that are summed to monthly quantities and incorporated as target series *TS* records in the DSS input file to be read as input for a monthly *SIM* simulation.

5. Analyses of simulation results to explore modeling issues and compare the monthly versus daily WAMs.

Authorized use (run 3) and current use (run 8) WRAP simulation model *SIM* input datasets for the Brazos WAM have been periodically revised and updated by the TCEQ since their creation in 2001. The work reported here began with a version of the authorized use scenario monthly Brazos WAM composed of five files with the following filenames: bwam3.dat (9/8/2008), bwam3.dis (8/27/2007), bwam3.eva (11/3/2017), bwam3.flo (11/3/2017), bwam3.his (11/3/2017). The dates for the latest revisions are shown in parenthesis. The authorized use scenario Brazos WAM consisting of these five files is expanded as described by this report. The files described on the next page were created as explained in the following chapters in the process of developing the expanded Brazos WAM.

Data Files Accompanying and Described by this Report

This report describes the files listed in Table 1.2 and procedures employed in developing them. The expanded monthly and daily Brazos WAM input dataset is composed of the first five files listed in the table. Selected monthly *SIM* and daily *SIMD* simulation results are stored in the sixth file. The last four DSS files listed in Table 1.2 were created in the process of developing the expanded Brazos WAM. These last four DSS files listed are also useful, independently of WRAP/WAM modeling, in exploring characteristics of stream flow and river system hydrology.

Table 1.2
Data Files Accompanying and Described by this Report

Brazos WAM Files

Brazos3M.DAT – monthly *SIM/SIMD* input file with information regarding water development, allocation, and use including *IF* and *TS* records at 19 control points that reference *TS* records in the DSS input file with SB3 environmental flow standard targets.

Brazos3D.DAT – daily *SIMD* input file with information regarding water development, allocation, and use including *IF*, *HC*, *ES*, and *PF* records modeling SB3 environmental flow standards at 19 control points and *FR*, *FF*, *FV*, and *FQ* records modeling reservoir operations during floods at ten reservoirs.

Brazos.DIS – parameters governing *SIM/SIMD* distribution of monthly naturalized flows from 77 primary to about 3,000 secondary control points. This is the original flow distribution file bwam3.dis without modification.

Brazos3D.DIF – *SIMD* lag and attenuation routing parameters for 67 control points and other daily simulation data

BrazosHYD.DSS – monthly and daily 1940-2017 *SIM* and/or *SIMD* time series input including monthly naturalized flows (*IN* records) in acre-feet/month at 77 control points, 67 sets of net evaporation-precipitation depths (*EV* records) in feet/month, dimensionless hydrologic index (*HI* records) for three regions, monthly SB3 environmental instream flow targets (*TS* records) in acre-feet/month at 19 control points, and daily flows (*DF* records) in acre-feet/day at 58 control points.

Brazos.DSS – *SIM* monthly, *SIMD* daily, and *SIMD* aggregated monthly simulation results.

Other DSS Files

BrazosPHDI.DSS –Palmer hydrologic drought index for ten zones and SB3 environmental flow standard hydrologic index for three defined regions (Chapter 5).

BrazosDailyFlows.DSS – gaged and computed daily flow data compiled in the process of analyzing and synthesizing *SIMD* daily flow pattern hydrographs (Chapter 6).

BrazosMonthlyFlows.DSS – monthly observed and naturalized stream flow data compiled in the process of compiling and analyzing monthly and daily flows (Chapter 7).

BrazosEvapPrecip.DSS – monthly precipitation rates, reservoir evaporation rates, and net reservoir evaporation less precipitation rates (Chapter 8).

Brazos WAM

The expanded Brazos WAM for the authorized use scenario with either a daily or monthly time step consists of *SIM* and *SIMD* and the first five input files listed in Table 1.2. The 1940-1997 hydrology dataset routinely employed by the TCEQ in monthly *SIM* simulations is adopted without modification. The 1998-2017 hydrology extension was compiled from available data that were developed differently than the original 1940-1997 hydrology as explained in Chapters 7 and 8. The 1998-2017 extension can be easily switched on or off in simulation studies. With the hydrology input data covering 1940-2017, a simulation for 1940-2017, 1940-1997, or any sub-period between 1940 and 2017 can be performed by setting *YRST* and *NYRS* on the *JD* record in the DAT file.

The use of a single DSS input file to store all *SIM* monthly and *SIMD* daily time series input data was added as the recommended standard in the July 2018 WRAP. The daily flows (*DF* records) at 58 control points, monthly naturalized flows (*IN* records) at 77 control points, net evaporation-precipitation depths (*EV* records) assigned to 67 control point identifiers, and hydrologic indices (*HI* records) for the upper, middle, and lower basin for SB3 environmental flow standards are stored in the same single DSS input file, as noted in Table 1.2, but alternatively can be stored in optional DIF, FLO, EVA, and HIS files. Monthly summations of daily targets for SB3 environmental flow standards computed by *SIMD* are also stored in the same DSS file (rather than TSF file) for input to a monthly *SIM* simulation.

A monthly simulation can be performed with the WRAP program *SIM* with a DAT file containing input records for a daily simulation, such as the file Brazos3D.DAT. Program *SIM* skips over daily input records in the DAT file, does not read the DIF file, and ignores the *DF* records in the DSS time series input file. The WRAP program *SIMD* has no option for skipping over the daily-only records in the DAT file, other than manually commenting (**) them out.

Additional Data Storage System (DSS) Files

This report is also accompanied by the last four DSS files listed in Table 1.2. The four supplemental DSS files were compiled along with expanding the Brazos WAM as described in the chapters of this report. These last four files listed in Table 1.2 files are read with *HEC-DSSVue* but are not designed to be read by *SIM* or *SIMD*. *HEC-DSSVue* provides flexible comprehensive capabilities for various types of time series data analyses. The datasets contained in these other four DSS files serve the following purposes.

1. The DSS files compile data relevant to the improved and updated 1940-2017 hydrology for the Brazos WAM. Model-users can access and explore the DSS datasets with *HEC-DSSVue* to develop a better understanding of Brazos WAM hydrology.

2. The DSS files can be used in future updates of the WAM hydrology.

3. The datasets in the DSS files can support other research independently of the WRAP/WAM *SIM* and *SIMD* simulation models involving comparative analyses of stream flow characteristics and exploring river system hydrology. *HEC-DSSVue* facilitates convenient graphical and tabular displays and statistical analyses of these datasets of time series variables.

CHAPTER 2
BRAZOS RIVER BASIN AND BRAZOS WAM

The Brazos River Basin encompasses a total area of 45,870 square miles, with about 43,160 square miles in Texas and the remainder in New Mexico. The Brazos River flows in a meandering path about 920 miles from the confluence of the Salt Fork and Double Mountain Fork to the city of Freeport at the Gulf of Mexico. The TCEQ WAM System combines the Brazos River Basin and adjoining much smaller San Jacinto-Brazos Coastal Basin in the same WRAP input dataset. The coastal basin located south of the City of Houston between the Brazos and San Jacinto River Basins has a watershed drainage area of 1,140 square miles. The small streams that drain into Galveston Bay and the Gulf of Mexico from the extensively urbanized flat plain of the coastal basin include Clear Creek, Oyster Creek, and Armand, Dickinson, Mustang, Chocolate, and Bastrop Bayous.

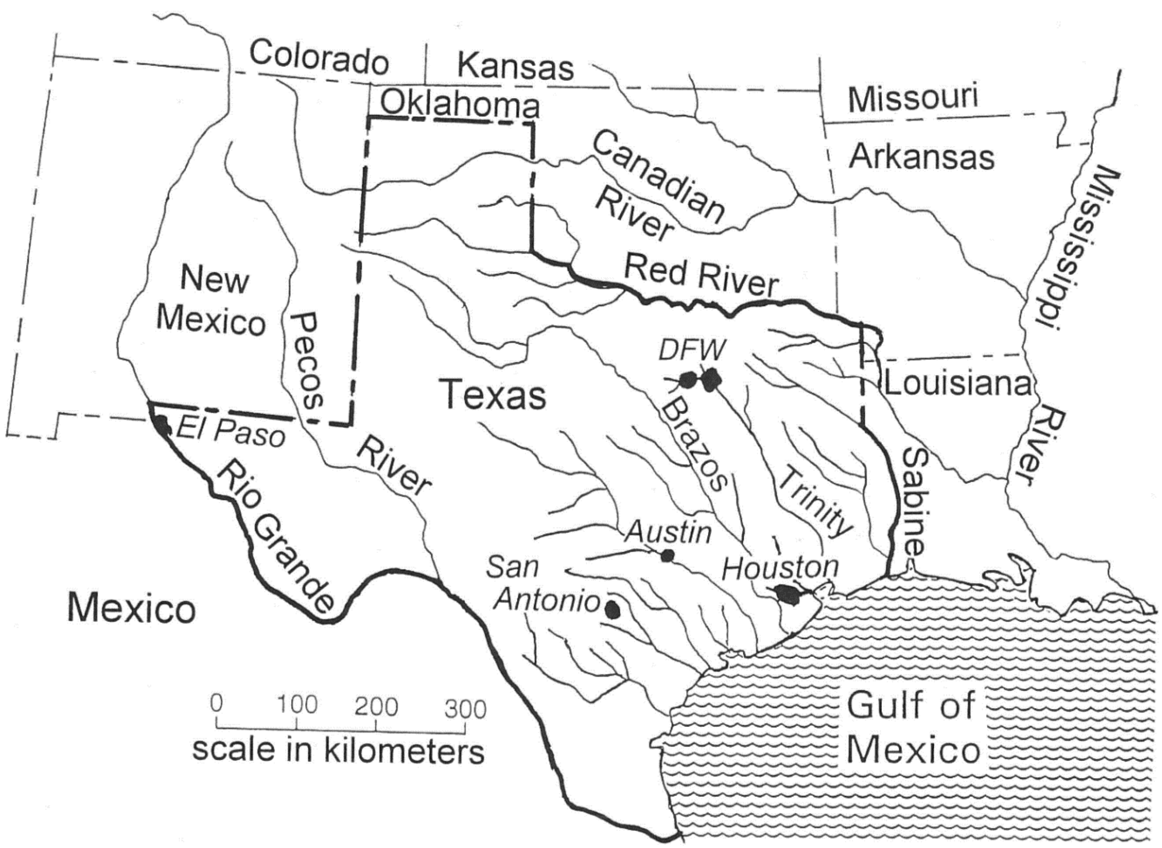

Figure 2.1 Largest Cities and Major Rivers of Texas including the Brazos River

The Brazos Basin is bordered on the west by the Colorado River Basin and on the east by the Trinity River Basin and the Buffalo Bayou watershed which extends through the City of Houston to the San Jacinto River. The climate, hydrology, and geography of the Brazos Basin vary greatly across Texas from New Mexico to the Gulf of Mexico. The upper basin in and near New Mexico is an arid flat area that rarely contributes to stream flow. In its upper reaches, the Brazos River is a gypsum-salty intermittent stream. Toward the coast it is a rolling river flanked by levees, agricultural fields, and hardwood bottoms. Mean annual precipitation varies from 19 inches in the upper basin which lies in the High Plains to 45 inches in the lower basin in the Gulf Coast region. The San Jacinto – Brazos Coastal Basin has a mean annual precipitation of 46.3 inches.

Largest Reservoirs in the Brazos River Basin

The Brazos River Basin contains 673 reservoirs cited in water right permits. Forty-three of these reservoirs have conservation storage capacities of 5,000 acre-feet or greater. The 16 reservoirs listed in Tables 2.1 and 2.6 and included on the map of Figure 2.2 are the only reservoirs in the Brazos River Basin that have a combined conservation and flood control storage capacity of greater than 75,000 acre-feet. There are no reservoirs of this size in the San Jacinto-Brazos Coastal Basin.

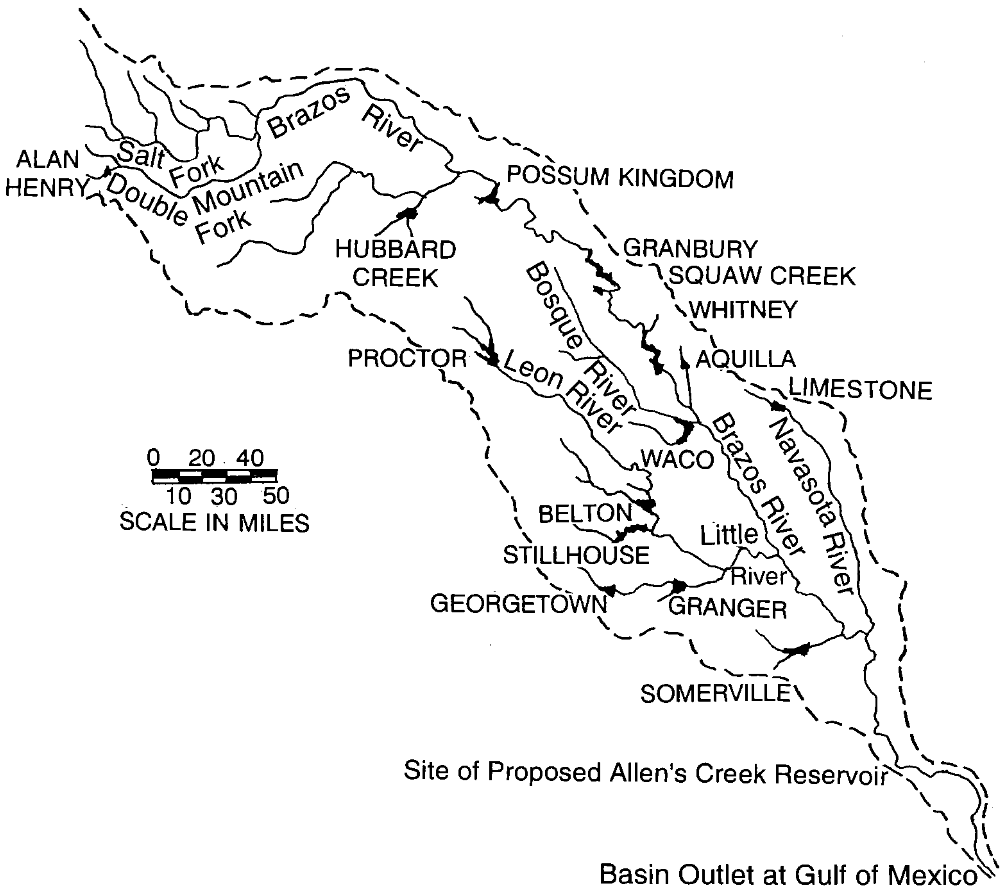

Figure 2.2 Major Tributaries and 16 Largest Reservoirs in the Brazos River Basin

The U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) owns and operates a system of nine multiple-purpose reservoirs. The Brazos River Authority (BRA) has contracted for the conservation storage capacity in the nine federal reservoirs and owns three other reservoirs. The City of Waco has water right permits for Lake Waco, and the BRA holds permits for the eleven other reservoirs of the 12-reservoir USACE/BRA system.

Possum Kingdom Lake has the largest conservation storage capacity in the Brazos River Basin, and Lake Whitney has the second largest conservation storage capacity. Considering the total of both flood control and conservation capacity, Lake Whitney is the largest reservoir in the Brazos River Basin and the seventh largest reservoir in Texas. Whitney, Granbury, and Possum Kingdom Reservoirs are on the Brazos River and the other reservoirs are on tributaries.

Table 2.1
Largest Reservoirs in the Brazos River Basin

Reservoir	Stream	Initial Impoundment	Storage Capacity Conservation (acre-feet)	Storage Capacity Flood Control (acre-feet)	Storage Capacity Total (acre-feet)
		Army Corps of Engineers and Brazos River Authority			
Whitney	Brazos River	1951	636,100	1,363,400	1,999,500
Aquilla	Aquilla Creek	1983	52,400	93,600	146,000
Waco	Bosque River	1965	206,562	519,840	726,400
Proctor	Leon River	1963	59,400	314,800	374,200
Belton	Leon River	1954	457,600	640,000	1,097,600
Stillhouse Hollow	Lampasas River	1968	235,700	394,700	630,400
Georgetown	San Gabriel	1980	37,100	93,700	130,800
Granger	San Gabriel	1980	65,500	178,500	244,000
Somerville	Yequa Creek	1967	160,110	347,290	507,400
		Brazos River Authority			
Possum Kingdom	Brazos River	1941	724,739	−	724,739
Granbury	Brazos River	1969	155,000	−	155,000
Limestone	Navasota River	1978	225,400	−	225,400
Allen′s Creek	Allen′s Creek	proposed	145,533	−	145,533
		City of Lubbock			
Alan Henry	Double Mountain	1993	115,937	−	115,937
		West Central Texas Municipal Water District			
Hubbard Creek	Hubbard Creek	1962	317,750	−	317,750
		Texas Utilities Services (cooling water for Comanche Peak Power Plant)			
Squaw Creek	Squaw Creek	1977	151,500	−	151,500

All of the controlled (gated) flood control storage capacity in the Brazos River Basin is contained in the nine USACE reservoirs listed in Table 2.1. The storage capacities of the designated flood control pools are tabulated in Table 2.1. These flood pool volumes are included in the daily Brazos WAM and are based on 2010 sediment conditions, unlike the conservation capacities in Table 2.1 which are from the water right permits. Flood control storage capacity is maintained empty except during and immediately following flood events. Flood control operations occur whenever lake levels rise above the top of conservation pool.

Flood control operations are based on emptying flood control pools as expeditiously as practical while making no releases that contribute to stream flows exceeding specified non-damaging levels a downstream gaging stations. Non-damaging flow limits designated for flood control operations are as follows at three of the many USGS gages used in flood control operations: Little River at Cameron (10,000 cfs), Brazos River below Whitney Dam (25,000 cfs), and Brazos River at Richmond (60,000 cfs). Simulation of flood control operations in SIMD is described in Chapter 4.

Hydroelectric power is generated at Whitney Reservoir. The Southwest Power Administration is responsible for marketing hydroelectric power generated at Lake Whitney, which it sells to the Brazos Electric Power Cooperative. Hydropower is generated by excess flows (spills) and releases for downstream water supply diversions. The inactive pool at Lake Whitney provides dead storage for hydropower. No water rights exist specifically for hydropower at Whitney Reservoir or any other sites in the Brazos River Basin. Hydroelectric power generation at Possum Kingdom Reservoir was terminated several years ago.

In addition to releases for water supply diversions from the lower Brazos River, Possum Kingdom and Granbury Reservoirs supply water as needed to maintain constant operating levels in Lakes Squaw Creek, Tradinghouse Creek, and Lake Creek which are owned and operated by utility companies for steam-electric power plant cooling. The BRA operates a desalting water treatment plant that allows use of water from Lake Granbury to supplement the water supply for the City of Granbury and other water users in Johnson and Hood Counties.

Observed Flows at USGS Gaging Stations

The observed daily flow data discussed throughout this report were downloaded from the National Water Information System (NWIS) website maintained by the U.S. Geological Survey (USGS). The locations of 14 large reservoirs and thirty USGS stream gaging stations are show in Figure 2.3. Stream flows at these and other gages are discussed in the various chapters of this report.

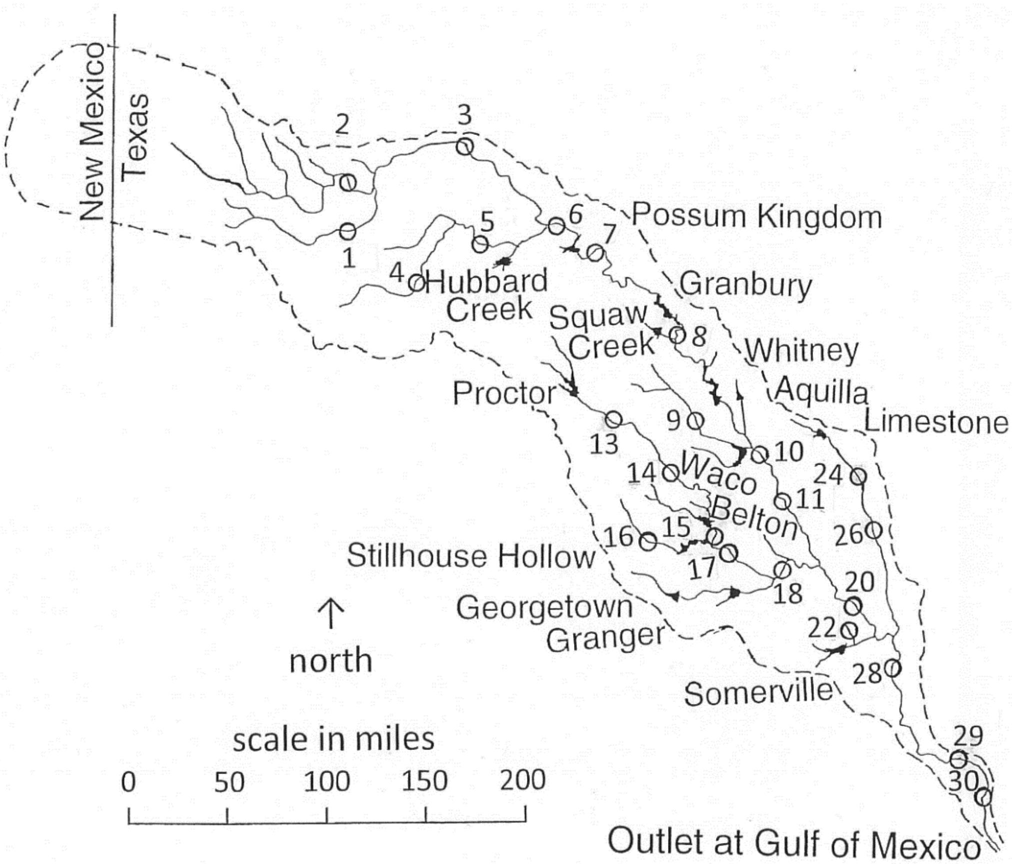

Figure 2.3 Largest Reservoirs and 30 Selected USGS Gaging Stations in the Brazos River Basin

Table 2.2
Selected USGS Stream Flow Gaging Stations in the Brazos River Basin

Map ID	USGS Gage ID	WAM CP ID	Location by River and Nearest City	County	Drainage Area
					(square miles)
1	08080500	DMAS09	Double Mountain Fork near Aspermont	Stonewall	1,891
2	08082000	SFAS06	Salt Fork Brazos River near Aspermont	Stonewall	2,504
3	08082500	BRSE11	Brazos River near Seymour	Baylor	5,996
4	08084000	CFNU16	Clear Fork Brazos near Nugent	Jones	2,236
5	08085500	CFFG18	Clear Fork Brazos near Fort Griffin	Shackelford	4,031
6	08088000	BRSB23	Brazos River near South Bend	Young	13,171
7	08089000	BRPP27	Brazos River near Palo Pinto	Palo Pinto	14,309
8	08091000	BRGR30	Brazos River near Glen Rose	Somervell	16,320
9	08095000	NBCL36	North Bosque River near Clifton	Bosque	977
10	08096500	BRWA41	Brazos River at Waco	Mclennan	20,065
11	08097500	–	Brazos River near Marlin	Falls	20,645
12	08098290	BRHB42	Brazos River near Highbank	Falls	20,900
13	08100000	LEHM46	Leon River near Hamilton	Hamilton	1,928
14	08100500	LEGT47	Leon River near Gatesville	Coryell	2,379
15	08102500	LEBE49	Leon River near Belton	Bell	3,579
16	08103800	LAKE50	Lampasas River near Kempner	Lampasas	817
17	08104500	LRLR53	Little River near Little River	Bell	5,266
18	08106500	LRCA58	Little River near Cameron	Milam	7,100
19	08108700	–	Brazos River at SH 21 near Bryan	Burleson	29,483
20	08109000	BRBR59	Brazos River near Bryan	Brazos	29,949
21	08110000	YCSO62	Yegua Creek near Somerville	Burleson	1,011
22	08110100	DCLY63	Davidson Creek near Lyons	Burleson	195
23	08110200	–	Brazos River at Washington	Washington	31,626
24	08110500	NAEA66	Navasota River at Easterly	Leon	936
25	08110800	–	Navasota River at Old Spanish Rd Bryan	Robertson	1,287
26	08111000	NABR67	Navasota River near Bryan	Brazos	1,427
27	08111010	–	Navasota River near College Station	Grimes	1,809
28	08111500	BRHE68	Brazos River near Hempstead	Washington	34,374
29	08114000	BRRI70	Brazos River near Richmond	Fort Bend	35,541
30	08116650	BRRO72	Brazos River near Rosharon	Fort Bend	35,773

The 30 USGS gaging stations included in Figure 2.3 and Tables 2.2 and 2.3 include the 19 gage sites with SB3 environmental flow standards (Table 5.1 and Figure 5.1) and other relevant sites with long gage records of observed daily flows. Other additional gages used along with these gages in developing WAM naturalized flows and pattern hydrographs are discussed later. The control point identifiers used in the WAM datasets are tabulated in the third column of Table 2.2.

The gages labeled 11, 20, 23, 26, and 27 on the map and tables are no longer active, but periods-of-record for the 25 other gages extend to the present. USGS gages 08097500 and 08098290 on the Brazos River near Marlin and Highbank cover different periods of time (10/1938-

9/1951 and 10/1965-present) but are located at close to the same location. These two gage records are combined into a single longer series of daily flows for control point BRHB42. The USGS replaced gage 08109000 at control point BRBR59 on the Brazos River near Bryan (ID 20) with gage 08108700 (ID 19) in 1993. The USGS replaced gage 08111000 at control point NABR67 on the Navasota River near Bryan (ID 26) with gage 08110800 (ID 25) in 1997.

Table 2.3
Frequency Statistics for Observed Daily Flows at 30 Gages

Map		Period-of-Record		Missing	Flow Statistics (cfs)			
ID	River and Nearest City	From	To	Days	Mean	90%	50%	10%
1	Double Mountain Fork Aspermont	1/1924	present	1,734	135.4	0	8	184
2	Salt Fork Brazos River Aspermont	1/1924	present	5,052	88.3	0.1	5.6	111
3	Brazos River near Seymour	12/1923	present	0	329.7	0	40	551
4	Clear Fork Brazos near Nugent	3/1924	present	0	87.7	0.3	10	101
5	Clear Fork Brazos near Fort Griffin	2/1924	present	0	203.5	0	21	271
6	Brazos River near South Bend	10/1938	present	0	737.4	5	108	1,250
7	Brazos River near Palo Pinto	2/1924	present	0	904.1	26	154	1,630
8	Brazos River near Glen Rose	10/1923	present	0	1,253	25	270	2,490
9	North Bosque River near Clifton	10/1923	present	0	289.0	1	22	336
10	Brazos River at Waco	10/1898	present	0	2,337	82	730	4,960
11	Brazos River near Marlin	10/1938	9/1951	0	2,923	210	1,060	6,220
12	Brazos River near Highbank	10/1965	present	0	2,696	174	911	6,070
13	Leon River near Hamilton	1/1925	present	14,584	183.1	0.2	15	500
14	Leon River near Gatesville	10/1950	present	0	308.4	2	37	710
15	Leon River near Belton	10/1923	present	0	598.4	5	58	1,880
16	Lampasas River near Kempner	10/1962	present	0	160.0	11	31	276
17	Little River near Little River	10/1923	present	12,145	989.5	60	216	3,120
18	Little River near Cameron	11/1916	present	0	1,736	65	435	4,820
19	Brazos River at SH 21 near Bryan	7/1993	present	0	4,661	378	1,260	13,300
20	Brazos River near Bryan	9/1899	present	5,719	5,287	407	1,780	13,000
21	Yegua Creek near Somerville	5/1924	6/2014	6,210	275.0	0	6	917
22	Davidson Creek near Lyons	10/1962	present	0	71.5	0	2.3	73
23	Brazos River at Washington	11/1965	3/1987	1,016	5,521	664	2,310	13,600
24	Navasota River at Easterly	3/1924	present	0	419.4	2	27	811
25	Navasota River Old Spanish Rd	4/1997	present	0	501.4	15	59	1,110
26	Navasota River near Bryan	1/1951	3/1997	801	570.4	4	54	1,480
27	Navasota River College Station	5/1977	9/1985	0	591.5	10	81	1,700
28	Brazos River near Hempstead	10/1938	present	0	6,821	646	2,390	18,000
29	Brazos River near Richmond	11/03(10/99)	present	150	6,171	426	1,800	16,780
30	Brazos River near Rosharon	4/1967	present	1,318	7,852	535	3,000	20,930

Statistics for the daily flows at the 30 gages for their periods-of-record through November 2015 are tabulated in the last four columns of Table 2.3. The daily flow statistics in cubic feet per second (cfs) include the mean and the quantities with exceedance frequencies (P) of 90%, 50%, and 10% computed with *HEC-DSSVue* based on the Weibull formula [(P = m/(N+1)100%].

Plots of Observed Flows at the Cameron, Waco, and Richmond Gages

Brazos WAM control points LRCA58, BRWA41, and BRRI70 are the sites of USGS gages on the Little River near Cameron, Brazos River at Waco, and Brazos River near Richmond (sites 18, 10, and 29 in Figure 2.3 and Tables 2.2 and 2.3). Observed daily flows through 2018 at these gages are plotted in Figures 2.4, 2.7, and 2.8, mean monthly flow rates in cfs are plotted as Figures 2.5, 2.8, and 2.11, and annual flow volumes in acre-feet/year are plotted in Figures 2.6, 2.9, and 2.12. Mean daily flows in cubic feet per second (cfs) from the USGS gage records are converted within *HEC-DSSVue* to mean monthly flow rates in cfs and annual flow volumes in acre-feet.

WAM control point BRRI70 is the site of USGS gage 08114000 on the Brazos River near Richmond. The period-of-record includes January 1, 1903 through June 30, 1906 and October 1, 1922 to the present, with a 1906-1922 gap. Only the 1922-1917 data are included in Figures 2.10-2.12. Although the period-of-record for the Little River gage near Cameron (18, LRCA58) extends back several years before October 1921, due to uncertainties regarding data prior to October 1921, the flows plotted in the Figures 2.4-2.6 cover the period October 1921 through December 2018. The plots begin after a major flood event that occurred in September 1921.

Time series graphs of flows at any or all of the gages, similar to those in Figures 2.4 through 2.12, are conveniently plotted in *HEC-DSSVue*. Plots viewed within *HEC-DSSVue* but not incorporated in this report were used for comparative analyses of observed and naturalized flow sequences as discussed later in this report. Frequency statistics are also quickly and easily computed with *HEC-DSSVue*. The DSS files listed in Table 1.2 serve as appendices to this report allowing further analyses by readers using *HEC-DSSVue* to explore issues of interest.

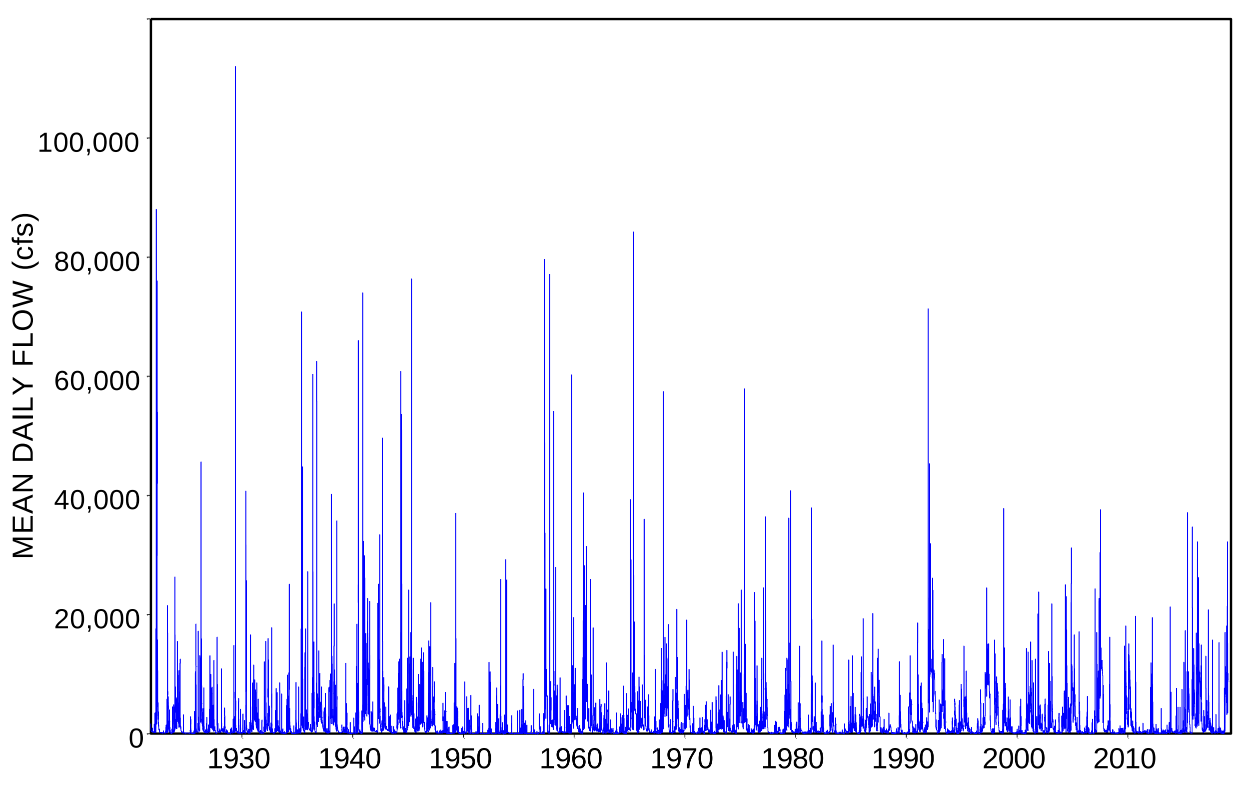

Figure 2.4 Daily Flows of Little River at Cameron during October 1, 1921 − January 20, 2019

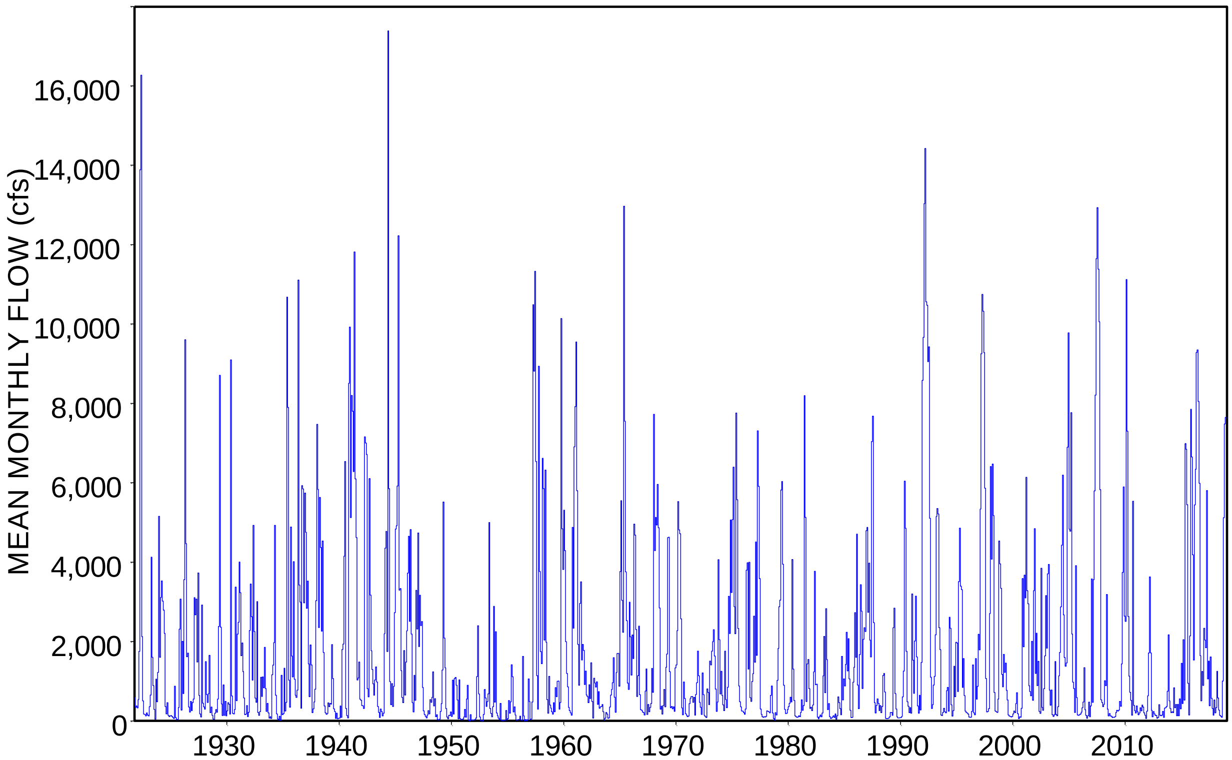

Figure 2.5 Monthly Observed Flows in cfs at the Gage on Little River at Cameron (LRCA58) during October 1921 through December 2018

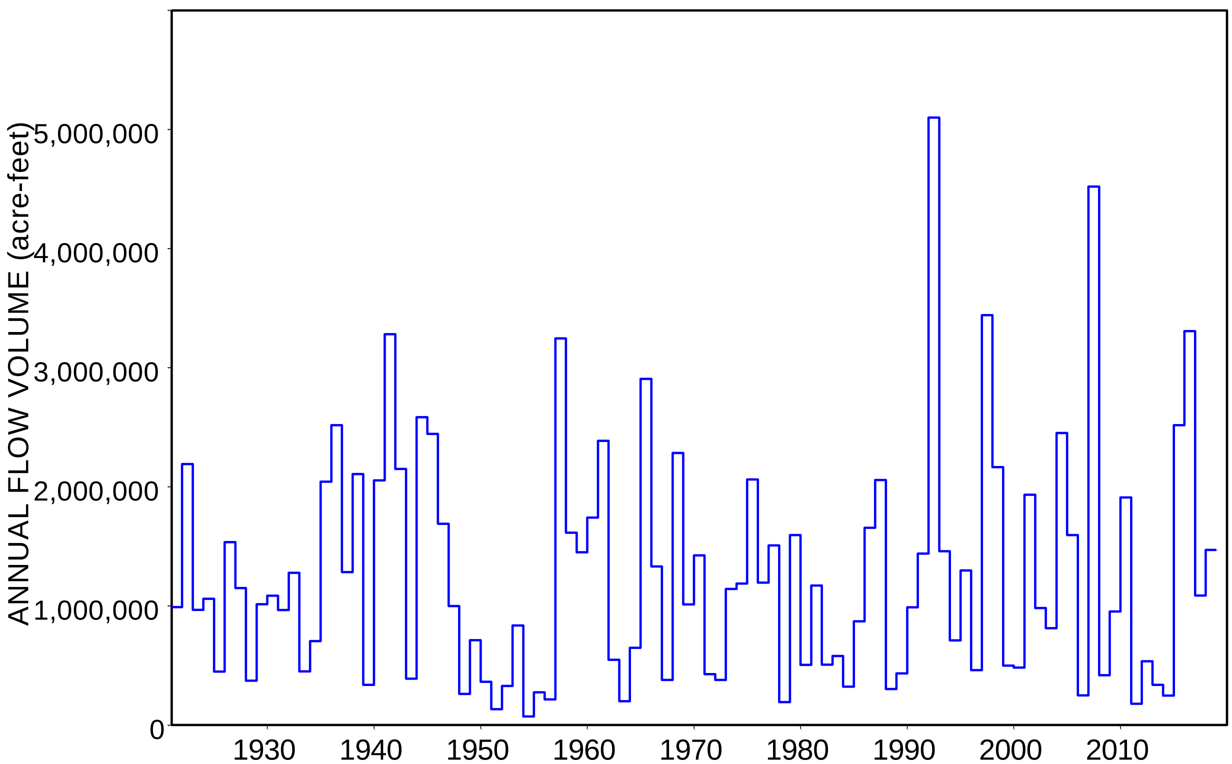

Figure 2.6 1922-2018 Annual Flows at the Gage on the Little River at Cameron (18, LRCA58)

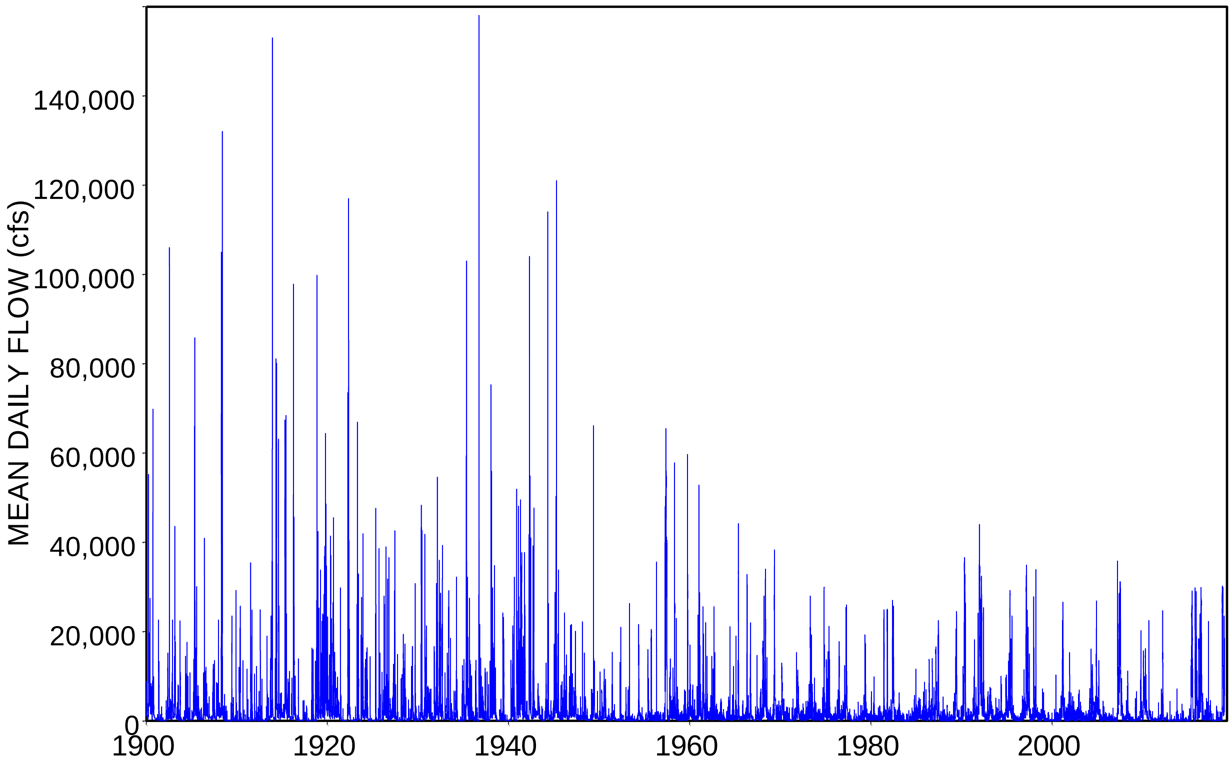

Figure 2.7 Daily Flows in cfs at the USGS gage on the Brazos River at Waco (10, BRWA41) during October 1, 1898 through January 20, 2019

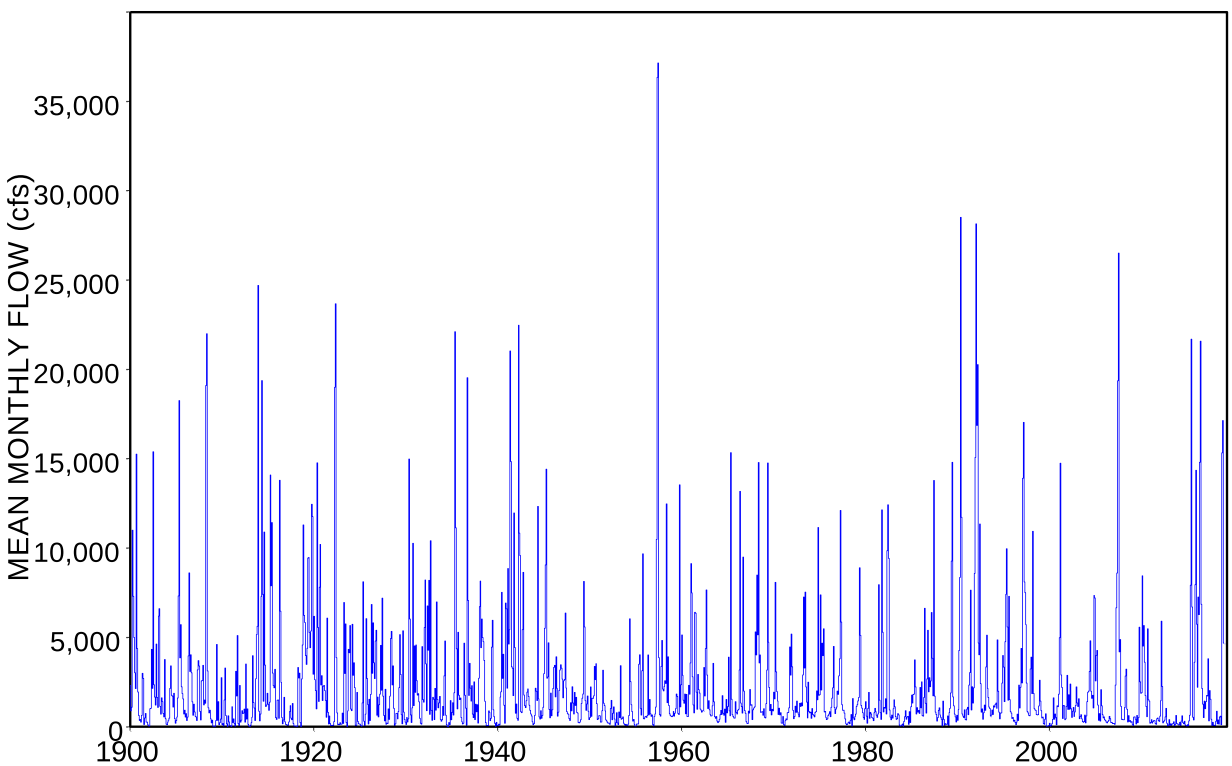

Figure 2.8 Monthly Flows in cfs at the Gage on the Brazos River at Waco (10, BRWA41) October 1898 through December 2018

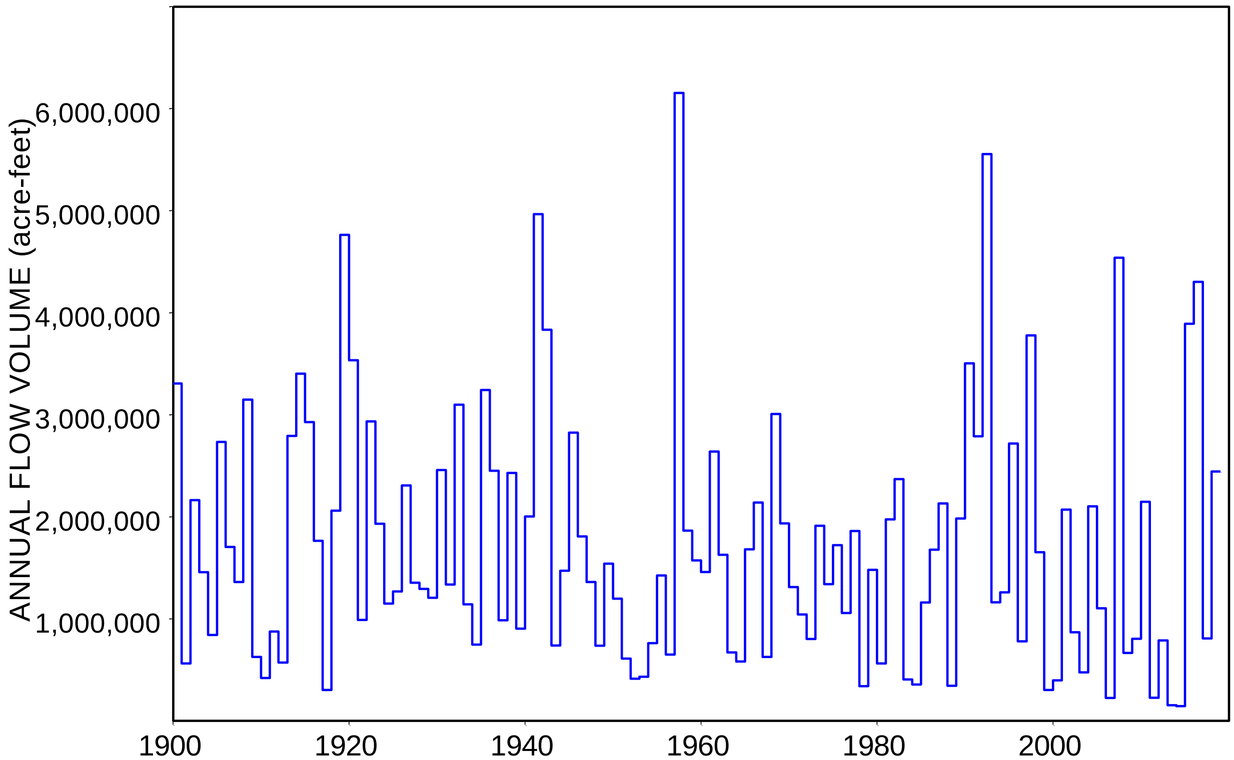

Figure 2.9 1899-2018 Annual Flows at the Gage on the Brazos River at Waco (10, BRWA41)

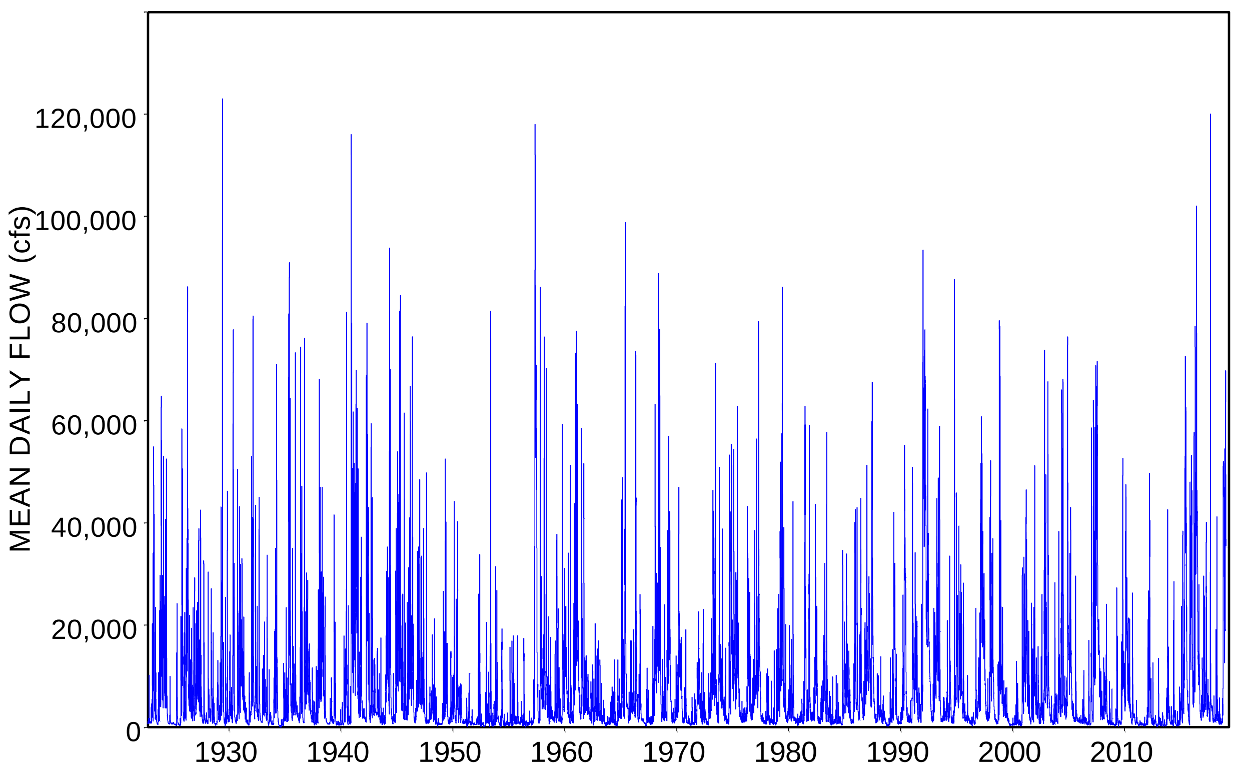

Figure 2.10 Daily Observed flows at the Gage on the Brazos River at Richmond (29, BRRI70) from October 2, 1922 through January 20, 2019

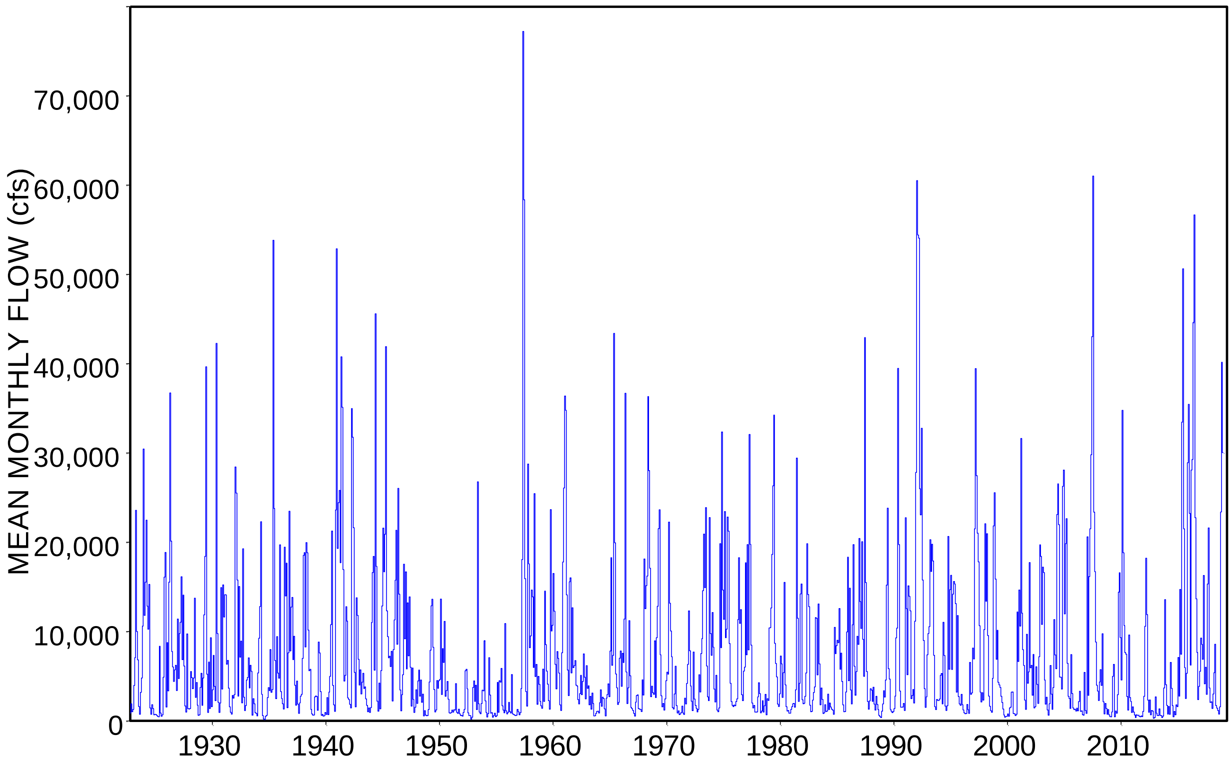

Figure 2.11 Monthly Flows at the USGS Gage on the Brazos River at Richmond (29, BRRI70) from October 1922 through December 2018

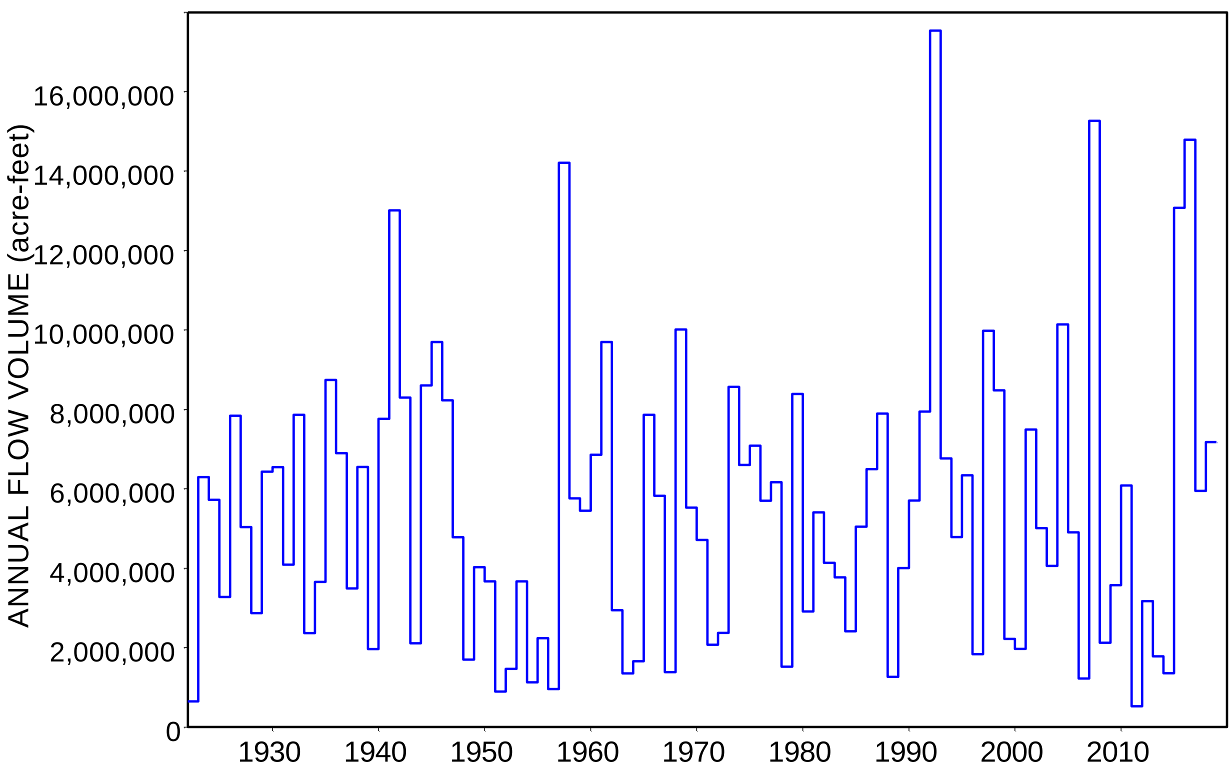

Figure 2.12 1922-2018 Annual Observed Flows of the Brazos River at Richmond (29, BRRI70)

Stream Flow Characteristics

Characteristics of river flows throughout Texas, including long-term changes in flow characteristics, are investigated in a 2014 report entitled *River System Hydrology in Texas* [20]. Stationarity (homogeneity), or lack thereof, and variability represent two different flow characteristics. Flows in all of the rivers of Texas including the Brazos River and its tributaries exhibit extreme variability. Flows fluctuate greatly and continuously. Stationarity or homogeneity refers to lack of long-term changes or trends. Long-term trends vary greatly between sites on the streams of Texas. Long-term changes or trends are difficult to detect and measure due to the great continuous variability. Long-term changes or trends vary greatly with location but are generally minimal compared to continuous extreme flow variability.

Three key observations regarding the characteristics of the flows of the Brazos River and its tributaries are as follows.

- Variability is dramatic with extremes of severe multiple-year droughts and major flood events as well as seasonality and continuous fluctuations.
- Long-term changes in observed monthly and annual flows at most gage sites appear to be relatively minimal but may be great just downstream of major dams.
- Flow variability and long-term changes vary depending on whether daily, monthly, and annual time intervals are adopted for aggregating and displaying quantities.

The attenuation (storage) effects on flows at downstream sites of flood control operations of the nine USACE reservoirs are evident in plots of observed daily flows on the Brazos River and tributaries but are dissipated in the plots of monthly and annual flows. The effects of the dams on stream flows also diminish with distance downstream. Construction of Possum Kingdom, Whitney and Waco dams, with initial impoundment in 1941, 1951, and 1965, is evident in the plot of daily flows of the Brazos River at the Waco gage in Figure 2.7. However, the dramatic decrease in daily flood flows in Figure 2.7 is lost in the monthly means of Figure 2.8. USACE flood control operations are based on a maximum allowable flow rate of 25,000 cfs at the Waco gage.

Stream flow rates change continuously. The USGS gage records are recorded as mean daily flows in cfs. The effects of averaging the daily means over the days of each month to obtain monthly means are demonstrated in the plots. Variability is reduced with the larger averaging time interval. Maximum flood peaks are lowered and minimum flows during low flow periods increase.

The flow data plotted in Figures 2.4 through 2.12 and other data found later in this report and elsewhere [13] show that the 1950-1957 drought is the most hydrological severe drought to occur in most but not necessarily all of the Brazos River Basin over the past more than 100 years. The 2010-2014 and other severe droughts are also evident in the flow plots. Stream flows were very high in 2015 and 2016, below average in 2017, and significantly above average during 2018.

Units of Measure for Flow Rates

Mean flow rates in units of cubic feet per second (cfs) are adopted to express the daily and monthly flow quantities in the preceding discussion. Mean annual flow volumes (rates) in acre-feet/year was adopted for the annual summations. Mean daily flow rates in cfs are converted to annual flow rates in acre-feet/year by multiplying by the conversion factor 724.482.

Monthly and daily flow rates in the WRAP/WAM simulation computations and input data are expressed in units of acre-feet/day or acre-feet/month. Unit conversions are relevant in the discussions in this report. All days have the same length of 86,400 seconds. The 12 months of the year have lengths of either 28, 29, 30, or 31 days. February has 29 days in leap years and 28 days in all other years. The 1940-2017 period-of-analysis contains the following leap years: 1940 and every fourth year thereafter in both reality and the *SIMD* simulation. The parameter CFS on *TABLES* 2FRE and 6FRE and time series input records activate routines within *TABLES* that convert flow volumes in acre-feet to mean flows in cfs. The routines activated by input parameter CFS consider the different number of days (28, 29 in leap years, 30, or 31) in each month. The conversion of daily volumes in acre-feet to daily means in cfs consists simply of applying the multiplier factor 0.50416667. Relevant conversion factors are as follows.

1.0 acre-feet/day = 0.50416667 cubic feet per second (cfs)
1.0 day = 86,400 seconds
1.0 acre-foot = 43,560 cubic feet
1.0 second-foot-day (sfd) = (1.0 ft^3/s)×(1.0 day) = 86,400 ft^3
1940-2017 contains 78 years = 936 months = 28,490 days

Brazos Water Availability Model (WAM)

The Brazos WAM files in the TCEQ WAM System have the filename roots Bwam3 and Bwam8, respectively, for the authorized use and current use scenarios (runs 3 and 8). The datasets have been periodically revised and updated by the TCEQ since their original creation during 1998-2001 [10, 11]. The set of five *SIM* input files labeled as the *Base WAM* in the second column of Table 2.4 provided an initial dataset from which to build the *SIM* and *SIMD* input files listed in the last two columns of Table 2.4. The term "*Base WAM*" is adopted here to refer to the DAT, DIS, FLO, EVA, and HIS files listed in the second column of Table 2.4, which contain revisions that have occurred up to the latest revision dates listed in the third column. These files are further revised in the work reported here to create the May 2019 expanded and updated WAM.

Table 2.4
Brazos WAM Authorized Use Scenario *SIM/SIMD* Input Files

File Contents	Base WAM Filename	Base WAM Last Revised	Expanded and Updated WAM Monthly	Expanded and Updated WAM Daily
water rights input data	bwam3.dat	9/8/2008	Brazos3M.DAT	Brazos3D.DAT
monthly flow distribution	bwam3.dis	8/27/2007	Brazos.DIS	
routing parameters				Brazos3D.DIF
time series input data	bwam3.flo	11/3/2017	BrazosHYD.DSS	
	bwam3.eva	11/3/2017		
	bwam3.his	11/3/2017		

The May 2019 expanded and updated authorized use scenario Brazos WAM consists of the files described in Table 1.2, listed in the last two columns of Table 2.4, and discussed in the following chapters of this report. The expanded Brazos WAM includes both monthly and daily versions. The daily Brazos WAM is described in Chapter 3. The expanded monthly WAM reflects the following three revisions to the Base WAM defined on the preceding page 19.

1. Available data are compiled to extend the 1940-1997 hydrologic period-of-analysis to cover 1940-2017 as documented by Chapters 7 and 8.
2. The SB3 environmental flow standards are modeled with *IF* and *TS* records that employ monthly instream flow targets computed in the daily *SIMD* simulation as explained in Chapter 5.
3. Consolidation of all times series input data into a single DSS file.

The filename roots Brazos3M and Brazos3D are adopted for the authorized use scenario (run 3) input DAT files for the monthly and daily versions of the Brazos WAM. The filename root Brazos is adopted for the hydrology input files which consist of the flow distribution DIS file and time series DSS file. Input filenames are listed in Table 2.4.

The flow distribution DIS file for the Base WAM is adopted without modification for the expanded 2019 WAM, including both monthly and daily versions of the 2019 WAM. The lag and attenuation routing parameters stored in the DIF file are employed only in a *SIMD* daily simulation.

All time series input data (*IN*, *EV*, *HI*, *TS*, *DF* records) are contained in a single DSS file with filename BrazosHYD.DSS that is read in both monthly *SIM* and daily *SIMD* simulations. The term HYD is always appended to the filename root of a *SIM* or *SIMD* input DSS file to distinguish it from the DSS output file.

Brazos WAM Versions and Components

Conversion of a monthly WAM to daily consists of adding several blocks of input records as discussed later in Chapter 3.

- A *JT* and a *JU* record are added to set simulation parameters.
- A DIF file with a set of 67 routing *RT* records is added.
- A set of 58 daily flow *DF* records is added to the DSS file.
- A block of 19 sets of *IF*, *HC*, *ES*, and *PO* records are added to model the SB3 environmental flow standards at 19 sites.
- A block of *FF*, *FR*, *FV*, and *FQ* records are added to model flood control operations at nine reservoirs. *SV/SA* records are extended for flood control pools.

These same blocks of additional input records can be inserted in any of the different versions of the monthly Brazos WAM, including those listed in Table 2.5, to convert that version to daily.

A summary of the number of model components (types of input records) is included in the message MSS file automatically created with each execution of *SIM* or *SIMD*. Counts from this MSS file summary table are shown in Table 2.5 for the following five alternative versions of the Brazos WAM.

1. The Base WAM adopted as the initial dataset to which the additions and updates described in this report are applied has an authorized use DAT file that was last revised

by the TCEQ in September 2008 and hydrology (FLO and EVA) files that were last revised in November 2017.

2. The second WAM in Table 2.5 is the current use version of the Base WAM.
3. The third WAM has a DAT file that was last updated in May 2017 and the same FLO and EVA files as the Base WAM. This WAM was developed by the TCEQ and BRA for the Brazos River Authority (BRA) system operation permit. The BRA Water Management Plan (WMP) and the SB3 environmental flow standards are modeled.
4. The 4th WAM in Table 2.5 is the monthly WAM developed as described in this report.
5. The 5th WAM in Table 2.5 is the daily WAM developed as described in this report.

Table 2.5
Number of System Components in Brazos WAM Datasets

	1	2	3	4	5
Version of WAM	Base WAM	Current Use	WMP	This Report	
Latest Update	2008/2017	2008/2017	2017	2019	2019
Water Use Scenario	Authorized	Current Use	Authorized	Authorized	Authorized
Filename Root	Bwam3	Bwam8	Bwam3	Brazos3M	Brazos3D
total number of control points	3,842	3,852	4,407	3,845	3,845
number of primary control points	77	77	77	77	77
control points with evap-precip	67	67	67	67	67
number of reservoirs	678	719	686	680	680
number of water right *WR* records	1,643	1,734	2,413	2,413	2,413
number of instream flow *IF* records	122	145	640	141	141
number of *FD* records in DIS file	3,152	3,157	3,164	3,152	3,152

The 77 primary control points with naturalized monthly flows on *IN* records and 67 control points with net monthly evaporation-precipitation rates on *EV* records are the same in all five versions of the WAM datasets in Table 2.5. These control points are listed in Tables 2.8 and 7.1.

The number of major reservoirs with greater than 5,000 acre-feet storage capacity are the same in the alternative versions of the WAM versions, but the number of small reservoirs vary. Table 2.5 shows the total *SIM* counts of 678 and 719 reservoirs in the September 2008 Bwam3 and Bwam8 DAT files. These are model reservoirs. The *SIM* simulation model includes an option to divide a reservoir into multiple components in order to model storage capacity allocated to multiple owners. The Bwam3 and Bwam8 datasets contain 673 and 714 actual reservoirs. The difference of five reservoirs in these counts is due to sub-dividing Whitney and Waco Reservoirs into component reservoirs in the model to reflect multiple owners.

The counts of *WR* and *IF* records represent model water rights which exceed the number of actual water rights. For many of the water rights, a particular water right is modeled by a single *WR* record. However, in many other cases, multiple *WR* records are used to model different aspects of the same water right permit.

The 2017 WAM with the Brazos River Authority (BRA) *System Operations Permit* and associated *Water Management Plan (WMP)* has a larger number of control points (*CP* records) and water rights (*WR* and *IF* records). These additional *CP*, *WR*, and *IF* records are employed to incorporate the BRA WMP and Senate Bill 3 (SB3) environmental flow standards.

Brazos River Authority
<u>System Operation Permit and Water Management Plan</u>

The BRA *System Operation Permit* with accompanying *Water Management Plan (WMP)* was approved and issued by the TCEQ on November 30, 2016. The *System Operation Permit* allows the Brazos River Authority (BRA) to use naturally occurring flows in the basin and return flows from wastewater treatment plants, along with the water supply provided by eleven reservoirs (Figure 2.13) to supply water customers. The uncontrolled flow originating downstream of the BRA reservoirs can be augmented by releases from BRA reservoirs upstream as necessary to achieve a "*system"* yield that is greater than the sum of the individual reservoir yields [12, 13].

http://www.brazos.org/About-Us/Water-Supply/SysOps

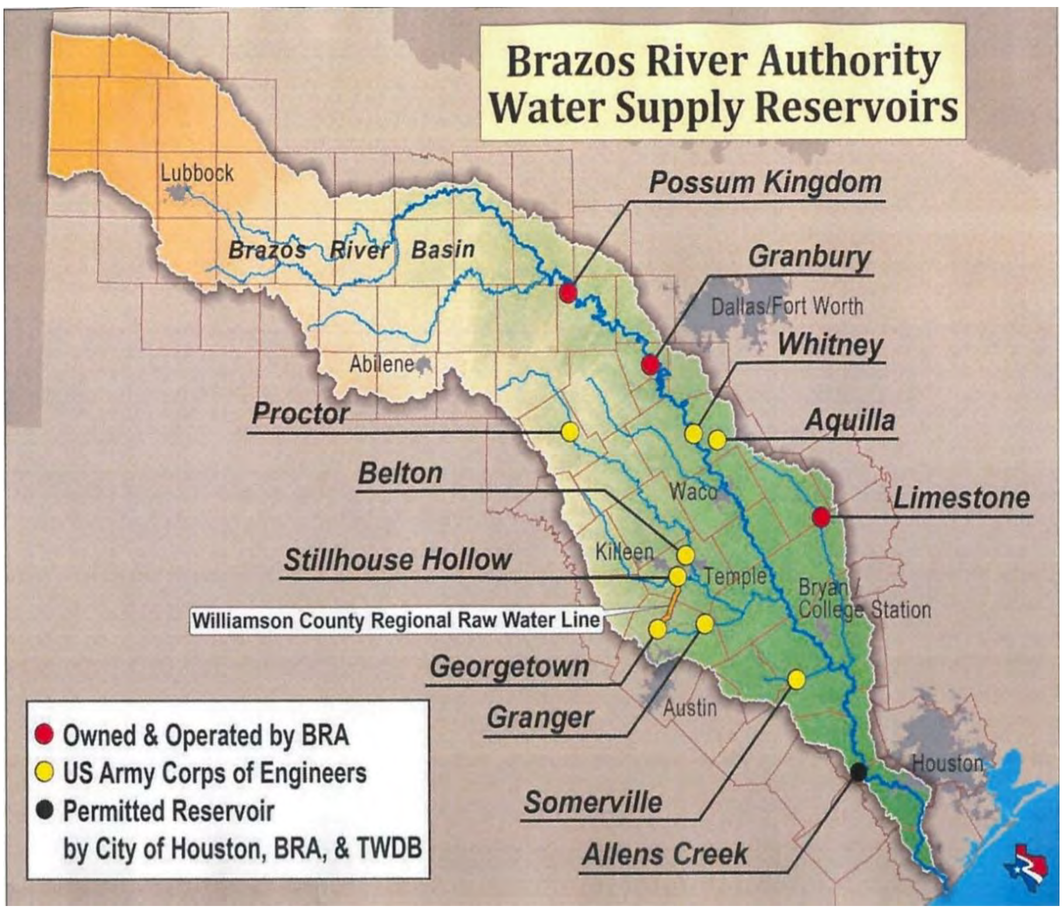

Figure 2.13 BRA Water Supply System (Freese and Nichols, BRA [11])

A *Water Management Plan (WMP)* [12] and *WMP Technical Report* [13] incorporated in the *System Operation Permit* govern the operating principles for diversion, storage, and use of water appropriated under the permit. The BRA filed an application with the TCEQ for the System Operation Permit in June 2004. The TCEQ issued its final order approving the permit on September 16, 2016 and formally issued the permit on November 30, 2016. The WMP [12], WMP Technical Report [13], and related WAM information are available at the BRA systems operation website. http://www.brazos.org/About-Us/Water-Supply/SysOps

Largest Water Rights

The original Brazos WAM completed in 2001 modeled 1,216 water rights, all with priority dates senior to February 2, 2000, which included 1,160 rights in the Brazos River Basin and 56 rights in the San Jacinto-Brazos Coastal Basin [8]. Diversion rights for municipal, industrial, agricultural irrigation, and other uses accounted for 47.6%, 30.1%, 18.0%, and 4.3% the total authorized consumptive water use in the Brazos Basin (95.2%) and adjoining San-Jacinto-Brazos Coastal Basin (4.8%). Water rights associated with the 16 largest reservoirs in the Brazos River Basin are listed in Table 2.6. There are no major reservoirs in the San Jacinto-Brazos coastal basin.

The totals of the water right diversion targets and storage capacities for the entire WAM datasets are shown at the bottom of Table 2.6. The diversion targets associated with the 16 largest reservoirs account for about 39.7 percent and 31.7 percent of the total authorized diversion amounts for the authorized use Bwam3 and current use Bwam8 datasets. The storage capacities of the 16 largest reservoirs account for about 79.7 percent and 80.7 percent of the total conservation storage capacity of the reservoirs in the authorized and current use datasets. The 16 largest reservoirs are listed in Tables 2.1 and 2.6. The reservoir data is from the TCEQ WAM System datasets, which are compiled from the water right permits which exclude flood control storage capacity since no water right permits have been issued for flood control. The flood control pools of the nine federal USACE reservoirs are included in the daily version of the Brazos WAM, though flood control pools and flood control operations are not included in the monthly WAM.

The system of nine reservoirs operated by the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) contains a little over 40 percent of the conservation storage capacity and all the flood control storage capacity in the Brazos River Basin. The federal Whitney, Aquilla, Waco, Proctor, Belton, Stillhouse Hollow, Georgetown, Granger, and Somerville Reservoirs are the only reservoirs in Tables 2.1 and 2.6 and Figure 2.2 with flood control pools. The USACE constructed, owns, and maintains the federal multiple-purpose reservoir system and is responsible for flood control operations. The Brazos River Authority (http://www.brazos.org/) has contracted for the conservation storage capacity of the nine federal reservoirs. The City of Waco holds water right permits for Lake Waco and the BRA holds the water rights for most of the water supply storage and diversions provided by the eight other federal reservoirs. The BRA constructed and owns the non-federal Possum Kingdom, Granbury, and Limestone Reservoirs.

Hydroelectric power is generated at Whitney Reservoir and in the past was generated at Possum Kingdom Reservoir. The Southwest Power Administration is responsible for marketing hydroelectric power generated at Lake Whitney, which it sells to the Brazos Electric Power Cooperative. Hydropower is generated by excess flows (spills) and releases for downstream water supply diversions. The inactive pool at Lake Whitney provides dead storage for hydropower. No water rights exist specifically for hydropower in the Brazos River Basin.

Table 2.6
Water Rights in 2008 Brazos WAM and 2019 Daily Brazos WAM

Reservoir	Reservoir Identifier	Control Point	Storage (acre-feet) Bwam3	Storage (acre-feet) Bwam8	Diversion (ac-ft/year) Bwam3	Diversion (ac-ft/year) Bwam8
Brazos River Authority System						
Possum Kingdom	POSDOM	515531	724,739	552,013	230,750	59,482
Granbury	GRNBRY	515631	155,000	132,821	64,712	36,025
Whitney	WHITNY	515731	387,024	311,998	0	0
	BRA	515731	50,000	50,000	18,336	18,336
	CORWHT	515731	199,076	199,076	0	0
Aquilla	AQUILA	515831	52,400	41,700	13,896	2,394
Waco	LKWACO	509431	39,100	39,100	39,100	37,448
	WACO2	509431	65,000	65,000	20,000	900
	WACO4	509431	88,062	88,062	20,777	0
	WACO5	509431	14,400	14,400	0	0
Proctor	PRCTOR	515931	59,400	54,702	19,658	14,068
Belton	BELTON	516031	457,600	432,978	112,257	107,738
Stillhouse Hollow	STLHSE	516131	235,700	224,279	67,768	67,768
Georgetown	GRGTWN	516231	37,100	36,980	13,610	11,943
Granger	GRNGER	516331	65,500	50,540	19,840	2,569
Limestone	LMSTNE	516531	225,400	208,017	65,074	39,337
Somerville	SMRVLE	516431	160,110	154,254	48,000	48,000
Allen's Creek	ALLENS	292531	145,533	–	99,650	–
City of Lubbock						
Alan Henry	ALANHN	4146P1	115,937	115,773	35,000	288
West Central Texas Municipal Water District						
Hubbard Creek	HUBBRD	421331	317,750	317,750	56,000	9,924
Texas Utilities Services						
Squaw Creek	SQWCRK	409702	151,500	151,015	23,180	17,536
Water Right Totals						
Total for the 16 reservoirs listed above			3,746,331	3,240,458	967,608	473,756
Percentage of basin total			(79.8%)	(80.5%)	(39.7%)	(31.7%)
All other water rights			948,520	782,892	1,469,730	1,022,675
Total for the entire river basin			4,694,851	4,023,350	2,437,338	1,496,431

In addition to releases for water supply diversions from the lower Brazos River, Possum Kingdom and Granbury Reservoirs supply water as needed to maintain constant operating levels in Lakes Squaw Creek, Tradinghouse Creek, and Lake Creek which are owned and operated by utility companies for steam-electric power plant cooling. The BRA operates a desalting water treatment plant that allows use of water from Lake Granbury to supplement the water supply for the City of Granbury and other water users in Johnson and Hood Counties. BRA holds a water right permit to impound 50,000 acre-feet of storage in Lake Whitney between elevations 520 feet (387,024 acre-feet) and 533 feet (642,179 acre-feet) to supply a diversion of 18,336 acre-feet/year for municipal use. the BRA has a water supply contract with the Corps of Engineers for the 50,000 acre-feet of storage capacity in Lake Whitney.

Allen's Creek Reservoir is the only proposed but not yet constructed project in Tables 2.1 and 2.6. The BRA, City of Houston, and Texas Water Development Board jointly hold a water right permit for the proposed project. The reservoir site is on Allen's Creek, a tributary of the lower Brazos River, in Austin County near the towns of Wallis and Simonton.

Lake Alan Henry in the upper basin is the most recently constructed of the 16 largest reservoirs. The Brazos River Authority was responsible for the initial planning for the Alan Henry Reservoir project and held the original water right permit. Lake Alan Henry is now owned and operated by the City of Lubbock for municipal water supply. The West Central Texas Municipal Water District operates Hubbard Creek Reservoir to supply the cities of Abilene, Albany, Anson, and Breckenridge and other water users.

Squaw Creek Reservoir owned by Texas Utilities Services Company provides cooling water for the Comanche Peak Nuclear Power Plant. The lake is located between the cities of Glen Rose and Granbury on Squaw Creek which flows into the Brazos River between Lakes Granbury and Whitney. The BRA supplies water from Lakes Possum Kingdom and Granbury as needed to maintain a constant water level in Squaw Creek Reservoir.

Instream Flow Requirements

The *IF* record water rights recently added to model SB3 environmental flow standards are described in Chapter 5. The Brazos WAM also still incorporates old pre-SB3 instream flow requirements. The version of the Brazos WAM authorized use Bwam3.DAT file last updated by the TCEQ in September 2008 contains the 122 *IF* records listed in Table 2.7. In WRAP terminology, an instream flow *IF* record is a type of water right that sets a minimum instream flow limit that may restrict streamflow depletions of junior *WR* record water rights. The entries in each field of the *IF* records as reproduced in Table 2.7 include:

- the control point location of the instream flow target
- minimum regulated flow limit as an annual flow rate in acre-feet/year
- identifier of the *UC* record containing the 12 distribution coefficients used to disaggregate the annual flow to 12 monthly flows
- priority (seniority) date in the format of year followed by month and day
- water right type 1 or 3 that specifies whether the *IF* record is linked to reservoir storage defined by one or more *WS* records
- water right identifier

IF records model instream flow requirements defined in water right permits. About 120 of the over 1,200 water right permits modeled in the Brazos WAM contain special conditions regarding minimum instream flow limit requirements. The special conditions attached to the permitted diversion are in the form of minimum instream flow rates, which may vary seasonally, at the diversion site or a downstream stream gaging station. Instantaneous flow limits in ft^3/s for each of the 12 months of the year specified in the permits are modeled as monthly volumes in acre-feet/month using instream flow *IF* records and use coefficient *UC* records. *IF* records restrict streamflow depletions of senior rights at and upstream of their sites.

Table 2.7
IF Records in Brazos WAM Authorized Use Bwam3.DAT File

	Control Point	Annual Flow (af/y)	UC Records	Priority Date	Type	IF Right Identifier
IF	578831	12	IF5788	20020930	1	IFP5788_1
IF	586631	18,095	UNIFO	20050531	1	IFA586631
IF	579101	365	5791IF	20021114	1	IFP5791_1
IF	380934	72	UNIFO	20020429	1	IF3809_1
IF	576701	119,155	5767IF	20020329	1	IF5767_1
IF	BRHE68	1,216,877	5752IF	20011018	1	IF5752_1
IF	575203	2,741	GAVIF	20011018	1	IF5752_2
IF	574432	7,058	5744IF	20010627	1	IF5744_1
IF	565801	94,093	UNIFO	19991018	1	IF5658_1
IF	565801	0	UNIFO	19991018	1	IF5658_2
IF	BRRI70	1,352,902	IF5665	20010621	1	IF5665_1
IF	568601	2,741	IFD129	20000628	1	IFP5686_1
IF	DMAS09	3,367	IFD011	20000719	1	IFP5692_1
IF	41430	12,172	UNIFO	19721218	1	IFC4143_1
IF	413931	21,719	UNIFO	19490803	1	IFC4139_1
IF	418502	362	UNIFO	19750714	1	IFC4185_1
IF	BRRI70	241,987	IFD031	19471114	1	IFC4013_1
IF	BRRI70	0	IFD031	19471114	1	IFC4013_2
IF	SADL44	1,448	UNIFO	19710329	1	IFC3532_1
IF	SADL44	1,448	UNIFO	19700504	1	IFC3543_1
IF	408401	3,547	UNIFO	19731119	1	IFC4084_1
IF	408601	10,136	UNIFO	19750902	1	IFC4086_1
IF	409702	1,086	UNIFO	19730425	3	IFC4097_1
IF	228302	12,827	IFLGC	19211231	1	IF4318_ON
IF	228302	0	IFLGC	19211231	1	IF4318_OF
IF	228302	12,827	IFLGC	20010118	1	IF4318_OA
IF	515831	362	UNIFO	19761025	3	IFC5158_1
IF	P41242	3,594	IFD063	19820621	1	IFP4124_1
IF	228101	3,585	IFD065	19600430	1	IFC2281_1
IF	555101	8,172	IFD067	19960403	1	IFP5551_1
IF	555101	15,038	MERID	20050908	1	IF5899
IF	P41351	15,217	IFD068	19830515	1	IFP4135_1
IF	365301	6,901	3653A	20020812	1	IFC3653_1N
IF	281421	8,329	3653B	20020812	1	IFC3653_2N
IF	LEBE49	1,810	UNIFO	19830207	1	IFP4024_1
IF	421812	3,386	IFD074	19841127	1	IFP4218_1
IF	P40121	10,136	UNIFO	19821213	1	IFP4012_1
IF	295811	7,240	IFD081	19760927	1	IFC2958_1
IF	299111	908	2991IF	20020429	1	IF2991_1
IF	LAKE50	16,020	TAYLIF	19660401	1	IF2996_1
IF	LAKE50	0	TAYLIF	19660401	1	IF2996_2
IF	LAKE50	16,020	TAYLIF	20030923	1	IF2996_3
IF	LABE52	4,344	IFD083	19840508	1	IFP4130_1
IF	LABE52	4,344	IFD083	19820920	1	IFC3007_1
IF	LABE52	4,344	IFD083	19860718	1	IFP5076_1
IF	LABE52	4,344	IFD083	19820920	1	IFP4000_1
IF	LABE52	4,344	IFD083	19820920	1	IFP4003_1
IF	LABE52	4,344	IFD083	19820920	1	IFP4002_1
IF	P37631	4,530	IFD08A	19800527	1	IFP3763_1
IF	LRLR53	125,887	IFD085	19990816	1	IFP4095_1
IF	LRLR53	12,377	IFD08B	19800527	1	IFP3762_1
IF	LRCA58	25,103	IFD086	19840228	1	IFP4109_1
IF	LRLR53	22,444	IFD087	19820920	1	IFP4015_1
IF	LRCA58	25,101	IFD086	19850709	1	IFP4279_1
IF	416611	3,403	UNIFO	19840731	1	IFP4166_1
IF	LRCA58	25,103	IFD086	19770829	1	IFC3759_1

IF	LRCA58	25,103	IFD086	19850103	1	IFP4212_1
IF	LRCA58	14,480	UNIFO	19800527	1	IFP3761_1
IF	LRCA58	25,103	IFD086	19860721	1	IFP5077_1
IF	LRCA58	232,926	IFD08D	20000929	1	IFC3775_1
IF	BRWA41	190,763	IFD091	19860814	1	IFP5085_1
IF	BRWA41	130,751	IFD092	19820830	1	IFP3936_1
IF	BRHB42	196,129	IFD098	19830207	1	IFP4042_1
IF	BRHB42	185,856	IFD096	19820922	1	IFP4014_1
IF	BRHB42	185,856	IFD096	19821129	1	IFP4013_1
IF	435533	72	UNIFO	19480401	3	IFC4355_1
IF	BRHB42	185,856	IFD096	19820503	1	IFC4358_1
IF	BRHB42	196,129	IFD098	19830711	1	IFP4063_1
IF	BRHB42	185,856	IFD096	19820503	1	IFC4359_1
IF	BRHB42	235,583	IFD093	19830906	1	IFP4076_1
IF	BRHB42	235,583	IFD093	19830926	1	IFP4078_1
IF	BRHB42	196,129	IFD098	19830207	1	IFP4023_1
IF	BRHB42	241,653	IFD099	19831031	1	IFC4366_1
IF	BRHB42	235,583	IFD093	19840515	1	IFP4145_1
IF	BRHB42	235,583	IFD093	19830919	1	IFP4080_1
IF	BRHB42	196,129	IFD098	19830207	1	IFC4371_1
IF	BRBR59	435,061	IFD09B	19810309	1	IFC4372_1
IF	BRHB42	235,583	IFD093	19831019	1	IFC4363_1
IF	BRHB42	261,415	IFD09F	19840710	1	IFC4364_1
IF	BRHE68	613,612	IFD09D	19840508	1	IFP4128_1
IF	BRHE68	209,398	IFD111	19821220	1	IFP4017_1
IF	LRCA58	14,480	UNIFO	19511212	1	IFC3758_1
IF	BRBR59	209,398	IFD09E	19511212	1	IFC3758_2
IF	529831	180	IFD103	19740701	1	IFC5298_1
IF	557021	40,905	IFD101	19970117	1	IFP5570_1
IF	531131	362	UNIFO	19770222	1	IFC5311_1
IF	530701	17,022	IFD104	19801215	1	IFC5307_1
IF	556601	35,780	IFD102	19970115	1	IFP5566_1
IF	BRHE68	557,820	IFD111	19821220	1	IFC5285_1
IF	BRHE68	557,820	IFD111	19821220	1	IFP4011_1
IF	BRHE68	557,820	IFD111	19821220	1	IFP4016_1
IF	BRHE68	0	IFD111	19821220	1	IFP4016_2
IF	BRHE68	557,820	IFD111	19821220	1	IFP4016_3
IF	BRHE68	613,616	IFD112	19840313	1	IFP4016_4
IF	BRHE68	613,616	IFD112	19900403	1	IFP5290_1
IF	BRHE68	557,820	IFD111	19830418	1	IFP4009_1
IF	BRRI70	554,696	IFD116	19850806	1	IFP4280_1
IF	2925A	2,604,379	MEDIAN	19990901	1	IFMETESTON
IF	2925A	0	MEDIAN	19990901	1	IFMETESTOF
IF	2925A	1,076,933	25THPT	19990901	1	IF25TESTON
IF	2925A	0	25THPT	19990901	1	IF25TESTOF
IF	2925D	2,604,379	MEDIAN	19990901	1	MEDIAN-REG
IF	2925C	1,076,933	25THPT	19990901	1	25THPT-REG
IF	2925A	531,399	7Q2	19990901	1	7Q2-REG
IF	423204	362	UNIFO	19850409	1	IFP4232_1
IF	BRRI70	721,379	IFD113	19970109	1	IFP5567_1
IF	BRRI70	553,178	IFD114	19960507	1	IFP5552_1
IF	BRRO72	6,655	IFD115	19290208	1	IFC5322_1
IF	BRRI70	553,178	IFD114	19840131	1	IFP4105_1
IF	533811	46,624	UNIFO	19850919	1	IFC5338_1
IF	534401	4,713	IFD121	19840508	1	IFP4201_1
IF	P40101	9,795	IFD122	19850103	1	IFP4221_1
IF	534601	7,254	IFD128	19890829	1	IFP5256_1
IF	CON241	3,989	IFD123	19850103	1	IFP4215_1
IF	P41321	3,808	IFD124	19860527	1	IFP5064_1
IF	534603	3,626	IFD125	19840522	1	IFP4132_1
IF	534602	3,989	IFD123	19840529	1	IFC5349_1
IF	CON241	5,258	IFD126	19860509	1	IFC5343_1
IF	534304	1,597	IFD127	19860509	1	IFC5343_2
IF	CBALC2	72	UNIFO	19681115	1	IFC5355_1
IF	536402	724	UNIFO	19910628	1	IFP5369_1
IF	523001	1,448	UNIFO	19890502	1	IFP5230_1

The term *Hale clause* refers to minimum instream flow limits in the Brazos River Basin that are specified to protect senior water rights. These minimum instream flow requirements incidentally also may benefit the environment. Over half of the 122 *IF* records in Table 2.7, including most of those specifying larger minimum flow rates, represent Hale clause provisions of water right permits. The other *IF* records with typically smaller minimum flow limits represent permit special conditions designed specifically to preserve environmental flows.

The Hale clause provision in diversion/storage permits include language that the special condition makes the instream flow requirement "*exclusive of any releases dedicated by the Brazos River Authority from its conservation storage for subsequent use downstream*." By default, each *IF* record instream flow target is applied as a minimum limit on total regulated flow. An option has been added to the *IF* record that allows the limit to be applied to regulated flows excluding reservoir releases made for use at downstream locations. However, this option had not yet been added when the Brazos WAM dataset was created during 1999-2001.

The annual flow target in acre-feet/year is tabulated in the third column of Table 2.7. The minimum flow limit target for a month, in acre-feet/month, is computed by *SIM* by multiplying the annual flow volume by a fraction computed using the coefficients on the *UC* records referenced by the identifiers in the fourth column of Table 2.7 The *UC* record contains 12 distribution coefficients that disaggregate the annual flow to 12 monthly flows.

Of the 122 *IF* record rights, 119 are type 1 and three are type 3. A type 3 *IF* record right includes releases from one or more specified reservoirs as needed to prevent violation of the instream flow target. Type 1 rights have no reservoir storage. With either type, junior *WR* record rights curtail diversions and refilling storage as necessary to maintain the instream flow target. The three *IF* type 3 rights have the identifiers IFC4097_1, IFC5158_1, and IFC4355_1. The 119 other *IF* records contained in the Brazos WAM connect to *UC* records but have no *WS* or records. These are type 1 *IF* rights with no reservoir storage. Junior *WR* record rights curtail diversions and storage refilling as necessary to maintain the instream flow targets. Upstream reservoirs controlled by junior *WR* record water rights make releases to pass inflows but do not otherwise release from storage for the instream flow targets.

The 122 *IF* records listed in Table 2.7 are actively functioning in the version of the DAT file that is labeled as last updated in September 2008. Other *IF* records have been deactivated (commented out with **) in this version of the Bwam3 DAT file.

If multiple *IF* records are assigned to the same control point, the *IF* record that sets the highest instream flow target in a particular time period (day or month) controls for that particular time period. SB3 environmental flow standards are added to the 2019 daily Brazos WAM as *IF* record instream flow rights as described in Chapter 5. The old existing *IF* record rights are not modified. Likewise, new *IF* records referencing *TS* records explained in Chapter 5 are inserted in the monthly WAM without modifying the old existing *IF* record rights. Again with multiple instream flow *IF* record rights at the same control point, the most stringently high target is the controlling constraint on water availability for more junior *WR* record water rights located upstream.

WAM Primary Control Points and
Corresponding USGS Gaging Stations

Primary control points are defined as the locations at which monthly naturalized stream flows are provided on inflow *IN* records in a FLO file or the DSS hydrology input file. Naturalized flows at all other control points (called secondary control points) are computed within the *SIM* or *SIMD* simulation based on the naturalized flows provided at the primary control points and watershed parameters provided on DIS file flow distribution *FD* and watershed parameter *WP* records and/or DAT file control point *CP* records.

The Brazos WAM has 77 primary control points. Sequences of monthly naturalized flows are synthesized during execution of *SIM* or *SIMD* for the over 3,000 secondary control points based on flows at the 77 primary control points and information in a flow distribution DIS file. The combined drainage area ratio and channel loss factor method (*CP* record *INMETHOD* option 6) is used in the Brazos WAM for distributing flows to secondary control points.

The following naming conventions for control point identifiers were established during development of the original Brazos WAM [8, 9]. Six-character identifiers for the 77 primary control points include two letters denoting the river followed by two letters denoting the nearest town and two-digit integer sequenced in upstream-to-downstream order. For example, the control point identifier BRRI70 denotes the site of the USGS gage on the Brazos River (BR) near Richmond (RI). Secondary control points have 6-digit integer identifiers, except for stream confluences which begin with CON followed by an integer.

The 77 primary control points with monthly naturalized flows are listed in Table 2.8 and shown in Figures 2.14 and 2.15 with the six-character control point identifiers used in the WAM data files. The first 73 control points listed in Table 2.8 are located in the Brazos River Basin, and the last four are in the San Jacinto-Brazos Coastal Basin. The watershed drainage areas shown in Table 2.8 are from the watershed parameter *WP* records in the DIS file and do not include non-contributing areas of the upper Brazos River Basin in and near New Mexico.

The naturalized monthly flow volumes for most of the primary control points were developed by adjusting observed flows at USGS stations as discussed in Chapter 7. Observed gaged daily flows at USGS gaging stations are also employed in developing the daily pattern hydrographs described in Chapter 6.

The 77 primary control points in the Brazos WAM include the sites of 72 USGS stream gaging stations, two sites at which reservoir releases have been measured, and three ungaged basin outlets. Twenty-two of the gages have records that include the original 1940-1997 Brazos WAM period-of-analysis. Twenty-one gages have records that include 1940 to the present. Fifty of the 72 gages at primary control points have records for 1998 to the present. Flow data are no longer available at the USGS NWIS website for gages 080809010 and 08093500 at control points WRSP02 and NBHI35. Reservoir storage data are available for gage 080809010 at WRSP02.

Table 2.8 shows the years of the period-of-record. The number of days within the period-of-record with missing data as counted by *HEC-DSSVue*, is noted in the last column of Table 2.8.

Table 2.8
77 Primary Control Points in the Brazos WAM Datasets

WAM CP ID	Stream	Nearest City	USGS Gage No.	Watershed Area (sq miles)	USGS Period of Record	Missing Days
RWPL01	Running Water Draw	Plainview	08080700	295	1939–present	10,166
WRSP02	White River Reservoir	Spur	08080910	689	1964-1976	missing
DUGI03	Duck Creek	Girard	08080950	300	1964-1989	0
SFPE04	Salt Fork Brazos River	Peacock	08081000	2,007	1950–1986	4,749
CRJA05	Croton Creek	Jayton	08081200	293	1959–1986	0
SFAS06	Salt Fork Brazos River	Aspermont	08082000	2,504	1924–present	5,058
BSLU07	Buffalo Spring Lake	Lubbock	–	245	Reservoir releases	–
DMJU08	Double Mountain Fork	Justiceburg	08079600	265	1961–present	5
DMAS09	Double Mountain Fork	Aspermont	08080500	1,891	1923–present	1,734
NCKN10	North Croton Creek	Knox City	08082180	250	1965–1986	0
BRSE11	Brazos River	Seymour	08082500	5,996	1923–present	2
MSMN12	Millers Creek	Munday	08082700	106	1963–present	0
CFRO13	Clear Fork Brazos	Roby	08083100	266	1962–present	0
CFHA14	Clear Fork Brazos	Hawley	08083240	1,456	1967–1989	0
MUHA15	Mulberry Creek	Hawley	08083245	208	1967–1989	0
CFNU16	Clear Fork Brazos	Nugent	08084000	2,236	1924–present	3
CAST17	California Creek	Stamford	08084800	476	1962–present	0
CFFG18	Clear Fork Brazos	Fort Griffin	08085500	4,031	1924–present	0
HCAL19	Hubbard Creek	Albany	08086212	612	1966–present	0
BSBR20	Big Sandy Creek	Breckenridge	08086290	289	1962–present	0
HCBR21	Hubbard Creek	Breckenridge	08086500	1,092	1955–1986	0
CFEL22	Clear Fork Brazos	Eliasville	08087300	5,738	1915–1982	6,027
BRSB23	Brazos River	South Bend	08088000	13,171	1938–present	0
GHGH24	Lake Graham	Graham	–	224	reservoir releases	–
CCIV25	Big Cedar Creek	Ivan	08088450	97	1964–1989	0
SHGR26	Brazos River	Graford	08088600	14,030	1976–1994	0
BRPP27	Brazos River	Palo Pinto	08089000	14,309	1924–present	0
PPSA28	Palo Pinto Creek	Santo	08090500	574	1924–1976	9,343
BRDE29	Brazos River	Dennis	08090800	15,733	1968–present	0
BRGR30	Brazos River	Glen Rose	08091000	16,320	1923–present	0
PAGR31	Paluxy River	Glen Rose	08091500	411	1924–present	8,005
NRBL32	Nolan River	Blum	08092000	282	1924–present	15,401
BRAQ33	Brazos River	Aquilla	08093100	17,746	1938–present	1
AQAQ34	Aquilla Creek	Aquilla	08093500	307	1939–2001	0
NBHI35	North Bosque River	Hico	08094800	360	1994–2003	missing
NBCL36	North Bosque River	Clifton	08095000	977	1923–present	0
NBVM37	North Bosque River	Valley Mills	08095200	1,158	1959–present	1,025
MBMG38	Middle Bosque River	McGregor	08095300	77	1959–present	8,029
HGCR39	Hog Creek	Crawford	08095400	181	1959–present	8,035
BOWA40	Bosque River	Waco	08095600	1,660	1959–1982	146
BRWA41	Brazos River	Waco	08096500	20,065	1898–present	0
BRHB42	Brazos River	Highbank	08098290	20,900	1965–present	3
LEDL43	Leon River	De Leon	08099100	267	1960–present	7,571
SADL44	Sabana River	De Leon	08099300	476	1960–present	4,639

Table 2.8 Continued
Primary Control Points in the Brazos WAM Datasets

WAM CP ID	Stream	Nearest City	USGS Gage No.	Watershed Area (sq miles)	USGS Period of Record	Missing Days
LEHS45	Leon River	Hasse	08099500	1,283	1939–present	5,772
LEHM46	Leon River	Hamilton	08100000	1,928	1925–present	14,580
LEGT47	Leon River	Gatesville	08100500	2,379	1950–present	0
COPI48	Cowhouse Creek	Pidcoke	08101000	455	1950–present	8
LEBE49	Leon River	Belton	08102500	3,579	1923–present	0
LAKE50	Lampasas River	Kempner	08103800	817	1962–present	0
LAYO51	Lampasas River	Youngsport	08104000	1,240	1924–1980	0
LABE52	Lampasas River	Belton	08104100	1,321	1963–present	3,470
LRLR53	Little River	Little River	08104500	5,266	1923–present	12,145
NGGE54	North Fork San Gabriel	Georgetown	08104700	248	1968–present	1
SGGE55	South Fork San Gabriel	Georgetown	08104900	132	1967–present	0
GAGE56	San Gabriel River	Georgetown	08105000	404	1924–1987	7,526
GALA57	San Gabriel River	Laneport	08105700	737	1965–present	3
LRCA58	Little River	Cameron	08106500	7,100	1916–present	0
BRBR59	Brazos River	Bryan	08109000	30,016	1899–1993	0
MYDB60	Middle Yegua Creek	Dime Box	08109700	235	1962–present	0
EYDB61	East Yegua Creek	Dime Box	08109800	239	1962–present	0
YCSO62	Yegua Creek	Somerville	08110000	1,011	1924–1991	6,210
DCLY63	Davidson Creek	Lyons	08110100	195	1962–present	0
NAGR64	Navasota River	Groesbeck	08110325	240	1978–present	0
BGFR65	Big Creek	Freestone	08110430	97	1978–present	0
NAEA66	Navasota River	Easterly	08110500	936	1924–present	0
NABR67	Navasota River	Bryan	08111000	1,427	1951–1997	801
BRHE68	Brazos River	Hempstead	08111500	34,374	1938–present	0
MCBL69	Mill Creek	Bellville	08111700	377	1963–1993	2,394
BRRI70	Brazos River	Richmond	08114000	35,454	1903–present	5,936
BGNE71	Big Creek	Needville	08115000	46	1947–present	640
BRRO72	Brazos River	Rosharon	08116650	35,775	1967–present	1,302
BRGM73	Brazos River	Gulf of Mexico	–	36,027	–	–
CLPEC1	Clear Creek	Pearland	08077000	38.8	1944–1994	2,339
CBALC2	Chocolate Bayou	Alvin	08078000	87.7	1959–present	1
SJGBC3	Coastal Basin	Galveston Bay	–	415	–	–
SJGMC4	Coastal Basin	Gulf of Mexico	–	1,004	–	–

The DSS files described later in this report contain recorded daily and aggregated monthly flows from 74 USGS gages. Daily mean flow rates in cfs were downloaded from the USGS National Water Information System (NWIS) website and aggregated to monthly volumes in acre-feet using *HEC-DSSVue*. The 77 primary control points listed in Table 2.8 include the sites of 72 USGS gages, but the gages at control points WRSP02 and NBHI35 are no longer found at the USGS website. Daily flows are recorded in the DSS file for the 70 gages listed in Table 2.8 plus the four gages listed in Table 2.9, which include gages 11, 19, and 25 from Table 2.2 and Figure 2.3.

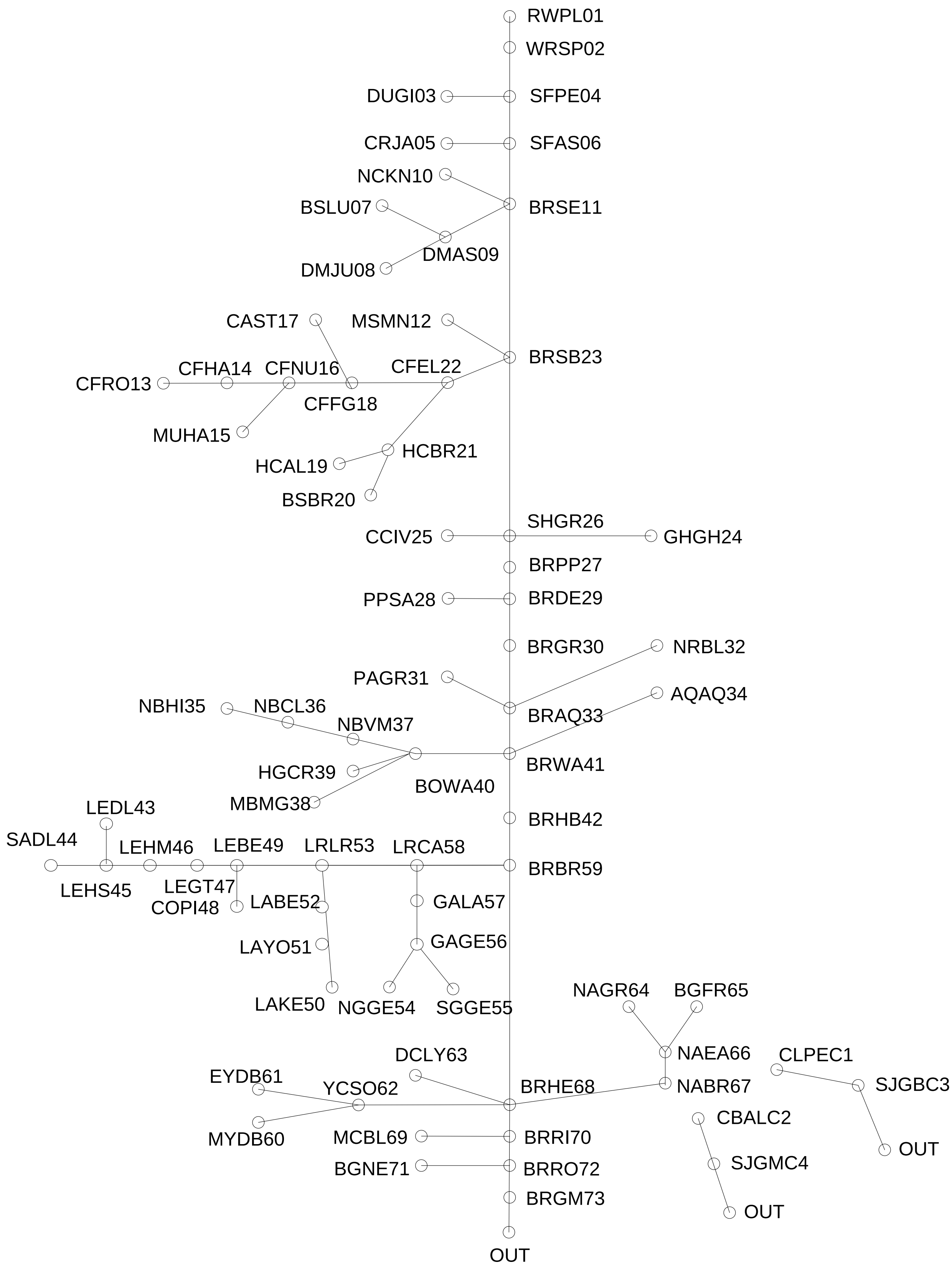

Figure 2.14 Schematic of 77 primary control points (not to scale)

Figure 2.15 Map of Brazos River Basin and San Jacinto-Brazos Coastal Basin
with Primary Control Points (Freese and Nichols, BRA [9])

The 74 gages included in the daily DSS file of Chapter 6 include 70 gages from Table 2.8, 29 of the 30 gages in Table 2.2 and Figure 2.3, and gage 08088610 listed in Table 2.9. The gage on the Brazos River at Washington, labeled 23 in Table 2.3, is not used due to its short record.

The four gages in Table 2.9 are not included in Table 2.8 but are located near four of the gage sites in Table 2.8. Flows are combined at pairs of gages to extend the periods-of-records.

Flows recorded since 1989 at gage 08088610 on the Brazos River at Graford below Possum Kingdom Dam can be combined with 1976-1994 flows at the old discontinued gage 08088600 at the dam for control point SHGR26.

Gages 08097500 (Table 2.9) and 08098290 (Table 2.8) on the Brazos River near Marlin and Highbank have close to the same location but different periods-of-record (10/1938-9/1951 and 10/1965-present) which are combined into a single longer series of flows at control point BRHB42.

The USGS replaced gage 08109000 on the Brazos River near Bryan (BRBR59) with gage 08108700 in 1993 and likewise replaced gage 08111000 on the Navasota River near Bryan (NABR67) with gage 08110800 in 1997.

Table 2.9
Four Additional USGS Gaging Stations
Combined with Gaging Stations Listed in Table 2.8

Fig. 2.3 ID	USGS Gage ID	WAM CP ID	Location by River and Nearest City	Drainage Area	Period-of-Record
				(square miles)	
−	08088610	SHGR26	Brazos River at Graford	14,030	10/1989-present
11	08097500	BRHB42	Brazos River near Marlin	20,645	10/1938-9/1951
19	08108700	BRBR59	Brazos River at SH 21 near Bryan	29,483	7/1993-present
25	08110800	NABR67	Navasota River at Old Spanish Rd Bryan	1,287	4/1997-present

CHAPTER 3
DAILY BRAZOS WATER AVAILABILITY MODEL

The May 2019 expanded Brazos WAM consisting of the files described in Tables 1.2 and 2.4 includes both monthly and daily versions. The 2008/2017 monthly Brazos WAM dataset provided by the TCEQ (Table 2.4) was modified as follows to develop the 2019 daily WAM.

1. The 1940-1997 monthly naturalized flows (*IN* records) and monthly net evaporation-precipitation depths (*EV* records) are extended and new and extended monthly hydrologic indices (*HI* records) are compiled. The data are stored in the hydrology input DSS file.
   - The 1940-2017 *IN* and *EV* records are applicable to both the monthly and daily WAMs. Extension of the *IN* and *EV* record sequences are described in Chapters 7 and 8.
   - Hydrologic index *HI* records are covered in Chapter 5. *HI* records can be employed in a monthly *SIM* simulation. However, with the strategy for modeling SB3 environmental flow standards adopted here, the *HI* records are used only with the daily *SIMD* simulation.

2. Compilation of daily flow *DF* records stored in the DSS hydrology input file is described in Chapter 6. *DF* record 1940-2017 daily flows serve as pattern hydrographs in the *SIMD* flow disaggregation computations.

3. Calibrated lag and attenuation parameters are added as routing *RT* records in a new DIF file. Development of routing parameters is covered in the present Chapter 3.

4. Flood control operation of reservoirs is modeled by adding *FR*, *FF*, *FV*, and *FQ* records to the DAT file as explained in Chapter 4.

5. SB3 environmental flow standards are modeled by adding instream flow *IF*, environmental standard *ES*, hydrologic condition *HC*, and pulse flow *PF* records to the DAT file, and hydrologic index *HI* records to the DSS file as described in Chapter 5.

The tasks listed above result in a daily version of the WAM with a 1940-2017 hydrologic period-of-analysis. The same hydrology DSS input file with filename BrazosHYD.DSS is read in both *SIM* monthly and *SIMD* daily simulations.

The completed daily WAM is employed to compute daily instream flow targets for SB3 environmental flow standards modeled with *IF*, *ES*, *HC*, *PF* and *HI* records that are summed to monthly targets within the *SIMD* simulation. The monthly instream flow targets are stored in the shared DSS input file as time series *TS* records which are employed by *IF* record instream flow rights in the monthly *SIM* simulation model.

Daily *SIMD* Simulation Input Dataset

With the exception of the monthly *IF/TS* record targets for SB3 environmental flow standards noted in the preceding paragraph, all of the *SIM* input files and input records in the monthly Brazos WAM dataset are also included in the daily Brazos WAM dataset to be read by *SIMD*. Additional "daily-only" input records are added in the conversion of the monthly WAM to daily. The "daily-only" *SIMD* input records listed in Table 3.1 are explained in Chapter 4 of the

Users Manual [2]. The only record required to switch a monthly WAM to daily is the *JT* record. The other records are all optional, with defaults activated for blank fields or missing records.

Table 3.1
SIMD Input Records for Daily Simulations
(Described in Chapter 4 of *Users Manual*)

	DAT File
JT, *JU*	Simulation job control options.
W2, *C2*, *C3*, *G2*, *R2*	Simulation results output control.
DW, DO, *PF*, *PO*	Daily water right data.
FR, *FF*, *FV*, *FQ*	Reservoir operations for flood control.
	DIF File
DW/SC, DO/SC	Optional placement of *DW* and *DO* records.
RT, *DC*	Routing and disaggregation parameters.
	DSS File
DF	Daily flows.

Some but not all of the records listed in Table 3.1 are employed in the daily Brazos WAM. The following daily records are included in the Brazos WAM: *JT* and *JU* (simulation options), *W2* and *C2* (output control), *FR*, *FF*, *FV*, *FQ* (flood control), *RT* (routing), *DF* (daily flows), and *PF* (pulse flow component of SB3 environmental flow standards).

The daily Brazos WAM *SIMD* input dataset is composed of DAT, DIS, DIF, and DSS files. The original 2008 flow distribution DIS file (*FD* and *WP* records) is used without modification in both the expanded monthly and daily versions of the WAM. The DSS hydrology input file is shared by both the expanded monthly and daily versions of the WAM. The DIF file is relevant only with the daily *SIMD*. *SIMD* will execute fine without the DIF file. With no DIF file, there is simply no routing. A warning message in the MSS file indicates that no DIF file was found.

A monthly simulation can be performed with *SIM* with a DAT file containing input records for a daily simulation, such as the file Brazos3D.DAT. *SIM* skips over daily input records in the DAT file, does not read the DIF file, and ignores the *DF* records in the DSS time series input file. However, *SIMD* has no option for skipping over the daily-only records in the DAT file, other than manually commenting (**) them out. *SIMD* can perform a monthly simulation if and only if no daily-only records are included in the input dataset.

DAT File Input Records with Simulation Control Option Parameters

The records replicated as Table 3.2 are found at the beginning of the DAT file. The *JT*, *JU*, and *OF* records control daily simulation input, output, and computation options. The *SIMD JT* and *JU* records are analogous to the *SIM/SIMD JD* and *JO* records. *SIM/SIMD* input records applicable in both monthly and daily simulations are covered in Chapter 3 of the *Users Manual*. *SIMD* input records applicable only in a daily SIMD simulation are explained in Chapter 3 of the *Users Manual*. The file options *OF* record is described in Chapter 3 of the *Users Manual* though *OF* record field 4 entry DSS(3) has options that are relevant only to a daily simulation.

Table 3.2
SIMD DAT File Input Records for Controlling Simulation Options

```
**      1       2       3       4       5       6       7       8
**345678901234567890123456789012345678901234567890123456789012345678901234567890
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!
JD    78    1940       1       0       0               4                     13
JO     6                   1
OF     1   0   2                                           Brazos
JT     0   0   0   0   0   0   0   0   0   0   0
JU     1   0   0   0   0
HI         LOWER  MIDDLE   UPPER
DF        227901  509431  515531  515631  515731  515831  515931  516031  516131
DF        516231  516331  516431  516531  AQAQ34  BGNE71
DF        BRAQ33  BRBR59  BRDE29  BRGR30  BRHB42  BRHE68  BRPP27  BRRI70  BRRO72
DF        BRSB23  BRSE11  BRWA41  CBALC2  CFFG18  CFNU16
DF        CLPEC1  CON070  CON095  CON102  CON129  CON137  CON145  CON147  CON231
DF        DMAS09  DMJU08  EYDB61  GAGE56  GALA57  LAKE50
DF        LEBE49  LEGT47  LRCA58  LRLR53  NABR67  NAEA66  NBCL36  NBVM37  PAGR31
DF        RWPL01  SFAS06  SGGE55  YCSO62
```

The following options activated on the records shown in Table 3.2 contribute to the conversion of the monthly WAM to daily.

- ADJINC option 7 selected in *JD* record field 8 (column 56) is the recommended standard negative incremental flow adjustment option for daily simulations with forecasting as explained in *Daily Manual* Chapter 3. *JO* record *ADJINC* options 4 or 6 are the recommended standards for monthly simulations or daily simulations without forecasting.

- TL of 13 is entered in *JD* record field 11 (column 80) to increase the number of entries allowed in the *SV/SA* record storage-area table to 13 from the default of 12. The *SV* and *SA* records are extended as necessary to encompass flood control pools of the nine USACE reservoirs.

- INEV option 6 in *JO* record field 2 (column 8) instructs *SIM* and *SIMD* to read *IN* and *EV* records from a DSS input file.

- The DSSHI entry of 1 in *JO* record field 6 (column 28) instructs *SIM* and *SIMD* to read *HI* record hydrologic index sequences from the DSS input file for the three control points (LOWER, MIDDLE, UPPER) listed on the *HI* record entered in the DAT file. *CP* records are added for these three control points that are used only as *HI* record identifiers.

- DSS(3) option 2 is selected in *OF* record field 4 (column 16) to instruct *SIMD* to record daily simulation results in a DSS output file. The blank *OF* record field 4 (column 20, DSS(4)=0) means that a default subset of variables will be included in the simulation results.

- The DSS input filename root Brazos is entered in *OF* record field 12 for DSSROOT. With field 12 blank, by default, the filename of the DSS input file is the same as the DIS file which by default is the same as the DAT file.

- The *JT* record is required for a daily simulation, and the *JU* record activates certain daily options. Defaults are activated for blank fields or entries of zero on the *JT* and *JU* records.
- Entries for OUTCP2 and OUTWR2 in *JT* record fields 2 and 3 in combination with *C2* and *W2* records control selection of control points and water rights to include in the daily simulation results output in the same manner that OUTCP and OUTWR on the *JD* record in combination with *CO* and *WO* records control output of monthly simulation results.
- Fields 8, 9, 10, 11, and 12 are blank (or zero) on the *JT* record in Table 3.2. These fields allow optional output tables to be created in the annual flood frequency AFF and message MSS files.
- The *JU* record controls disaggregation and forecasting options. The blank (or zero) *JU* record field 3 (column 12) activates the default DFFILE option 1, meaning daily flow *DF* records are read from the DSS file for the 58 control points listed on the DAT file *DF* records in Table 3.2.
- Flow disaggregation DFMETH option 1 (uniform) is set as the global default in *JU* record field 2 used for computational control points that do not reflect actual real streamflow sites. Three *DC* records placed in the DIF file with REPEAT and DFMETHOD options 2 and 4 activate disaggregation option 4 based on *DF* record pattern hydrographs for all control points on the Brazos River and its tributaries and the streams in the San Jacinto Brazos coastal basin.
- Options for placing routed flow changes at the beginning or within the priority sequenced simulation computations are controlled by entries for WRMETH and WRFCST in *JU* record fields 4 and 5 (columns 16 and 20).
- Forecasting is activated by FCST option 2 in *JU* record field 6 (column 24). The forecast period FPRD set in *JU* record field 7 can be easily set or changed. If FCST=2 is entered in *JU* record field 6 and field 7 is blank, the forecast period FPRD is automatically computed within *SIMD*.

Other Groups of Input Records

The following groups of records are included in the water rights section of the DAT file.

1. Flood control operations of nine USACE reservoirs are modeled as described in Chapter 4 by adding *FR*, *FF*, *FV*, and *FQ* records to the DAT file. Flood storage (drought) index *DI* records are added to vary *FF* record flows with reservoir storage.
2. SB3 environmental flow standards at 19 control points are modeled by adding *IF*, *ES*, *HC*, and *PF* records to the DAT file as described in Chapter 5.

The original *SV/SA* record storage volume versus surface area tables extend to the top of flood control pool or higher for six of the nine USACE reservoirs. The existing *SV/SA* record tables in the DAT file are extended to include flood control pools in the other three USACE reservoirs. Evaporation allocation *EA* records are revised to include flood control pools for the multiple owner (component) Whitney and Waco Reservoirs.

Lag and attenuation routing coefficients developed as described later in this chapter are recorded on *RT* records stored in a DIF file.

Daily flow *DF* records developed as explained in Chapter 6 are stored in the DSS input file along with the *IN*, *EV*, *HI*, and *TS* records.

Monthly-to-Daily Disaggregation

The daily WAM is based on performing the *SIMD* simulation computations with a daily time step. Naturalized flow volumes in acre-feet/month are distributed to daily volumes in acre-feet/day in proportion to the daily flows of input flow pattern hydrographs, which tends to result in great within-month variability. Stream flow is extremely variable as illustrated Figures 2.4 through 2.12 of Chapter 2. All other monthly time series input data in the daily Brazos WAM are uniformly disaggregated from monthly to daily. Monthly reservoir net evaporation-precipitation depths are uniformly disaggregated to daily depths. *SIMD* provides no non-uniform distribution options for evaporation-precipitation.

Monthly naturalized flows are disaggregated to daily at most control points in the WAM using DFMETHOD(cp) option 4 based on daily flow pattern hydrographs input on *DF* records stored in the DSS input file. Monthly volumes are distributed to daily volumes in proportion to daily flows while maintaining monthly volumes. The procedure described in the following paragraph is activated by three DIF file *DC* records with REPEAT and DFMETHOD options 2 and 4 activated, which are assigned to control point BRGM73, which is the Brazos River outlet, and control points SJGBC3 and SJGMC, which are the outlets to the Gulf of Mexico of streams in the coastal basin. Flows at computational control points not encompassed within the actual stream system are disaggregated uniformly by the default DFMETH option 1 in *JU* record field 2.

Monthly naturalized stream flows at over 3,000 Brazos WAM control points are disaggregated to daily using 1940-2017 daily flows at 58 control points which are stored as *DF* records in the hydrology input DSS file. The automated procedure in *SIMD* for repeating daily flows at multiple control points is described on page 28 of Chapter 2 of the *Daily Manual* [4]. The automated procedure consists of using flows at the nearest downstream control point if available, otherwise finding flows at the nearest upstream control point, and lastly if necessary using flows from another tributary.

Monthly water supply diversion targets are uniformly disaggregated to daily. Daily diversion targets in acre-feet/day are computed by dividing monthly diversion target volumes by the number of days in the month. *SIMD* includes options for non-uniformly disaggregating monthly diversion targets to daily, activated by input parameters on *JU*, *DW*, and *DO* records, but these options are not employed in the daily Brazos WAM version presented in this report. Releases from flood control pools and targets for SB3 flow standards are computed on a daily basis.

SIMD directly computes daily *IF* record instream flow targets for SB3 environmental flow standards based on *HC*, *ES*, and *PF* record specifications as explained in Chapter 5, rather than disaggregating computed monthly targets to daily. However, for other *IF* record instream flow requirements, computed monthly target volumes are uniformly sub-divided to daily volumes. Non-uniform *IF* target distribution options provided by *SIMD JU*, *DW*, and *DO* records are not employed in the Brazos WAM.

Routing and Forecasting

Streamflow depletions for diversions and refilling reservoir storage, reservoir releases, and return flows result in stream flow changes that propagate through river reaches to downstream control points. The monthly *SIM* simulation has no routing; flow changes are assumed to propagate to the river system outlet within the current month. The daily *SIMD* routing computations consist of lag and attenuation adjustments to the flow changes that occur as each of the water rights is considered in the priority-based simulation computations. Without routing, streamflow changes propagate to the outlet in the same day that they originate, with no lag, in a daily *SIMD* simulation. Forecasting is designed to mitigate the effects of routing on the water right priority system and on flood control operations controlled by maximum allowable flow limits at downstream gages.

Forecasting of Water Availability and Flood Control Flow Capacity

Forecasting is relevant only if routing is employed. Forecasting should not be activated unless routing is employed. Forecasting and accompanying reverse routing, as explained in Chapter 3 of the *Daily Manual* [4], are designed specifically to deal with the effects of water right actions in a particular time step on downstream stream flows in future time steps, as reflected in routing computations. Due to routing (lag and attenuation), stream flow depletions, return flows, and reservoir releases in the current time step can affect both (1) stream flow availability for downstream senior water rights in future time periods and (2) flood flow capabilities for releases from flood control pools. Forecasting serves the two purposes of: (1) protecting water rights from the lag effects associated with stream flow depletions of junior water rights located upstream and (2) facilitating reservoir flood control operations by preventing releases from flood control pools that contribute to flooding in future time steps.

Forecasting is switched on or off with input parameter FCST in *JU* record field 6. The forecast period FPRD is entered in *JU* record field, with a blank field activating a *SIMD* routine that automatically computes the forecast period. The automatic default forecast period for the Brazos WAM is 93 days which is excessive. A forecast period of 15 days is adopted as being more reasonable. Forecasting greatly increases computer execution (run) time. Forecasting can be switched off with a blank *JU* field 6 to reduce execution time in preliminary simulations.

Routing Flow Changes

Routing of flow changes through downstream control points is incorporated in a *SIMD* simulation by a DIF file with routing parameters on *RT* records. Routing can be switched off simply by deactivating the *RT* records in the DIF file or removing the DIF file.

The lag and attenuation routing method and calibration of routing parameters are described in Chapters 3 and 4 of the *Daily Manual* [4]. Routing *RT* records are described in Chapter 4 of the *Users Manual* [2]. Lag and attenuation routing is activated as RTYPE(cp) option 1 in *RT* record field 3. Lag (LAG and LAGF) and attenuation (ATT and ATTF) routing parameters in units of days are provided on *RT* records in a DIF file. Separate values for lag and attenuation are provided for normal water right operations (LAG and ATT) and flood control operations (LAGF and ATTF). The parameters are for the river reach below the control point in *RT* record field 2. The routing computations are performed at the control points specified on the *RT* records but conceptually represent changes occurring gradually along river reaches. Routing parameters are not necessarily required for all control points. The daily Brazos WAM with over 3,000 control points includes routing parameters at 67 control points.

Routing is very approximate with inherent simplifications, uncertainties, inaccuracies, and variabilities. However, in general, this may not be a major concern because simulation results tend to not be overly sensitive to routing. In many typically situations, reasonable simulation results can be obtained without routing and, with routing, results vary only minimally with significant changes to routing parameter values. Various aspects of routing inaccuracies include the following.

Calibrating routing parameters and performing routing computations in the *SIMD* simulation for the river reaches between all control points is not feasible. Routing parameters are determined for only selected river reaches defined by stream flow gages. The routing computations are performed for only a sub-reach of each of the selected reaches.

Observed actual lag and attenuation characteristics of flow changes in actual gaged river reaches exhibit great apparently random variability that is difficult to describe or explain. Calibrated values for lag and attenuation parameters for the *SIMD* routing algorithm also exhibit great unexplained variability and associated uncertainty.

The routing algorithm incorporated in the *SIMD* simulation is a very simplistic model of a very complex phenomena. However, adding greater complexity to the model would likely not improve the accuracy of the model.

The routing algorithm simulates lag and attenuation of flow changes in free flowing stream reaches, not reservoirs. However, surcharge storage in reservoirs can be modeled in the flood control routines using *FV/FQ* record reservoir storage volume versus outflow tables.

Lag and Attenuation Routing Parameters

Calibration studies performed in the initial development of the original daily Brazos WAM [15, 21] employed the optimization-based calibration procedure explained in Chapter 4 of the *Daily Manual* [4]. A new set of routing parameter values for the Brazos WAM was recently developed based on applying the new statistical-based procedure also explained in Chapter 4 of the *Daily Manual* [4]. These parameters and related information are tabulated in Table 3.3. The lag parameters LAG and LAGF and attenuation parameters ATT and ATTF are calibrated based on observed flow changes between gaging stations for normal flows and high flows, respectively, and applied in the *SIMD* simulation routing algorithm for normal water right operations and flood control operations, respectively.

The routing parameters for 67 reaches contained on *RT* records in the DIF file for the 2019 daily Brazos WAM and tabulated in Table 3.3 are from calibration studies performed for 72 reaches of the Brazos River and its tributaries [22]. The calibration study resulted in ATT and ATTF values of 1.0 day for all of the 67 reaches. ATT and ATTF by definition cannot be less than 1.0 day and in general are expected to be 1.0 for many or most river reaches. The LAG and LAGF for each of the 67 selected reaches are tabulated in the fourth and fifth columns of Table 3.3.

The 67 river reaches with their upstream and downstream control points (USGS gage sites) are delineated in the map of Figure 3.1. Estimates of the approximate length of each reach is tabulated in the sixth column of Table 3.3. The normal lag LAG per mile (day/mile) is tabulated in the seventh column Table 3.3 and shown by color-code in Figure 3.1.

Table 3.3
Lag Parameters and Related Metrics

Upstream Control Point	Adjacent Downstream CP	Down-Stream CP	Normal LAG (days)	High Flow LAGF (days)	Reach Length (miles)	Normal Lag/mile (days/mile)	High Flow Lag/mile (days/mile)	Normal Travel Speed (miles/day)	High Flow Travel Speed (miles/day)
WRSP02	CON004	SFPE04	6.75	1.72	90	0.0750	0.0191	13.3	52.3
SFPE04	CON005	SFAS06	2.06	1.02	30	0.0687	0.0340	14.6	29.4
SFAS06	W12382	BRSE11	4.16	3.04	106	0.0392	0.0287	25.5	34.9
BRSE11	CON017	BRSB23	2.18	1.80	93	0.0234	0.0194	42.7	51.7
BRSB23	345301	SHGR26	3.25	3.22	65	0.0500	0.0495	20.0	20.2
SHGR26	399901	BRPP27	1.00	0.99	20	0.0500	0.0495	20.0	20.2
BRPP27	400001	BRDE29	2.01	1.84	79	0.0254	0.0233	39.3	42.9
BRDE29	404502	BRGR30	1.93	1.77	76	0.0254	0.0233	39.4	42.9
BRRI70	BRRI7A	BRRO72	0.92	0.92	36	0.0256	0.0256	39.1	39.1
BRGR30	CON063	BRAQ33	1.10	0.99	73	0.0151	0.0136	66.4	73.7
BRAQ33	432001	BRWA41	1.00	1.01	35	0.0286	0.0289	35.0	34.7
BRWA41	CON216	BRHB42	1.07	1.00	57	0.0188	0.0175	53.3	57.0
BRHB42	435902	BRBR59	1.81	1.00	67	0.0270	0.0149	37.0	67.0
BRBR59	CON122	BRHE68	1.98	1.00	86	0.0230	0.0116	43.4	86.0
BRHE68	CON150	BRRI70	2.62	2.62	104	0.0252	0.0252	39.7	39.7
BRRO72	532701	BRGM73	1.57	0.87	58	0.0271	0.0150	36.9	66.7
DUGI03	CON002	SFPE04	3.00	1.01	53	0.0566	0.0191	17.7	52.5
CRJA05	CON005	SFAS06	1.58	0.78	23	0.0687	0.0339	14.6	29.5
DMJU08	CON160	DMAS09	4.23	3.22	127	0.0333	0.0254	30.0	39.4
DMAS09	569204	BRSE11	3.12	3.00	113	0.0276	0.0265	36.2	37.7
BSLU07	370631	DMAS09	7.46	4.30	185	0.0403	0.0232	24.8	43.0
NCKN10	CON011	BRSE11	2.07	1.99	75	0.0276	0.0265	36.2	37.7
CFRO13	CON021	CFHA14	2.12	1.96	68	0.0312	0.0288	32.1	34.7
CFHA14	413302	CFNU16	1.98	1.10	20	0.0990	0.0550	10.1	18.2
CFNU16	CON026	CFFG18	2.92	1.89	95	0.0307	0.0199	32.5	50.3
CFFG18	418601	CFEL22	2.01	1.00	62	0.0324	0.0161	30.8	62.0
CFEL22	422504	BRSB23	1.05	1.05	15	0.0700	0.0700	14.3	14.3
CAST17	CON027	CFFG18	2.08	1.69	67	0.0310	0.0252	32.2	39.6
HCAL19	CON031	HCBR21	1.15	0.78	16	0.0719	0.0488	13.9	20.5
HCBR21	CON033	CFEL22	2.01	1.36	28	0.0718	0.0486	13.9	20.6
BSBR20	CON239	HCBR21	1.22	0.83	17	0.0718	0.0488	13.9	20.5
GHGH24	CON034	SHGR26	1.84	1.55	58.5	0.0315	0.0265	31.8	37.7
CCIV25	CON039	SHGR26	1.82	1.32	35	0.0520	0.0377	19.2	26.5
PPSA28	403803	BRDE29	1.96	1.96	33	0.0594	0.0594	16.8	16.8
PAGR31	574432	BRAQ33	1.12	1.00	74	0.0151	0.0135	66.1	74.0
NRBL32	W12271	BRAQ33	1.09	0.85	42	0.0260	0.0202	38.5	49.4
AQAQ34	433501	BRWA41	1.71	1.72	35	0.0489	0.0491	20.5	20.3
NBHI35	226101	NBCL36	4.28	3.92	51	0.0839	0.0769	11.9	13.0
NBCL36	229201	NBVM37	1.09	1.00	13	0.0838	0.0769	11.9	13.0
NBVM37	230000	BOWA40	2.35	2.15	28	0.0839	0.0768	11.9	13.0
BOWA40	231703	BRWA41	0.26	0.26	9	0.0289	0.0289	34.6	34.6
MBMG38	CON077	BOWA40	1.34	1.23	16	0.0838	0.0769	11.9	13.0
HGCR39	CON078	BOWA40	1.34	1.23	16	0.0838	0.0769	11.9	13.0
LEDL43	CON051	LEHS45	0.96	0.58	23	0.0417	0.0252	24.0	39.7
LEHS45	CON080	LEHM46	1.92	1.15	46	0.0417	0.0250	24.0	40.0
LEHM46	286202	LEGT47	1.95	1.78	76	0.0257	0.0234	39.0	42.7
LEGT47	290201	LEBE49	2.10	1.92	82	0.0256	0.0234	39.0	42.7
LEBE49	293901	LRLR53	0.91	1.12	19	0.0479	0.0589	20.9	17.0
LRLR53	409521	LRCA58	1.09	1.04	62	0.0176	0.0168	56.9	59.6

LRCA58	376301	BRBR59	1.21	1.25	66	0.0183	0.0189	54.5	52.8
SADL44	354401	LEHS45	0.67	0.40	16	0.0419	0.0250	23.9	40.0
COPI48	CON092	LEBE49	2.22	1.11	40	0.0555	0.0278	18.0	36.0
LAKE50	298802	LAYO51	2.00	1.00	36	0.0556	0.0278	18.0	36.0
LAYO51	300301	LABE52	1.28	0.64	23	0.0557	0.0278	18.0	35.9
LABE52	300701	LRLR53	1.25	1.25	20	0.0625	0.0625	16.0	16.0
GAGE56	373901	GALA57	1.19	1.00	32	0.0372	0.0313	26.9	32.0
GALA57	374905	LRCA58	1.96	1.16	38	0.0516	0.0305	19.4	32.8
MYDB60	CON124	YCSO62	3.76	3.76	33	0.1139	0.1139	8.8	8.8
EYDB61	CON124	YCSO62	3.19	3.19	28	0.1139	0.1139	8.8	8.8
YCSO62	CON123	BRHE68	2.58	2.06	67	0.0385	0.0307	26.0	32.5
DCLY63	CON123	BRHE68	3.12	2.62	74	0.0422	0.0354	23.7	28.2
NAGR64	528931	NAEA66	2.48	2.53	32	0.0775	0.0791	12.9	12.6
NAEA66	CON135	NABR67	2.79	2.85	36	0.0775	0.0792	12.9	12.6
NABR67	CON139	BRHE68	3.14	3.14	100	0.0314	0.0314	31.8	31.8
BGFR65	CON132	NAEA66	3.88	3.96	50	0.0776	0.0792	12.9	12.6
MCBL69	CON151	BRRI70	2.23	2.25	70	0.0319	0.0321	31.4	31.1
BGNE71	532601	BRRO72	2.48	2.53	32	0.0775	0.0791	12.9	12.6

Travel speeds (wave celerity) in miles/day corresponding to the lags are tabulated in Table 3.3 for general information. The travel speeds in Table 3.3 are computed by dividing reach length by lag time. Travel speeds provide insight on river flow characteristics and whether estimates of lag appear to be reasonably valid.

The following naming conventions for the six-character control point identifiers are employed in the Brazos WAM. For primary control points (Table 2.8), the identifiers consist of two letters denoting the river followed by two letters denoting the nearest town and two-digit integer sequenced in upstream-to-downstream order. Secondary control points have 6-digit integer identifiers, except for stream confluences which begin with CON followed by an integer.

The 67 reaches for which lag and attenuation parameters were calibrated are defined by the upstream and downstream control points listed in the first and third columns of Table 3.3, which are sites of USGS gaging stations and WAM primary control points. Multiple other control points are located within the reaches used for the parameter calibration. The routing computations occur at one selected control point within each of the calibration reaches. The control points listed in the second column are located immediately downstream of those listed in the first column and, with the three exceptions of MYDB60, EYDB61, and DCLY63, are adopted for the routing computations by entering the control point identifiers in field 2 of the *RT* records. Control points MYDB60, EYDB61, DCLY63 are adopted for routing control points on the *RT* records to better accommodate their different downstream stream reach configurations.

Selection of control points at which to apply the calibrated routing parameters is an significant issue. The *SIMD* input parameters LAG and LAGF are calibrated for the river reaches between the upstream and downstream control points (gaging stations) listed in the first and third columns of Table 3.3. The routing algorithm in *SIMD* performs computations at a specified control point to model the lag occurring between that control point and the adjacent control point located immediately downstream. The river reach for which the LAG and LAGF are applied is a sub-reach of the reach for which the LAG and LAGF are calibrated. Return flows occur at locations downstream of the corresponding streamflow depletions for water supply diversion rights.

Conceptually, perhaps the *SIMD* routing sub-reach should be near the center of the calibration reach but conceivably could be anyplace within the calibration reach. With the three previously noted exceptions (MYDB60, EYDB61, DCLY63), the upstream end of the routing reaches somewhat arbitrarily adopted on the *RT* records are the control points listed in the second column of Table 3.3. These are the control points located immediately downstream of the gage-site calibration control points listed in the first column of Table 3.3.

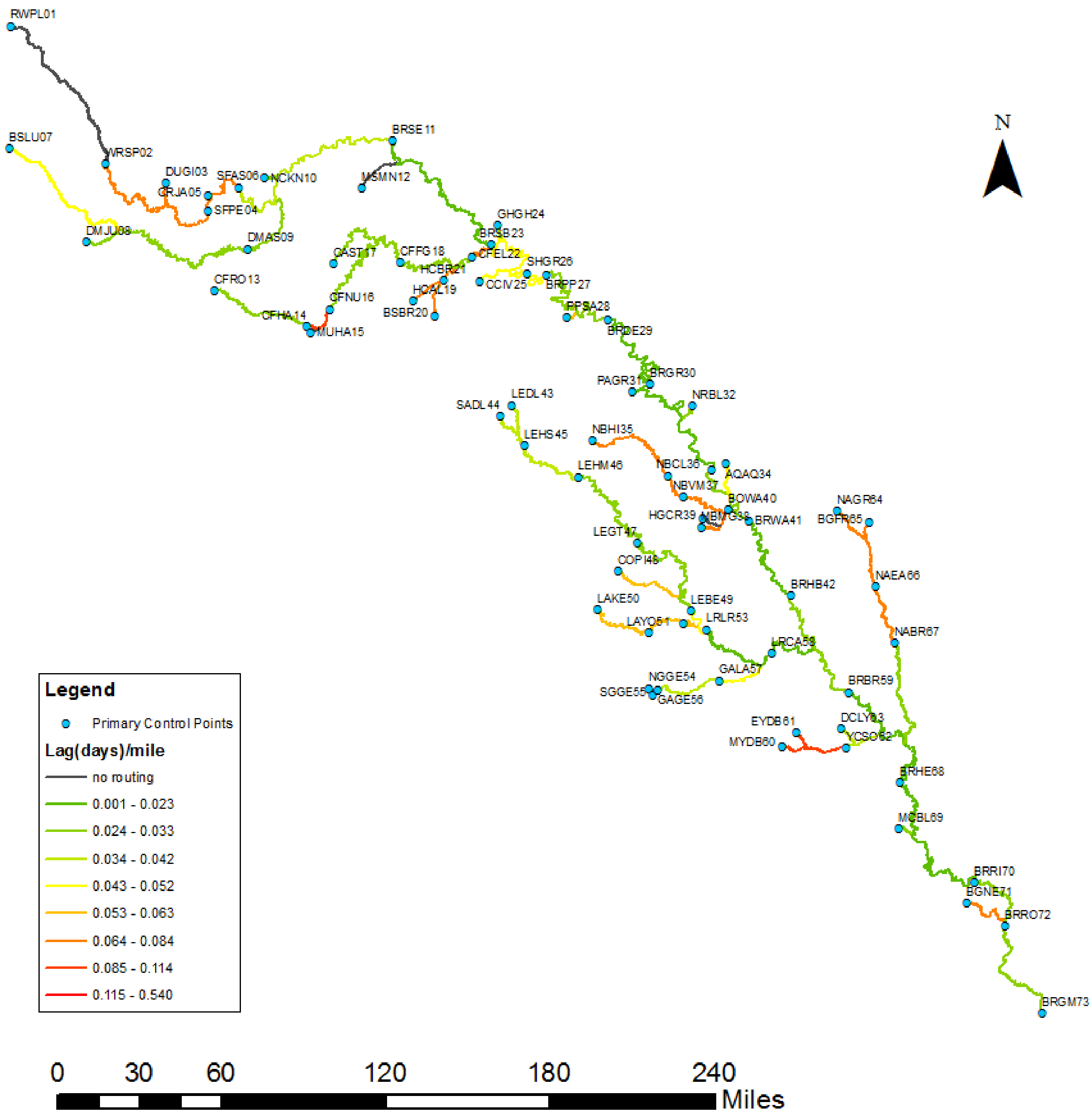

Figure 3.1 Lag in Days/Mile for River Reaches in Table 3.3 [22]

CHAPTER 4
SIMULATION OF RESERVOIR FLOOD CONTROL OPERATIONS

Converting the monthly Brazos WAM to daily allows incorporation of reservoir flood control operations. Relatively small computational time steps are required to accurately model reservoir operations during floods due to the great fluctuations in flow rates over short time spans that occur during flood events. A daily time step is adequate for modeling flood control operations of large river and reservoir systems such as the Brazos. Accurate modeling of small systems may require hourly or smaller time steps not available in *SIMD*. Operation of gate-controlled flood control pools based on flows at downstream gage sites is simulated with flood reservoir *FR* and flood flow *FF* records combined with use of *FV* and *FQ* records to model outlet structure outflow capacities. Operation of the flood control pools of the nine multiple-purpose reservoirs in the Brazos River Basin owned and operated by the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) is incorporated in the daily WAM as described in this chapter.

FV/FQ record reservoir storage volume versus outflow tables can also be used to model surcharge storage above the conservation pool of water supply reservoirs that have no designated flood control pool. However, this modeling strategy is not employed in the daily Brazos WAM. Information required to model outlet structure hydraulics is not readily available for the numerous water supply reservoirs that have no designated flood control pools.

Flood Control Reservoir Operations in the Brazos River Basin

The nine USACE multiple-purpose reservoirs in the Brazos River Basin that contain flood control pools are listed in Table 4.1 with their designated top of conservation and flood control pool elevations. Flood control storage capacity for these reservoirs is added to the conservation storage capacity in the Brazos WAM dataset. Of the 43 major reservoirs in the Brazos River Basin with storage capacities of 5,000 acre-feet or greater, the nine USACE FWD reservoirs are the only reservoirs with designated flood control pools. The nine USACE reservoirs are included in the 16 largest reservoirs in the basin shown on the map of Figure 2.2 on page 8. Storage capacities are tabulated in Tables 2.1 and 4.5 on pages 9 and 51.

USACE maximum allowable discharges for the Brazos River Basin can be found in a table at the website http://www.swf-wc.usace.army.mil/pertdata/BRAZOS.htm. Information from the website table is reproduced in Tables 4.2, 4.3, and 4.4. Maximum allowable discharge rates are specified at the dams and at USGS stream gaging stations located downstream of the dams. As long as the water surface elevation is below the top of flood control pool elevation, releases are made to empty flood control pools as expeditiously as feasible without contributing to flows exceeding the maximum allowable rates shown in the tables. If the flood control pool capacity is exceeded, emergency operations are activated to protect the dam following release rules that assure the designated maximum design water surface is never overtopped, even though the releases contribute to downstream flooding.

Whenever the actual water surface level is above the top of conservation pool elevation and below the top of flood control pool elevation in the reservoirs, operation is based on emptying the flood control pool as quickly as practical without contributing to downstream flooding based on the criteria in Tables 4.2, 4.3, and 4.4. The gage sites in Table 4.2 are below only Whitney, Waco, and/or Aquilla Reservoirs. Table 4.3 covers the Little River sub-basin. Table 4.4 includes USGS gaging stations that are located downstream of all nine reservoirs.

As an example of the operating criteria, referring to Tables 4.2 and 4.4, if the water surface in Whitney Reservoir is between 533.0 and 571.0 feet above mean sea level (within the flood control pool), releases through the overflow spillway and outlet conduits at Whitney Dam are made to draw the storage contents down to the top of conservation pool (elevation 533.0 feet) expeditiously, subject to making no release that would contribute to flow between Whitney Dam and the Brazos/Bosque River confluence exceeding 25,000 cfs or the flow at one or more of the USGS gages on the Brazos River at Waco, Bryan, Hempstead, and Richmond exceeding 60,000 cfs. As the water surface approaches the top of the flood control pool (elevation 571.0 feet msl), operations are switched to an emergency release strategy designed to assure that the maximum design water surface is never overtopped, though allowing downstream flow limits to be exceeded.

Table 4.1
Elevations Defining Reservoir Conservation and Flood Control Pools

Reservoir	Elevations in feet above mean sea level (msl)		
	Top of Conservation	Top of Flood Control	Top of Dam
Whitney	533.0	571.0	584.0
Aquilla	537.5	556.0	582.5
Waco	462.0	500.0	510.0
Proctor	1,162.0	1,197.0	1,205.0
Belton	594.0	631.0	662.0
Stillhouse Hollow	622.0	666.0	698.0
Georgetown	791.0	834.0	861.0
Granger	504.0	528.0	555.0
Somerville	238.0	258.0	280.0

Table 4.2
USACE Flood Control Operating Criteria for Brazos and Bosque Rivers and Aquilla Creek
(Reservoir Pool Elevations in feet above msl, River Flow Rates in cubic feet per second (cfs))

Reservoir	Reservoir Elevations	% Flood Storage	Maximum Release	Aquilla Creek	Brazos River to Bosque R	Bosque River Gage	Brazos River Gage at Waco
Whitney	533.0 - 571.0	0 – 100	–		25,000	–	60,000
Aquilla	537.5 - 556.0	0 – 100	–	3,000	25,000	–	60,000
	556.0 - 564.5	Surcharge	–	3,000	25,000	–	60,000
Waco	462.0 – 463.8	0 – 3	–	–	–	3,000	60,000
	463.8 – 466.1	3 – 7	–	–	–	5,000	60,000
	466.1 – 469.7	7 – 14	–	–	–	10,000	60,000
	469.7 - 474.0	14 – 23	–	–	–	20,000	60,000
	474.0 - 500.0	23 – 100	–	–	–	30,000	60,000

Table 4.3
USACE Flood Control Operating Criteria for Little River and Tributaries
(Reservoir Pool Elevations in feet above msl, River Flow Rates in cubic feet per second (cfs))

Reservoir	Elevations	% Flood Storage	Max Release	Leon River	Leon River	Little River	N. Fork S Gabriel	S. Fork S Gabriel	Little River	Yegua Creek
				Hasse	Gates ville	Little River	George town	Laneport	Came ron	
Proctor	1162.0-1197.0	0 – 100	–	2,000	5,000	–	–	–	–	
Belton	594.0 - 596.5	0 - 5	–	–	–	3,000	–	–	10,000	–
	596.5 - 10.0	5 - 35	–	–	–	6,000	–	–	10,000	–
	610.0 - 631.0	35-100	–	–	–	10,000	–	–	10,000	–
Stillhouse	622.0 - 625.0	0 - 5	–	–	–	3,000	–	–	10,000	–
Hollow	625.0 - 640.0	5 - 34	–	–	–	6,000	–	–	10,000	–
	640.0 - 666.0	34-100	–	–	–	10,000	–	–	10,000	–
Georgetown	791.0 – 797.5	0-10	1,500	–	–	–	6,000	6,000	10,000	–
	797.5 - 834.0	10-100	3,000	–	–	–	6,000	6,000	10,000	–
Granger	504.0 – 506.0	0 – 5.1	650	–	–	–	–	6,000	10,000	–
	506.0 - 518.0	5.1 - 47	3,000	–	–	–	–	6,000	10,000	–
	518.0 - 528.0	47-100	6,000	–	–	–	–	6,000	10,000	–
Somerville	238.0 - 243.0	0 - 18	–	–	–	–	–	–	–	1,000
	243.0 - 258.0	18-100	–	–	–	–	–	–	–	2,500

Table 4.4
USACE Flood Control Operating Criteria for Lower Brazos River
(Reservoir Pool Elevations in feet above msl, River Flow Rates in cubic feet per second (cfs))

Reservoirs	Reservoir Elevations	% Flood Storage	Brazos River Bryan	Brazos River Hempstead	Brazos River Richmond
Whitney	533.0 - 571.0	0 – 100	60,000	60,000	60,000
Aquilla	537.5 - 556.0	0 – 100	60,000	60,000	60,000
	556.0 - 564.5	Surcharge	60,000	60,000	60,000
Waco	455.0 - 500.0	0 – 100	60,000	60,000	60,000
Proctor	1,162.0 – 1,197.0	0 – 100	60,000	60,000	60,000
Belton	594.0 - 631.0	0 – 100	60,000	60,000	60,000
Stillhouse Hollow	622.0 - 666.0	0 – 100	60,000	60,000	60,000
Georgetown	791.0 - 834.0	0 – 100	60,000	60,000	60,000
Granger	504.0 - 528.0	0 – 100	60,000	60,000	60,000
Somerville	238.0 - 258.0	0 – 100	60,000	60,000	60000

Referring to Tables 4.3 and 4.4, with the water surface level in Belton Reservoir between 594.0 and 596.5 feet above msl (within bottom 5% of flood control pool), flood control operations are based on making no release that would contribute to flows exceeding 3,000 cfs at the USGS gage on the Little River near the town of Little River, 10,000 cfs at the USGS gage on the Little River near Cameron, or 60,000 cfs at the USGS gages on the Brazos River near Washington, Hempstead, or Richmond. The maximum allowable flows of the Little River near Little River guiding the operations of Proctor, Belton, and Stillhouse Hollow Reservoirs increase from 3,000 cfs to 6,000 cfs to 10,000 cfs with greater encroachment into the reservoir flood control pools. Releases from the flood control pools of Georgetown and Granger Reservoirs are constrained by maximum flow rates at the dam sites as well as at downstream gaging stations.

***SIMD* Capabilities for Simulating Reservoir Operations During Floods**

Flood control reservoir operations are treated as a type of water right in *SIMD*. Within WRAP, a water right is a set of water control requirements, reservoir facilities, and operating rules. Flood control rights are activated by *FR* records and are simulated along with all other *WR* and *IF* record water rights. The same reservoir may have any number of *WR* or *IF* record rights, with associated auxiliary records, and any number of *FR* record flood control rights.

The flood control reservoir *FR* record, flood flow *FF* record, and the volume and outflow *FV/FQ* record pair are the only *SIMD* input records specifically for flood control. These records are described in Chapter 4 of the *Users Manual* [2]. *FR* and *FF* records are used to model reservoir operations for flood control analogously to applying *WR*, *WS*, *OR*, and *IF* records to model operations for water supply, hydropower, and environmental instream flow requirements.

FV and *FQ* records can also be used to model the lag and attenuation effect of river flows through the outlet structures of a water supply reservoir with no flood control pool when the conservation pool is full to capacity and overflowing. The *FV/FQ* table of reservoir storage volume versus outflow represents the hydraulics of the outlet structures. The routing methodology based on parameters on *RT* records covered in the preceding Chapter 3 model the lag and attenuation (temporary storage) of flows through river reaches. Analogously, the *FV/FQ* record routing feature models flows over spillways and through outlet conduits of dams. Surcharge storage above the top of a full conservation pool occurs when reservoir inflow exceeds outflow due to limited spillway outflow capacity.

SIMD creates an optional output file with the filename extension AFF with annual series of peak flows and storages. The maximum naturalized flow, regulated flow, and storage volume are listed for each year of the simulation at specified control points. The *SIMD* AFF file is read by *TABLES* to perform flood frequency and damage analyses specified by a 7FFA record.

Reservoir Pools

In *SIMD*, a reservoir consists of any or all of the four pools shown in Figure 4.1. *SIM* includes only the bottom two pools. In either *SIM* or *SIMD*, inactive and conservation pool storage capacities are specified on storage *WS* records associated with water right *WR* records. *SIMD* allows controlled and uncontrolled flood control storage to be specified by *FR* records. A flood control pool defined by *FR* record fields 8 and 10 may include zones defined by *FR* record field 9 with outflows through either gated or ungated outlet structures. Pools governed by a gated structure in *SIMD* are referred to as controlled flood control pools. Pools governed by an ungated structure in *SIMD* are referred to as uncontrolled flood control pools.

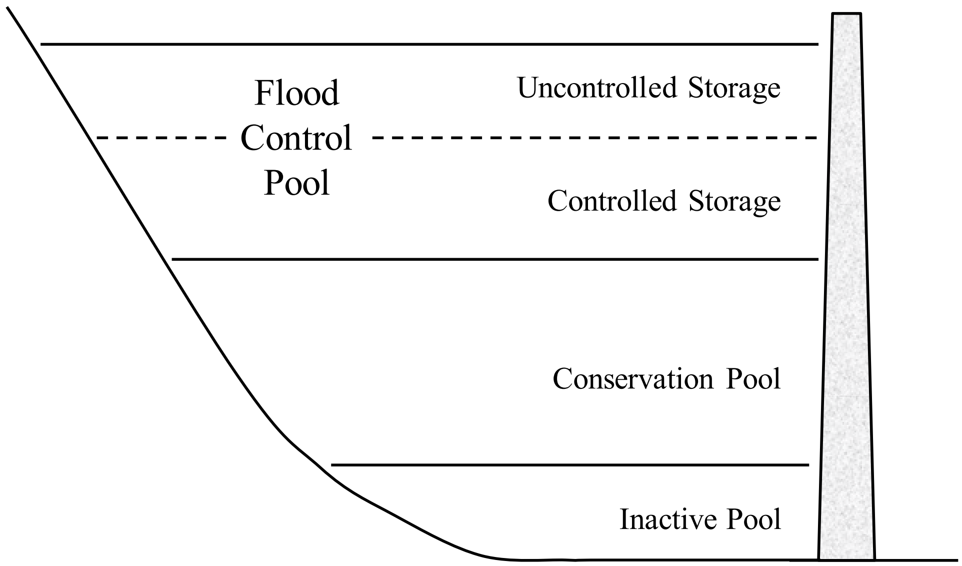

Figure 4.1 Reservoir Pools Defined by *SIMD WS* and *FR* Records

The division of the flood control pool between controlled and uncontrolled storage pools is defined by input parameter FCGATE in *FR* record field 9. Both portions of the flood control pool are optional. Releases from the lower controlled portion of the flood control pool are constrained by stream flow limits entered on *FF* records. Releases from the upper uncontrolled pool are defined completely by the *FV/FQ* record storage-outflow table.

Storage Capacities and Reservoir Outlet Gate Operations

Reservoir operations for either flood control or conservation storage purposes in *SIMD* consist of storing inflows and making releases. *WR* record rights fill storage to the top of the conservation pool only. *FR* record rights can fill storage to the top of the flood control pool. However, if the conservation pool is not full when a *FR* record stores inflows, the empty conservation space is filled as the storage level rises into the flood control pool. The optional *FR* record parameter *FCDEP* controls whether downstream control points are considered in computing the amount of stream flow available for filling flood control pools. With the default *FCDEP* option, the control point flow availability computation is applied in the conventional manner and all relevant downstream control points are considered. The alternative *FCDEP* option is to store all regulated flow at the control point of the dam with the exception of releases from conservation storage to downstream water rights. Releases from the controlled flood control pool are governed by operating rules defined by parameters entered on the *FR* and *FF* records.

Outlet Structure Capacities

FV/*FQ* record tables of reservoir storage volume versus outflow rates model the flow capacity of the outlet structures for fully-opened gates or a specified fixed gate opening. Outflow over spillway crests and through outlet conduits increase with increasing head as the reservoir water surface rises. For a *FR* record reservoir with both *FF* and *FV*/*FQ* records, releases each day are constrained to the lesser of: (1) the release specified by one or more *FF* records, (2) the release set by the *FV*/*FQ* records, or (3) the maximum release FCMAX entered in *FR* record field 7.

For reservoirs with designated flood control pools, uncontrolled outflows from surcharge storage above the top of flood control pool can be modeled with *FV* and *FQ* records. The same *FV* and *FQ* records can be used to model outlet structure outflow discharge capacities for storage levels above the top of conservation pool and below the top of flood control pool.

In the daily Brazos WAM, the modeling features activated by *FR*, *FF*, *FV*, and *FQ* records are applied only to flood control operations of the nine USACE reservoirs, which contain flood control pools. *FV*/*FQ* records model the outflow capacity of the outlet structures. The *SIMD* simulation sets outflow equal to inflow whenever storage exceeds the top of the flood control pool.

FR, *FV*, and *FQ* records (without *FF* records) can also be used to model surcharge storage above the top of conservation (water supply or hydropower) pool for reservoirs that contain no flood control storage capacity. Surcharge storage occurs when the conservation storage is full to capacity and stream inflows exceed the discharge capacity of the outlet structures as modeled by *FV/FQ* records. Surcharge storage may be negligible in a reservoir with a large gated overflow spillway with a crest elevation below the top of conservation pool. Development of a *FV/FQ* record storage-outflow tables requires information regarding the hydraulics of the overflow spillway and outlet conduit structures. Surcharge storage is not modeled in the daily Brazos WAM. *SIMD* sets outflow equal to inflow when storage contents exceed the conservation storage capacity.

Forecasting of Future Flows

The *SIMD* forecast simulation records downstream future water availability for use with curtailing current day water availability for *WR* record rights. The forecast simulation can also record future regulated flow in the absence of future depletions and releases from controlled flood control storage at the location of the *FF* record rights. Forecasted regulated flow at the location of the *FF* record rights is used in conjunction with the *FR* record operating rules to begin impounding stream flow in controlled flood control storage. Forecasting can also reduce the amount of water released from controlled flood control storage. Due to approximations related to forecasting and routing, water may be stored in greater quantities and longer than absolutely necessary. However, future days extending past the forecast period are not considered in reservoir operating decisions. Routed reservoir releases could contribute to flooding at downstream control points in future days after the end of the forecast period. Approximations related to imperfect forecasting and routing are an issue in modeling of reservoir operations as well as in actual real-world reservoir operations.

Brazos WAM Simulation of Reservoir Flood Control Operations

Flood control operations both in actual reality and in the *SIMD* simulation model are based on maintaining empty flood control pools in the nine USACE multiple-purpose reservoirs listed in Table 4.5 except during and immediately following flood events. The flood control pools are emptied as expeditiously as feasible without contributing to regulated flows exceeding the maximum allowable flows listed in Table 4.5 at the nine dams and the maximum flows in Table 4.6 at 13 downstream gaging stations. Releases from the flood control pools of some of the reservoirs are also constrained by outlet structure discharge capacities, with outflows increasing with storage levels. In some cases, more stringent flood flow limits at downstream gaging stations are applied for smaller encroachments into the reservoir flood control pools, with the maximum allowable flow limits increasing with higher flood pool levels.

Table 4.5
Flood Control Reservoirs Owned and Operated by the Corps of Engineers

Control Point	Reservoir	Stream	Drainage Area	Storage Capacity at Top of Conservation	Storage Capacity at Top of Flood Control	Max Flow Limit at Dam
			(sq mile)	(acre-feet)	(acre-feet)	(cfs)
515731	Whitney	Brazos River	17,690	636,100	1,999,500	25,000
515831	Aquilla	Aquilla Creek	254	52,400	146,000	3,000
509431	Waco	Bosque River	1,655	206,562	726,400	30,000
515931	Proctor	Leon River	1,280	59,400	374,200	2,000
516031	Belton	Leon River	3,568	457,600	1,097,600	10,000
516131	Stillhouse	Lampasas R.	1,313	235,700	630,400	10,000
516231	Georgetown	San Gabriel R.	247	37,100	130,800	3,000
516331	Granger	San Gabriel R.	726	65,500	244,000	6,000
516431	Somerville	Yegua Creek	1,008	160,110	507,400	2,500

Table 4.6
Maximum Allowable Flood Flow Limits at USGS Stream Gaging Stations

Control Point	Stream	Nearest Town	Drainage Area	Flood Flow Limit
			(sq miles)	(cfs)
BRWA41	Brazos River	Waco	20,065	60,000
BRBR59	Brazos River	Bryan	30,016	60,000
BRHE68	Brazos River	Hempstead	34,374	60,000
BRRI70	Brazos River	Richmond	35,454	60,000
AQAQ34	Aquilla Creek	Aquilla	307	3,000
BOWA40	Bosque River	Waco	1,660	3,000 to 30,000
LEHS45	Leon River	Hasse	1,283	2,000
LEGT47	Leon River	Gatesville	2,379	5,000
LRLR53	Little River	Little River	5,266	3,000 to 10,000
LRCA58	Little River	Cameron	7,100	10,000
NGGE54	North Fork San Gabriel	Georgetown	248	1,500 to 3,000
SGGE55	South Fork San Gabriel	Georgetown	132	650 to 6,000
YCSO62	Yequa Creek	Somerville	1,011	1,000 to 2,500

The total storage capacities below the top of conservation pool and below the top of flood control pool are shown in Table 4.5. The flow rates in the last column of Table 4.5 are maximum limits on releases from the flood control pools set based on outlet structure capacities and non-damaging channel flow capacities of the river reach immediately downstream of the dam. Maximum allowable flow limits at downstream gages are tabulated in Table 4.6. Flow limits at several gages vary with upstream reservoir storage contents. Reservoir operations in the *SIMD* simulation are based on making no releases from flood control pools that contribute to flows exceeding the flow limits shown in the last columns of Tables 4.5 and 4.6, which are replicated from the actual USACE operating criteria outlined in Tables 4.2, 4.3, and 4.4.

Regular and Emergency Operations

Whitney, Waco, and Proctor Reservoirs have gated spillways with crest elevations at the top of conservation pool and large release capacities. If the flood control storage capacity is not exceeded, reservoir releases from flood control pools are limited in the *SIMD* simulation solely by downstream flood flow limits, not outlet structure capacity. The other six reservoirs have ungated spillways with crest elevations at the top of flood control pool. Assuming the flood control storage capacity is not exceeded, releases from the flood control pool are made through a conduit through the dam. For these six dams with uncontrolled emergency spillways with crest elevations at the top of flood control pool rather than top of conservation pool, release capacities limited to flows through the conduits are much less than the large gated spillways at Whitney, Waco, and Proctor Reservoirs used for routine flood control operations.

The reservoirs are operated by the USACE Fort Worth District as a multiple reservoir system to reduce downstream flood flows. The operating objective is to empty the flood control pools as expeditiously as possible without making releases that contribute to river flows exceeding the allowable flow limits at the downstream sites shown in Tables 4.2, 4.3, and 4.4. Releases may also be constrained by the outlet structure (conduit) discharge capacities. Regular operations continue as long as flood control pool storage capacities are not exceeded.

During rare extreme flood events that exceed the flood control storage capacity, larger releases are based on protecting the dam from overtopping or otherwise structurally failing rather than the downstream allowable flood flow limits. The emergency operating plans can conceivably be modeled in *SIMD* with *FV* and *FQ* records based on information regarding the hydraulic characteristics of the outlet structures and the release rules that have been established. However, the emergency operating plans are not incorporated in the Brazos WAM. If the flood control pool is overtopped in the model, the excess flows pass through the reservoir without storage attenuation.

Multiple Reservoir System Operations

Flexible options for defining multiple-reservoir operating rules are provided in *SIMD* and explained in the *Daily Manual*. However, actual flood control operations necessarily depend somewhat on imprecise operator judgments that cannot be precisely modeled. In both real world operations and the simulation model, the balance of storage contents between reservoirs can vary significantly depending on choices regarding which reservoirs release at different times. The allocation of storage contents between the flood control pools of multiple-reservoir systems in both actual reality and *SIMD* simulation results can vary significantly with variations in specified operating rules, even though the alternative variations in operating rules may represent equally valid real world operating practices and operator judgments or modeling approximations thereof.

FR/FF record flood control operating decisions are based on the following criterion. Releases from a flood control pool are not allowed in any day of the simulation in which the allowable flow rate at the dam or one or more of the downstream gaging station control points equals or exceeds the allowable flow rate in that day or during the forecast period. Releases are made each day to empty or draw-down the flood control pool to the extent possible subject to the constraint of making no release that contributes to flows exceeding of the maximum flow limit at any control point during the current day or forecast period.

Storage and release priorities are entered on the *FR* record as two separate parameters. Priorities control the sequential order in which rights (sets of water control facilities and operating practices) are considered in the simulation computations in each day. The flood release priority for a particular reservoir is always junior to its flood storage priority. Multiple reservoirs with the same storage priorities or same release priorities are operated as a multiple-reservoir system based on balancing flood pool storage expressed as a percentage of capacity. If the percentage storage contents of the reservoirs are the same, the order of *FR* records in the DAT file controls.

Additions to the *SIMD* Input Dataset to Model Flood Control Operations

Flood control operations of the nine USACE reservoirs are incorporated into the daily *SIMD* input dataset developed in the preceding Chapter 3 as described in the present Chapter 4. The following additional information is added to the *SIMD* input files. With the exception of LAGF and ATTF on *RT* records in the DIF file, the additional input data are inserted in the DAT file.

- Two sets of lag (LAG and LAGF) and attenuation (ATT and ATTF) routing parameters are input on routing *RT* records in the DIF file as discussed in the preceding Chapter 3. The second set (LAGF and ATTF) are for routing releases from *FR* record flood control pools and reverse routing in determination of remaining flood flow channel capacity.
- *SV/SA* record reservoir storage volume versus area tables are extended to encompass the flood storage pools above the top of conservation pools if and as necessary.
- *FR* and *FF* records are added to model operation of the flood control pools of the nine USACE reservoirs based on flows at downstream gaging station. *WS* records are used with *FR* records to provide reservoir identifiers. Storage or drought index *DI/IS/IP* records are employed with a *FF* record to model the variation of flood flow limits with reservoir storage capacity. Any number of reservoirs can be operated based on flows at any number of downstream gages.
- *FV* and *FQ* records are employed to model outlet structure flow capacity and flow capacity of the stream reach below a dam that is relevant to single individual reservoirs rather than systems of two or more reservoirs.

With the exception of the flood routing parameters on the *RT* records in the DIF file, all of the additional *SIMD* input data compiled specifically to model flood control operations are contained in the DAT file. Routing parameters are described in Chapter 3, tabulated in Table 3.3, and stored on *RT* records in the DIF file. The routing parameters LAGF and ATTF are employed in the *SIMD* simulation to route releases from the flood control pools of *FR* record reservoirs and perform reverse routing in determining available channel capacity associated with *FF* record flow limits. The parameters LAG and ATT are applied for all other routed flow changes.

The *SV* and *SA* records storage volume versus surface area tables were extended to the top of flood control pool for Belton, Georgetown, and Granger Reservoirs. The original *SV* and *SA* records for the other six flood control reservoirs already covered their flood control pools. The parameter TL in *JD* record field 11 is increased to 13 to accommodate the *SV/SA* record extension.

Whitney and Waco Reservoirs are modeled in the original monthly WAM as well as the daily WAM as multiple-owner reservoirs represented in the WAM by multiple components. The entries of 2 and -1 for input parameters IEAR and SA in *WS* record fields 9 and 10 connects the flood control pool with the following *EA* records and corresponding *SV/SA* records. Component reservoirs WTNYFC and WACOFC are added to the *EA* records to model flood control pools.

```
EA     1       2  WHITNY     BRA  CORWHT  WTNYFC
EA     2       2  LKWACO   WACO2   WACO4   WACO5  WACOFC
```

Flood Reservoir *FR*, Flood Flow *FF*, and Volume/Outflow *FV/FQ* Records in the DAT File

Flood control pool operations for the nine federal reservoirs are modeled in *SIMD* with flood reservoir *FR*, flood flow *FF*, and reservoir volume-outflow *FV/FQ* records in accordance with the guidance provided in Chapter 5 of the *Daily Manual* and Chapter 4 of the *Users Manual*. The *SIMD* input records with information describing flood control operations are developed based on flood control operating rules and criteria followed by the USACE, flood control pool elevations, and available reservoir storage capacity and outlet capacity data. Operating rules are based on specified maximum allowable flow rates at the dams and downstream gaging stations. The reservoir flood control operation specifications tabulated in Tables 4.1, 4.2, 4.3, and 4.4 are adapted to *SIMD FR* and *FF* records. Flow forecasting is controlled by *JU* record parameters. Default *SIMD* computation of the flood control forecasting periods is adopted on the *FF* records.

SIMD provides considerable flexibility for modeling flood control operations. The actual USACE criteria for flood control operations outlined in Tables 4.1, 4.2, 4.3, and 4.4 provide a general framework that allows a significant degree of flexibility for operator judgement during flood events. Various alternative strategies for employing *FR*, *FF*, *FV*, *FQ*, and other auxiliary records for modeling the flood control operations were explored in the *SIMD* simulation study. The strategy finally adopted is outlined in the remainder of this chapter. The simulations discussed in Chapter 10 employ the input records described as follows in the present Chapter 5.

The *FR* and *WS* records incorporated in the daily Brazos WAM DAT file are replicated as Table 4.7. The *FF* records are presented in Table 4.8. The storage (drought) index referenced by the *FF* record for control point LRLC53 is shown in Table 4.9. The *FV* and *FQ* records are in Table 5.10. The remainder of this chapter explains how flood control operations are modeled in the *SIMD* simulation with these DAT file input records.

Information entered on *FR* records is tabulated in Tables 4.11 and 4.12. The *FR* records and *WS* records with the WAM reservoir identifiers for the nine reservoirs are replicated as Table 4.7. The total storage volumes at the top and bottom of the flood control pools (FCTOP and FCBOTTOM) tabulated in Table 4.11 are entered in *FR* record fields 8 and 9. The maximum allowable release rate FCMAX in cfs from the flood control, which is 25,000 cfs at Whitney Dam and 3,000 cfs at Aquilla Dam, is entered in *FR* record field 7. The control point identifiers are placed in *FR* record field 2. The gate closure and reservoir release priorities from Table 4.7 are entered in *FR* record fields 3 and 4. Optional water right identifiers for storing and releasing flood waters are found in the last two fields of the *FR* records.

The priorities adopted for storage and release operations of the multiple reservoir flood control pools are outlined in Table 4.12. The *FR* record flood control rights are assigned priorities junior to all other water rights. Downstream flood flow limit criteria can typically be satisfied by alternative allocations of storage contents between the different flood control pools. The storage and release priorities are designed to control these daily multiple-reservoir release decisions.

Table 4.7
FR and *WS* Records in the DAT File

```
**      1         2         3         4         5         6         7         8         9        10
**34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678
**     |       |       |       |       |       |       |       |       |       |               |
FR515731901000009098000   0   2  25000. 1363400       0       0               WTNYFC-FRSTOR   WTNYFC-FRREL
WSWTNYFC1363400.                                     -1       1      -1
FR509431902000009097000   0   2  30000.  519838     1.0       0               WACOFC-FRSTOR   WACOFC-FRREL
WSWACOFC 519838.                                     -1       2      -1
FR515831908000009091000   0   2   3000.  146000           52400               AQUILA-FRSTOR   AQUILA-FRREL
WSAQUILA
FR515931905000009094000   0   2   2000.  374200           59400               PRCTOR-FRSTOR   PRCTOR-FRREL
WSPRCTOR
FR516031904000009096000   0   2  10000. 1097600          457600               BELTON-FRSTOR   BELTON-FRREL
WSBELTON
FR516131904000009096000   0   2  10000.  630400          235700               STLHSE-FRSTOR   STLHSE-FRREL
WSSTLHSE
FR516231907000009092000   0   2   3000.  130800   37100   37100               GRGTWN-FRSTOR   GRGTWN-FRREL
WSGRGTWN
FR516331906000009093000   0   2   6000.  244000   65500   65500               GRNGER-FRSTOR   GRNGER-FRREL
WSGRNGER
FR516431903000009095000   0   2   2500.  507400  160110  160110               SMRVLE-FRSTOR   SMRVLE-FRREL
WSSMRVLE
```

Table 4.8
FF Records in the DAT File

```
FFLEHS45   2000.
FFLEGT47   5000.
FFLRLR53  10000.                 2
FFLRCA58  10000.
FFBRWA41  25000.
FFBRHE68  60000.
FFBRRI70  60000.
```

Table 4.9
DI/IS/IP Record Storage Indices Referenced by FF Record

```
DI      2       2  BELTON  STLHSE
IS      9      0. 393300. 393400. 745035. 745100. 1051498 1051600 1728000 2000000
IP             0.      0.     30.     30.     60.     60.    100.    100.    100.
**                     0%      0%      5%      5%  34/35%  34/35%    100%
```

Table 4.10
FV and *FQ* Records in the DAT File

```
** Georgetown       0%     10%     10%    100%
FVGRGTWN      0.  37100.  46470.  46500. 130800.
FQ            0.   1500.   1500.   3000.   3000.
** Granger          0%    5.1%    5.1%     47%     47%    100%
FVGRNGER      0.  65500. 74603.5  74700. 149395. 149500. 244000.
FQ            0.    650.    650.   3000.   3000.   6000.   6000.
** Somerville       0%     18%     18%    100%
FVSMRVLE      0. 160110. 222622. 222700. 507400.
FQ            0.   1000.   1000.   2500.   2500.
** Waco       0%      3%      3%      3%      7%      7%     14%     14%     23%     23%    100%
FVWACOFC      0.    100.  15595.  15600.  36389.  36400.  72777.  72800. 119563. 119600. 519838.
FQ            0.   3000.   3000.   5000.   5000.  10000.  10000.  20000.  20000.  30000.  30000.
```

Table 4.11
Flood Control Reservoir Operations Criteria on *FR* Records

Reservoir	Reservoir ID	Field 2 CP	Field 7 FCMAX	Field 8 FCTOP	Field 9 FCBOTTOM
			(ft^3/s)	(acre-feet)	(acre-feet)
Whitney	WTNYFC	515731	25,000	1,363,400	0
Belton	BELTON	516031	10,000	1,097,600	457,600
Waco	WACOFC	509431	30,000	519,838	0
Somerville	SMRVLE	516431	2,500	507,400	160,100
Stillhouse	STLHSE	516131	10,000	630,400	235,700
Proctor	PRCTOR	515931	2,000	374,200	59,400
Granger	GRNGER	516331	6,000	244,000	65,500
Georgetown	GRGTWN	516231	3,000	130,800	37,100
Aquilla	AQUILA	515831	3,000	146,000	52,400

Table 4.12
Flood Control Operation Priorities in *SIMD* Simulation

Reservoir	Flood Control Capacity	Gate Closure Priority	Release Priority
	(acre-feet)		
Whitney	1,363,400	90100000	90980000
Aquilla	93,600	90800000	90910000
Waco	519,840	90200000	90970000
Proctor	314,800	90500000	90940000
Belton	640,000	90400000	90960000
Stillhouse Hollow	394,700	90400000	90960000
Georgetown	93,700	90700000	90920000
Granger	178,500	90600000	90930000
Somerville	347,290	90300000	90950000

The priority numbers on *WR*, *IF*, and *FR* records control the sequencing of the water rights in the simulation computations. Simulations were performed to investigate alternative sets of flood storage and release priorities as well as variations of other aspects of the flood control operations. Adoption of the priorities in Table 4.12 is somewhat arbitrary but reasonable. Other variations are possible. The Table 4.12 priorities place flood control operations junior to all other water rights in the priority-based simulation. An alternative strategy explored but not adopted in Chapter 10 assigns the SB3 EFS instream flow rights priorities that are junior to flood control operations.

Altering the relative priorities of the *FR* record flood control pools can result in shifting storage contents between reservoirs. In the Table 4.12 priorities, the greatest reliance for storing flood waters is placed on Whitney Reservoir, which has the largest flood control storage capacity. The smaller reservoirs store later and release sooner in the priority computation sequence. Storage in Belton and Stillhouse Reservoirs is evenly balanced by assigning them the same priorities.

The maximum allowable non-damaging flood flow limits employed by the USACE are listed in Tables 4.2, 4.3, and 4.4, are summarized in Table 4.13, and are entered in field 3 of the *FR* records of Table 4.7 or as flow limits on the *FF* records of Table 4.8 or *FQ* records of Table 4.10. Flows are entered in cfs on the *FR*, *FF*, and *FQ* records. *SIMD* converts flow rate quantities in cfs to volumes in acre-feet for the simulation computations. The flows are converted between units in Table 4.13.

Table 4.13
Flood Control Operating Criteria on *FF* Records

Location	Reservoir or CP ID	Flood Flow Limit (ft^3/s)	Flood Flow Limit (ac-ft/day)	Flood Flow Limit (ac-ft/year)
Brazos River below Whitney Dam (*FR*)	WTNYFC	25,000	49,590	18,110,000
Brazos River at Waco (*FF* record)	BRWA41	60,000	119,010	43,470,000
Bosque River at Waco (*FV/FQ* records)	WACOFC	3,000	5,950	2,173,000
(Flow limits vary with storage in Waco		5,000	9,920	3,622,000
Reservoir)		10,000	19,830	7,245,000
		20,000	39,670	14,490,000
		30,000	59,500	21,730,000
Leon River at Hasse (*FF* record)	LEHS45	2,000	3,970	1,449,000
Leon River at Gatesville (*FF* record)	LEGT47	5,000	9,920	3,622,000
Little River at Little River (*FF* record)	LRLR53	3,000	5,950	2,173,000
(Flow limits vary with storage in	(*DI/IS/IP*)	6,000	11,900	4,347,000
Belton and Stillhouse Reservoirs)		10,000	19,830	7,245,000
Georgetown Dam (*FV/FQ* records)	GRGTWN	1,500	2,975	1,087,000
		3,000	5,950	2,173,000
Granger Dam (*FV/FQ* records)	GRNGER	650	1,290	470,900
		3,000	5,950	2,173,000
		6,000	11,900	4,347,000
North Fork San Gabriel River (not used)	SGGE55	6,000	11,900	4,347,000
San Gabriel River at Laneport (not used)	NGGE54	6,000	11,900	4,347,000
Little River at Cameron (*FF* record)	LRCA58	10,000	19,830	7,245,000
Yequa Creek below Somerville Dam	YCSO62	1,000	1,980	724,500
(*FV* and *FQ* records))		2,500	4,960	1,811,000
Brazos River at Bryan (not used)	BRBR59	60,000	119,010	43,470,000
Brazos River at Hempstead (*FF* record)	BRHE68	60,000	119,010	43,470,000
Brazos River at Richmond (*FF* record)	BRRI70	60,000	119,010	43,470,000

The maximum allowable flood flow limits at several USGS gaging stations (control points) vary depending on the storage contents of the reservoirs located upstream as outlined in Tables

4.2, 4.3, and 4.4. These relationships are tabulated in Table 4.14. The variation of the maximum flow limit at the gage on the Little River at Little River (control point LRLR53) with the storage contents of Belton and Stillhouse Reservoirs is modeled with the *FF* record for LRLR53 in Table 4.8 and the storage (drought) index of Table 4.9. The *FV* and *FQ* records in Table 4.10 model the other variations of flow limits with reservoir storage contents.

Table 4.14
Flood Flow Limits that Vary with Upstream Reservoir Storage Contents

1	2	3	4	5	6	7	8	9
Reservoir		Storage Volume in acre-feet				Total	Flow	Flow
or CP	Reservoir	Top of Con	Top of FC	FC	% of FC	Storage	Limit	Limit
					(%)	(acre-feet)	(cfs)	(%)
BOWA40	Waco	206,562	726,400	519,838	3	222,157	3,000	10
					7	242,951	5,000	16.667
					14	279,339	10,000	33.333
					23	326,125	20,000	66.667
					100	726,400	30,000	100.00
LRLR53	Belton	457,600	1,097,600	640,000	5	745,035	3,000	30.00
	Stillhouse	235,700	630,400	394,700	35&34	1,051,498	6,000	60.00
	Total	693,300	1,728,000	1,034,700	100	1,728,000	10,000	100.00
516231	Georgetown	37,100	130,800	93,700	10	46,470	1,500	50.00
					100	130,800	3,000	100.00
516331	Granger	65,500	244,000	178,500	5.1	74,605	650	10.833
					47	149,395	3,000	50.00
					100	244,000	6,000	100.00
YCSO62	Somerville	160,110	507,400	347,290	18	222,622	1,000	40.00
					100	507,400	2,500	100.00

Reservoir storage contents may be employed as an index of either drought severity or flood severity. Water right targets or, in the case of flood control operations, maximum allowable stream flow limits are allowed to vary as a function of reservoir storage contents. Storage index *DI* records and accompanying index storage *IS* and index percentages *IP* records are explained in Chapter 4 of the *Reference Manual* and Chapter 3 of the *Users Manual*. *DI/IS/IP* record indices, if used, are referenced by an integer identifier in *FF* record field 5 as noted in Chapter 4 of the *Users Manual*.

Pairs of FV/FQ records also allow stream flow limits to vary with reservoir storage contents. The *FV* and *FQ* records are designed for modeling either reservoir/dam outlet capacities and/or maximum allowable non-damaging flood flow limits for the stream reaches immediately below the dam as described in the *Daily Manual* and Chapter 4 of the *Users Manual*.

CHAPTER 5
INCORPORATION OF SENATE BILL 3
ENVIRONMENTAL FLOW STANDARDS

The following topics are covered in this chapter.

1. The environmental flow standards (EFS) at 19 gaging stations adopted by the TCEQ in 2014 pursuant to the 2007 Senate Bill 3 (SB3) are described.
2. Addition of the SB3 environmental flow standards to the daily Brazos WAM is explained.
3. A procedure is documented in which daily *IF* record instream flow targets for the SB3 environmental flow standards computed in a daily *SIMD* simulation are summed to monthly totals and incorporated in the monthly *SIM* input dataset for the Brazos WAM.

Senate Bill 3 (SB3) Environmental Flow Standards (EFS)

Senate Bill 3 (SB3) enacted by the 80th Texas Legislature in 2007 established a new regulatory approach to provide for environmental needs for certain stream flow conditions through the use of standards developed through a stakeholder process culminating in TCEQ rulemaking. Water right permits in effect prior to the effective date of September 1, 2007 are not impacted. Only new water rights and water right amendments that are submitted after this date are subject to the new requirements established pursuant to the 2007 Senate Bill 3 [16].

Information regarding SB3 environmental instream flow standards can be found at the following TCEQ website.

https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows

This website provides convenient access to the environmental flow standards (EFS) that have been adopted to date, which are published as Subchapters B through F of Chapter 298 of Title 30 of the Texas Administrative Code. Rules for the different river systems are published as individual subsections of Chapter 298. Modifications to these existing standards and establishment of standards for additional regions and river reaches are expected in the future. The EFS relevant to the Brazos WAM are found in "*Subsection G: Brazos River and its Associated Bay and Estuary System*" [23] which was adopted February 12, 2014 and became effective on March 6, 2014.

The expanded regulatory process created by Senate Bill 3 results in determination of environmental flow needs and establishment of set-asides to satisfy the environmental flow needs. *Set-asides* refer to commitment of previously unappropriated water in the TCEQ Water Availability Modeling (WAM) System to meet specified environmental flow standards. Environmental flow standards (requirements, needs, or targets) for particular locations in particular stream systems are defined in terms of flow regimes. Senate Bill 3 defines an environmental flow regime as: *A schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies.* Senate Bill 3 (SB3) environmental flow standards (EFS) are based on a flow regime that includes subsistence flows, base flows, within-bank high pulse flows, and overbank high pulse flows [16, 23, 24, 25, 26, 27].

The Brazos River Basin and Bay Expert Science Team (BBEST) submitted its Environmental Flow Regime Recommendation Report [24] to the Basin and Bay Area Stakeholders Committee (BBASC), Environmental Flows Advisory Group, and TCEQ in March 2012. The BBASC submitted its Environmental Flow Standards and Strategies Recommendation Report [25] to the TCEQ in August 2012. The BBASC recommended flow requirements are based upon but differ in some respects from the BBEST recommended flow regime and serve as a basis for the final EFS adopted on February 12, 2014 and published as Subchapter G of Chapter 298 of Title 30 of the Texas Administrative Code [23].

<u>SB3 Environmental Flow Standards (EFS) at 19 USGS Gaging Stations</u>

The geographic area covered by "*Subsection G: Brazos River and its Associated Bay and Estuary System*" of Chapter 298 of Title 30 of the Texas Administrative Code and preceding BBASC and BBEST reports consists of the entire Brazos Basin in Texas, the Oyster Creek and Austin Creek watersheds in the San Jacinto-Brazos coastal basin to the east, and the San Barnard River Basin which adjoins the lower Brazos Basin to the west. Environmental instream flow recommendations are developed at 19 stream gaging stations on the Brazos River and its tributaries and one gaging station on the San Bernard River. However, the Brazos WAM does not include the Bernard River, and thus the 20th site is not relevant to the Brazos WAM and this discussion.

The 19 USGS gaging stations in the Brazos River Basin at which SBS EFS have been established are listed in Table 5.1. Their locations are shown on the map of Figure 5.1. The USGS discontinued gage 08109000 on the Brazos River near Bryan in 1994, but gage 08108700 installed nearby allowed the two records to be combined to extend the period-of-record to the present.

Eighteen of the 19 sites recommended by the BBEST and BBASC are adopted in the final EFS listed in Table 5.1. These 18 USGS gaging stations that serve as EFS sites are primary control points in the Brazos WAM. The BBEST and BBASC recommendations include another EFS at gage 08085500 on the Clear Fork of the Brazos River near Fort Griffin (control point CFFG18) that was dropped and replaced with gage 08084200 on the Clear Fork of the Brazos River near Lueders in the final adopted EFS. The gage on the Clear Fork near Lueders has a period-of-record of October 2010 to present and is not included as a control point in the WAM. This EFS is assigned to control point CON023 in the daily WAM. Control point CON026 is the confluence of Deadman Creek with the Clear Fork of the Brazos River. The EFS site at gage 08084200 is located on the Clear Fork of the Brazos River a short distance downstream of the Deadman Creek confluence.

The Brazos and San Bernard Rivers do not have bays. Their estuaries are classified as riverine in contrast to the lagoon-type estuaries (shallow bays) that dominate the Texas coast. No additional environmental flow requirements have been recommended specifically for freshwater inflows to the estuaries.

The SB3 EFS are based on the natural flow regime paradigm adopted by the Texas Instream Flow Program that considers magnitude, frequency, duration, timing, and rate of change in flow within the framework of the following flow regime components: subsidence, base, within-bank high pulse, and overbank high pulse flows [26, 27]. Subsistence and base flow limits and high pulse flow metrics are tabulated in Tables 5.2 and 5.3. The WAMs do not distinguish between within-bank versus overbank high pulse flows. The Brazos EFS have no overbank pulse flows.

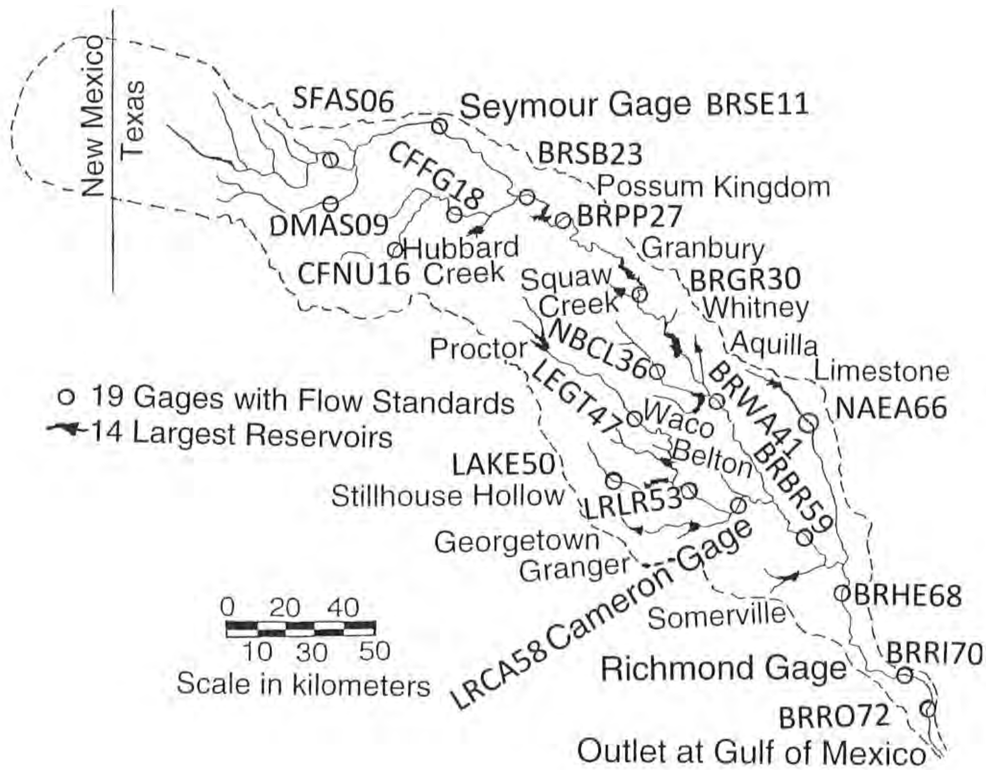

Figure 5.1 USGS Gage and WAM Control Point Locations for SB3 EFS

Table 5.1
Brazos WAM Control Point Locations for SB3 Environmental Flow Standards

WAM CP ID	Stream	Nearest City	USGS Gage No.	Watershed Area	Gage Period of Record
				(square miles)	
SFAS06	Salt Fork Brazos River	Aspermont	08082000	2,504	1924–present
DMAS09	Double Mountain Fork	Aspermont	08080500	1,891	1923–present
BRSE11	Brazos River	Seymour	08082500	5,996	1923–present
CFNU16	Clear Fork Brazos	Nugent	08084000	2,236	1924–present
CON026	Clear Fork Brazos	Lueders	08084200	2,542	2010–present
BRSB23	Brazos River	South Bend	08088000	13,171	1938–present
BRPP27	Brazos River	Palo Pinto	08089000	14,309	1924–present
BRGR30	Brazos River	Glen Rose	08091000	16,320	1923–present
NBCL36	North Bosque River	Clifton	08095000	977	1923–2008
BRWA41	Brazos River	Waco	08096500	20,065	1898–present
LEGT47	Leon River	Gatesville	08100500	2,379	1950–present
LAKE50	Lampasas River	Kempner	08103800	817	1962–present
LRLR53	Little River	Little River	08104500	5,266	1923–present
LRCA58	Little River	Cameron	08106500	7,100	1916–present
BRBR59	Brazos River	Bryan	08109000	30,016	1899–1993
NAEA66	Navasota River	Easterly	08110500	936	1924–present
BRHE68	Brazos River	Hempstead	08111500	34,374	1938–present
BRRI70	Brazos River	Richmond	08114000	35,454	1903–present
BRRO72	Brazos River	Rosharon	08116650	35,775	1967–present

Seasons and hydrologic conditions are defined as follows for the Brazos EFS. The year is divided into three seasons.

Winter:	November, December, January, February
Spring:	March, April, May, June
Summer:	July, August, September, October

Hydrologic conditions are based on the Palmer hydrologic drought index (PHDI).

low (dry) conditions:	PHDI within lowest 25% PHDI quartile
medium (average) conditions:	PDHI between 25th and 75th percentiles
high (wet) conditions:	PHDI within highest 75% PHDI quartile

Table 5.2
Subsistence and Base Flow Limits

Gage and Control Point	Subsist Flow (cfs)	Base Flow (cfs)								
		Winter			Spring			Summer		
		Dry	Avg	Wet	Dry	Avg	Wet	Dry	Avg	Wet
SFAS06	1	1	4	9	1	2	5	1	1	3
DMAS09	1	1	4	15	1	3	8	1	2	7
BRSE11	1	10	25	46	7	19	35	4	13	32
CFNU16	1	5	8	13	3	6	12	1	4	9
CON026	1	7	10	16	4	7	15	1	5	11
BRSB23	1	36	73	120	29	60	100	16	46	95
BRPP27	17	40	61	100	39	75	120	40	72	120
BRGR30	16	42	77	160	47	92	170	37	70	160
NBCL36	1	5	12	25	7	16	33	3	8	17
BRWA41	56	120	210	480	150	270	690	140	250	590
LEGT47	1	9	20	52	10	24	54	4	12	27
LAKE50	10	18	27	39	21	29	43	16	23	32
LRLR53	55	82	110	190	95	150	340	84	120	200
LRCA58	32	110	190	460	140	310	760	97	160	330
BRBR59	300	540	860	1,760	710	1,260	2,460	630	920	1,470
NAEA66	1	9	14	23	10	19	29	3	8	16
BRHE68	510	920	1,440	2,890	1,130	1,900	3,440	950	1,330	2,050
BRRI70	550	990	1,650	3,310	1,190	2,140	3,980	930	1,330	2,190
BRRO72	430	1,140	2,090	4,700	1,250	2,570	4,740	930	1,420	2,630

Water right permits for storing or diverting water issued or amended after the March 6, 2014 effective date of the EFS must contain provisions for protecting the EFS. The EFS published in Chapter 298 of Title 30 of the Texas Administrative Code with the metrics replicated here as Tables 5.2 and 5.3 are incorporated the daily Brazos WAM as described later in this chapter. The EFS adopted in the Texas Administrative Code [23] includes special conditions exempting permit holders with small diversions from the pulse flow components of the EFS. The exemptions are not included in the WAM. The BBASC [25] recommendations reflect significant changes to the pulse flow components of the BBEST recommended flow regimes [24]. The main change to the BBASC recommendations reflected in the final adopted EFS was removal of the EFS at the Fort Griffin gage on the Clear Fork of the Brazos River and addition of the EFS at the Lueders gage.

Table 5.3
High Flow Pulse Components of the Environmental Flow Standards

	Winter				Spring				Summer			
	Qp (cfs)	Freq	Vol (ac-ft)	Dur (days)	Qp (cfs)	Freq	Vol (ac-ft)	Dur (days)	Qp (cfs)	Freq	Vol (ac-ft)	Dur (days)
SFAS06	Salt Fork Brazos at Aspermont											
dry	–	–	–	–	160	1	720	10	140	1	560	8
average	–	–	–	–	160	2	720	10	140	2	560	8
wet	–	–	–	–	300	1	1,350	11	260	1	1,090	10
DMAS09	Double Mountain at Aspermont											
dry	–	–	–	–	280	1	1,270	10	230	1	990	9
average	–	–	–	–	280	2	1,270	10	230	2	990	9
wet	–	–	–	–	570	1	2,600	12	480	1	2,160	12
BRSE11	Brazos River at Seymour											
dry	–	–	–	–	560	1	2,960	10	370	1	1,870	8
average	–	–	–	–	560	2	2,960	10	370	2	1,870	8
wet	–	–	–	–	1,040	1	5,870	12	800	1	4,290	11
CFNU16	Clear Fork Brazos at Nugent											
dry	–	–	–	–	180	1	860	9	100	1	460	8
average	–	–	–	–	180	2	860	9	100	2	460	8
wet	26	1	160	9	590	1	2,800	12	390	1	1,890	12
CON026	Clear Fork Brazos at Lueders											
dry	–	–	–	–	18	1	74	2	18	1	74	2
average	–	–	–	–	37	2	148	2	37	2	148	2
wet	26	1	158	9	355	1	2,054	9	170	1	779	5
BRSB23	Brazos River at South Bend											
dry	–	–	–	–	1,260	1	7,280	10	580	1	3,140	8
average	–	–	–	–	1,260	2	7,280	10	580	2	3,140	8
wet	–	–	–	–	2,480	1	15,700	13	1,180	1	7,050	11
BRPP27	Brazos River at Palo Pinto											
dry	850	2	3,690	5	1,400	2	6,600	6	1,230	2	5,920	6
average	850	4	3,690	5	1,400	4	6,600	6	1,230	4	5,920	6
average	1,390	2	7,180	7	3,370	2	20,200	10	2,260	2	13,000	9
wet	850	4	3,690	5	1,400	4	6,600	6	1,230	4	5,920	6
wet	1,390	3	7,180	7	3,370	3	20,200	10	2,260	3	13,000	9
BRGR30	Brazos River at Glen Rose											
dry	930	2	5,400	8	2,350	2	14,300	10	1,320	2	7,830	8
average	930	4	5,400	8	2,350	4	14,300	10	1,320	4	5,920	6
average	1,700	2	10,800	10	6,480	2	46,700	14	3,090	2	21,200	12
wet	930	4	5,400	8	2,350	4	14,300	10	1,230	4	7,830	6
wet	1,700	3	10,800	10	6,480	3	46,700	14	3,090	2	21,200	12
NBCL36	North Bosque River at Clifton											
dry	–	–	–	–	710	1	3,490	12	–	–	–	–
average	–	–	–	–	710	3	3,490	12	–	–	–	–
wet	120	2	750	10	710	3	3,490	12	130	2	500	6
BRWA41	Brazos River at Waco											
dry	2,320	1	12,400	7	5,330	1	32,700	10	1,980	1	10,500	7
average	2,320	3	12,400	7	5,330	3	32,700	10	1,980	3	10,500	7
wet	4,180	2	25,700	9	13,600	2	102,000	14	4,160	2	26,400	10

Continued on next page.

Table 5.3 Continued
High Flow Pulse Components of the Environmental Flow Standards

	Winter				Spring				Summer			
	Qp (cfs)	Freq	Vol (ac-ft)	Dur (days)	Qp (cfs)	Freq	Vol (ac-ft)	Dur (days)	Qp (cfs)	Freq	Vol (ac-ft)	Dur (days)
LEGT47	Leon River at Gatesville											
dry	–	–	–	–	340	1	1,910	10	58	1	220	4
average	–	–	–	–	340	3	1,910	10	58	3	220	4
wet	100	2	540	6	630	2	4,050	13	140	2	600	6
LAKE50	Lampasas River at Kempner											
dry	78	1	430	8	780	1	4,020	13	77	1	270	4
average	78	3	430	8	780	3	4,020	13	77	3	270	4
wet	190	2	1,150	11	1,310	2	6,860	16	190	2	680	6
LRLR53	Little River at Little River											
dry	520	1	2,350	5	1,420	1	9,760	10	430	1	1,560	4
average	520	3	2,350	5	1,420	3	9,760	10	430	3	1,560	4
wet	1,600	2	11,800	11	3,290	2	32,200	17	1,060	2	5,890	8
LRCA58	Little River at Cameron											
dry	1,080	1	6,680	8	3,200	1	23,900	12	560	1	2,860	6
average	1,080	3	6,680	8	3,200	3	23,900	12	560	3	2,860	6
wet	2,140	2	14,900	10	4,790	2	38,400	14	990	2	5,550	8
BRBR59	Brazos River at Bryan											
dry	3,230	1	21,100	7	6,050	1	49,000	11	2,060	1	12,700	7
average	3,230	3	21,100	7	6,050	3	49,000	11	2,060	3	12,700	7
wet	5,570	2	41,900	10	10,400	2	97,000	14	2,990	2	20,100	8
NAEA66	Navasota River at Easterly											
dry	260	1	1,610	9	720	1	4,590	11	–	–	–	–
average	260	3	1,610	9	720	3	4,590	11	–	–	–	–
wet	800	2	5,440	12	1,340	2	8,990	13	49	2	220	5
BRHE66	Brazos River at Hempstead											
dry	5,720	1	49,800	10	8,530	1	85,000	13	2,620	1	17,000	7
average	5,720	3	49,800	10	8,530	3	85,000	13	2,620	3	17,000	7
wet	11,200	2	125,000	15	16,800	2	219,000	19	5,090	2	40,900	9
BRRI70	Brazos River at Richmond											
dry	6,410	1	60,600	11	8,930	1	94,000	13	2,460	1	16,400	6
average	6,410	3	60,600	11	8,930	3	94,000	13	2,460	3	16,400	6
wet	12,400	2	150,000	16	16,300	2	215,000	19	5,430	2	46,300	10
BRRO72	Brazos River at Rosharon											
dry	9,090	1	94,700	12	6,580	1	58,500	10	2,490	1	14,900	6
average	9,090	3	94,700	12	6,580	3	58,500	10	2,490	3	14,900	6
wet	13,600	2	168,000	16	14,200	2	184,000	18	4,980	2	39,100	9

Instream Flow Target Based on Subsistence and Base Flow Requirements

Subsistence flow and base flow limits are tabulated in Table 5.2. The subsistence flow limit in the second column is a constant for each site. The base flow limits are functions of season and hydrologic condition. The three seasons of the year are defined as follows: Winter (November through February), Spring (March through June), Summer (July through October). As discussed later, hydrologic conditions are defined as low (dry), medium (normal), or high (wet) based on Palmer hydrologic drought index (PHDI) quartiles (lowest 25%, 25% to 50%, and highest 25%).

The subsistence and base flow limits are applied differently for dry hydrologic conditions than for average and wet hydrologic conditions. A 50% rule is applied if the hydrologic condition is dry as measured by the PHDI being in the lowest quartile. A target for a particular day at a particular location is set based on subsistence and base flow requirements as follows.

- Under average or wet hydrologic conditions, the instream flow target is equal to the base flow limit in Table 5.2 which varies between the three seasons of the year.
- Under dry hydrologic conditions:
  1. If the flow in that day is less than the subsistence flow limit in Table 5.2, then the instream flow target is set equal to the subsistence flow limit.
  2. If the flow equals or exceeds the subsistence flow limit but is less than the base flow limit in Table 5.2, then the instream flow target is equal to the subsistence flow limit plus 50 percent of the difference between the actual flow and the subsistence flow limit.

<u>Instream Flow Target Based on High Flow Pulse Requirements</u>

The quantities used to set high flow pulse targets are tabulated in Table 5.3. A qualifying pulse event is initiated when the flow exceeds the prescribed peak trigger flow (Qp) tabulated in Table 5.3 in units of cubic feet per second (cfs). A pulse flow event is terminated when either the volume limit (*Vol* in acre-feet in Table 5.3) or the duration limit (*Dur* in days in Table 5.3) is reached. Pulse flow events initiated in a particular season or year continue into the following season or year if and as necessary to meet the volume and/or duration termination criteria.

Pulse flow events are tracked in the WRAP/WAM modeling system to set minimum instream flow targets for each day of the tracked flow event. The daily pulse flow target is computed as the lesser of the (1) daily regulated flow, (2) peak trigger volume Q_P tabulated in Table 5.3, or (3) remaining volume that will satisfy the volume criterion. The daily minimum instream flow target is the greater of the subsistence and base flow target and high pulse target.

The metrics in Table 5.3 used in defining high flow pulse events are defined as follows.

Q_P − The trigger flow rates Q_P for high pulse events were originally established as the peak daily flow rates associated with specified annual exceedance frequencies. Tracking of a pulse flow event is initiated in the day in which the flow rate exceeds the Q_P. For a tracked flow pulse, the instream flow target for each day is the minimum of Q_P, the actual flow rate, or the remaining volume required to meet the volume criterion.

Freq − The frequency (Freq) is the target number of pulse events with the specified metrics to initiate, track, and preserve in the specified season.

Volume − The summation of the daily flow volumes from the day in which tracking of a pulse event begins through the current day serves as one of the criteria for terminating the tracking of a pulse event. Accumulated flow volume is in acre-feet

Duration − The prescribed pulse duration in days in Table 5.3 also serves as a criterion for terminating the tracking of a high flow pulse event.

A pulse event is initiated when the flow exceeds its Q_P, which is tabulated in Table 5.3. During the tracking of this pulse event, flows may increase to a magnitude that exceeds the greater Q_P of a larger pulse in Table 5.3. In this case, the parameters of the higher flow pulse take control of the continued tracking. The higher magnitude pulse event is considered to satisfy any and all lower magnitude events in the same season.

An accounting is maintained of the number of pulse flow events that satisfy the prescribed criteria outlined in Table 5.3. Pulses are used to set instream flow targets only to the extent necessary to satisfy the frequency criteria in Table 5.3. For example, after two pulses that satisfy the two-per-season event criteria are activated for use in target setting, additional pulses occurring in that season are not employed to satisfy that two-per-season frequency criterion.

In general, pulse-based target-setting procedures are the same for both within-bank and overbank flows. However, the EFS metrics in Table 5.3 represent only in-bank pulse flow requirements. The final Brazos EFS adopted by the TCEQ include no over-bank pulse flows.

Hydrologic Conditions Defined by Palmer Hydrologic Drought Index (PHDI)

Different alternative mechanisms for defining hydrologic conditions have been adopted by the science teams, stakeholder committees, and TCEQ for the Senate Bill 3 (SB3) environmental flow standards (EFS) for the different river systems [1]. The Brazos is the only river system to date for which the Palmer hydrological drought index (PHDI) has been adopted for SB3 EFS. Hydrologic conditions for the EFS for the other river systems are defined based on preceding reservoir storage levels or preceding 12-month stream flow.

Hydrologic conditions are defined in the daily Brazos WAM by hydrologic indices recorded on three hydrologic index *HI* records in the hydrology input DSS file representing three regions (watersheds) of the Brazos River Basin: Upper Basin above Possum Kingdom Dam, Lower Basin below Whitney Dam, and Middle Basin between Possum Kingdom Dam and Whitney Dam. Each *HI* record contains a monthly 1940-2017 (936 months) sequence of numbers that are either 1, 2, or 3 signifying dry (1), average (2), or wet (3) conditions in the lower, middle, and upper Brazos River Basin. The hydrologic conditions are defined based on the PHDI.

1. low (dry) conditions	PHDI within lowest 25% PHDI quartile
2. medium (average) conditions	PDHI between 25th and 75th percentiles
3. high (wet) conditions	PHDI within highest 75% PHDI quartile

The control point identifier UPPER, MIDDLE, or LOWER is entered for CPHC in field 2 of each hydrologic condition *HC* record to reference the relevant *HI* record in the DSS file. Three control point *CP* records are inserted in the DAT file to define these identifiers. The only entries on these three *CP* records are the identifiers UPPER, MIDDLE, and LOWER.

Palmer Hydrologic Drought Index (PHDI) for Upper, Middle, and Lower Brazos Basin

The National Weather Service (NWS) has compiled monthly PDHI values for each month since January 1895 for the ten climatic divisions of Texas listed in Table 5.4. The monthly PDHI are updated regularly. PHDI data and related information are available at the following websites.

http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/

https://www.drought.gov/drought/data-gallery/climate-division-datasets-nclimdiv

The PHDI is different than the Palmer drought severity index, and there are alternative variations in the details of defining and applying the PHDI. The PHDI uses an arbitrary scale from -6.0 to +6.0 that represents the severity of long-term drought conditions from extremely dry to extremely wet. The National Weather Service uses the following terms to describe conditions represented by ranges of PHDI: extreme drought (−4.00 and below), severe drought (−3.00 to −3.99), moderate drought (−2.00 to −2.99), mid-range (−1.99 to 1.99), moderately moist (2.00 to 2.99), very moist (3.00 to 3.99), and extremely moist (4.00 and above).

The PHDI for the lower (watershed below Whitney Dam), middle (between Whitney and PK), and upper (watershed above Possum Kingdom) Brazos River Basin have been computed as area-weighted averages of monthly PHDI quantities published by the NWS for the ten climatic regions of Texas. The area weighting factors (area percentages) noted in the Brazos EFS chapter of the Texas Administrative Code [23] and employed in the computations discussed here are listed in Table 5.4.

Table 5.4
Percentage of Climatic Division Comprising Upper, Middle, and Lower Basin [23]

NWS Zone Identifier	Climatic Region	Percentage in Each Zone		
		Upper Basin	Middle Basin	Lower Basin
4101	High Plains	2.7%	–	–
4102	Low Rolling Plains	64.7%	–	–
4103	North Central	32.6%	100%	61.9%
4104	East Texas	–	–	14.7%
4105	Trans Pecos	–	–	
4106	Edwards Plateau	–	–	5.7%
4107	South Central	–	–	13.2%
4108	Upper Basin	–	–	4.5%
4109	Southern	–	–	–
4110	Lower Valley	–	–	–
	Total	100.0%	100.0%	100.0%

The original version of the EFS recommended by the Expert Science Team (BBEST) Report [24] included area-weighted PDHI sequences for each of the 20 individual EFS gage sites. The final EFS published in the Texas Administrative Code [23] are simplified by assigning each of the 20 EFS gage sites to either the upper, middle, or lower basin. The 1895-2010 monthly PHDI sequences for the ten climatic regions were compiled in conjunction with the original BBEST Recommendations Report [24]. The 1895-2017 monthly PHDI series for the ten climatic regions were compiled again in conjunction with developing the May 2019 daily Brazos WAM, and the 1940-2017 area-weighted PHDI series for the upper, middle, and lower basin were recomputed.

The 1895-2017 monthly PHDI series for the upper, middle, and lower Brazos River Basin are plotted in Figure 5.2 using HEC-DSSVue. The exceedance frequency statistics of Table 5.5 were developed using the Tools/Math Functions/Statistics/Duration feature of HEC-DSSVue. The frequency statistics in Table 5.5 are repeated for periods-of-analysis of 1895-2010 and 1895-2017. A 1985-2010 period-of-analysis was employed by the Expert Science Team, Stakeholder Committee, and TCEQ in creating the EFS. The 25% and 75% exceedance frequencies used to define the EFS hydrologic conditions are highlighted in bold font in Table 5.5.

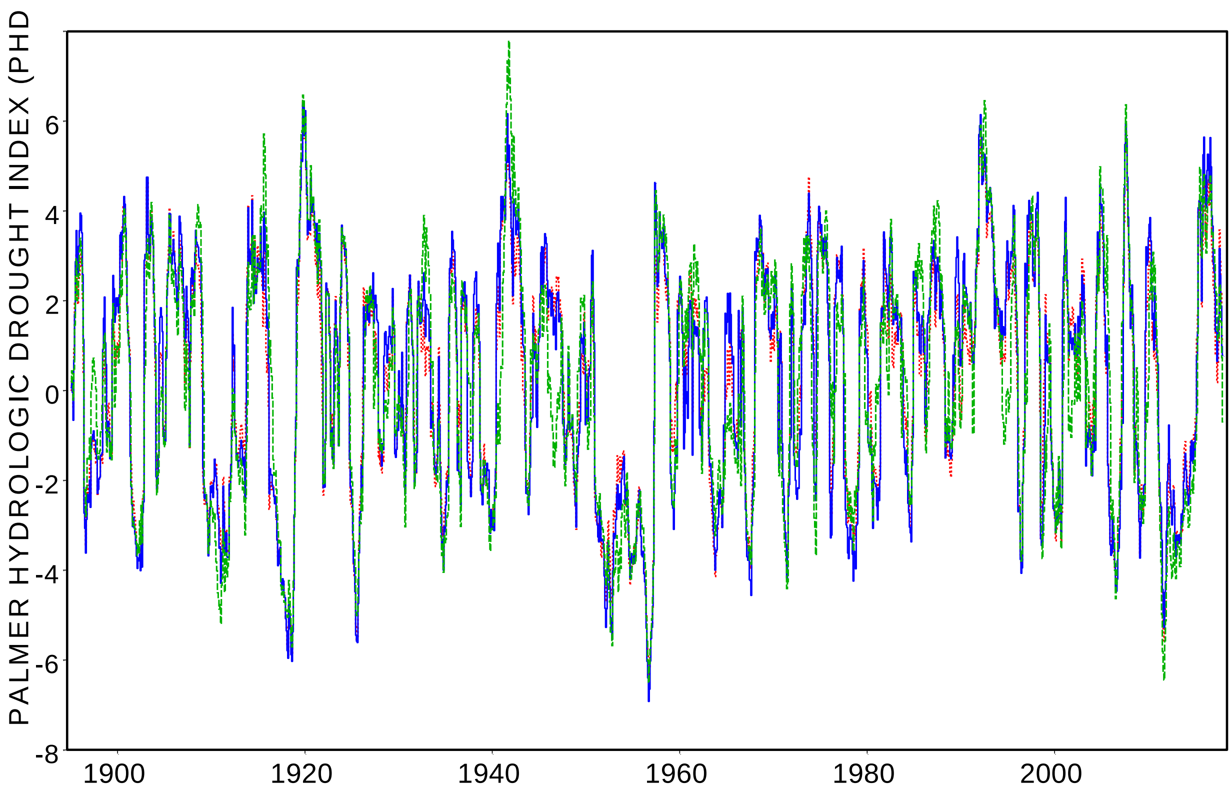

Figure 5.2 January 1895 through December 2017 Monthly PHDI for Upper (green dashed), Lower (red dotted line), and Middle (blue solid line) Brazos River Basin

Hydrologic Conditions as Defined for the SB3 Environmental Flow Standards

Hydrologic index *HI* records stored in a *SIM*/*SIMD* hydrology input DSS file (or HIS file) are designed for using the PHDI, or other indices, or parameters derived from these indices, in modeling instream flow requirements. The *HI* records in the Brazos WAM contain a hydrologic condition parameter with values of 1, 2, or 3 indicating dry, average, or wet hydrologic conditions for each month for the lower, middle, or upper basin. Each of the 19 SB3 EFS gage sites are located in either the upper, middle, or lower basin. PHDI quantities falling into the lower or upper quartiles of the PHDI values are assigned a monthly *HI* record input value of 1 or 3, respectively. The remaining data falling within the range of the middle two quartiles are assigned a value of 2. The hydrologic index *HI* records in the hydrology input DSS file are referenced by hydrologic condition *HC* records included in the sets of DAT file records that define the instream flow *IF* record water rights that model the SB3 environmental flow standards (EFS). The hydrologic condition indices (1, 2, or 3) on the *HI* records are plotted in Figure 5.3 using HEC-DSSVue.

Table 5.5
PHDI Frequency Statistics

Exceedance Frequency	1895-2010 Lower	1895-2010 Middle	1895-2010 Upper	1895-2017 Lower	1895-2017 Middle	1895-2017 Upper
0.100	6.3789	6.3843	7.6100	6.3706	6.3809	7.5719
0.200	6.1665	6.2578	7.0334	6.1339	6.2360	6.9689
0.500	5.6126	5.9014	6.4521	5.5174	5.8230	6.4488
1.000	5.1165	5.2740	5.9167	5.1128	5.4646	5.8104
2.000	4.5362	4.6784	5.1874	4.5885	4.7684	5.0120
5.000	3.7352	3.9700	4.1024	3.8486	4.0700	4.1318
10.000	3.1860	3.4700	3.4222	3.2160	3.5030	3.4444
15.000	2.7892	3.0705	2.9045	2.8299	3.1000	2.9670
20.000	2.5088	2.7200	2.5097	2.5237	2.7260	2.5541
25.000	**2.1273**	**2.3900**	**2.1807**	**2.1293**	**2.3900**	**2.2064**
30.000	1.8952	2.0900	1.9514	1.8849	2.0800	1.9587
40.000	1.3126	1.5880	1.2677	1.2960	1.5700	1.2448
50.000	0.6515	1.0200	0.2765	0.5854	0.9400	0.2326
60.000	-0.3841	-0.8180	-0.6259	-0.5552	-0.8800	-0.7323
70.000	-1.3863	-1.6110	-1.3617	-1.4474	-1.6600	-1.5179
75.000	**-1.7379**	**-1.9575**	**-1.7811**	**-1.8655**	**-2.0475**	**-1.9331**
80.000	-2.1417	-2.3040	-2.2086	-2.2332	-2.3360	-2.3368
85.000	-2.5719	-2.7200	-2.6278	-2.6553	-2.7500	-2.7634
90.000	-3.0841	-3.2870	-3.1174	-3.1378	-3.3030	-3.2738
95.000	-3.6965	-3.8335	-3.8849	-3.7088	-3.8415	-3.9742
98.000	-4.5185	-4.7742	-4.7078	-4.6825	-4.7838	-4.8762
99.000	-5.2760	-5.4549	-5.0888	-5.3040	-5.3884	-5.3415
99.500	-5.7178	-5.9621	-5.5708	-5.7009	-5.9292	-5.7412
99.800	-5.9540	-6.4535	-6.0360	-5.9036	-6.4115	-6.3100
99.900	-6.3065	-6.8139	-6.3495	-6.2904	-6.7912	-6.4784

Table 5.6
Official PHDI Ranges Defining Dry, Average, and Wet Hydrologic Conditions [23]

Geographic Area	Dry	Average	Wet
Upper Basin	less than −1.78	−1.78 to 2.18	greater than 2.18
Middle Basin	less than −1.95	−1.95 to 2.39	greater than 2.39
Lower Basin	less than −1.73	−1.73 to 2.13	greater than 2.13

The quartile quantities in Table 5.6 copied from the Brazos EFS chapter of the Texas Administrative Code can be compared with the statistics in Table 5.5 computed in conjunction with developing the May 2019 daily Brazos WAM. The official quantities shown in Table 5.6 were actually used in developing the *HI* record indices for the May 2019 daily Brazos WAM.

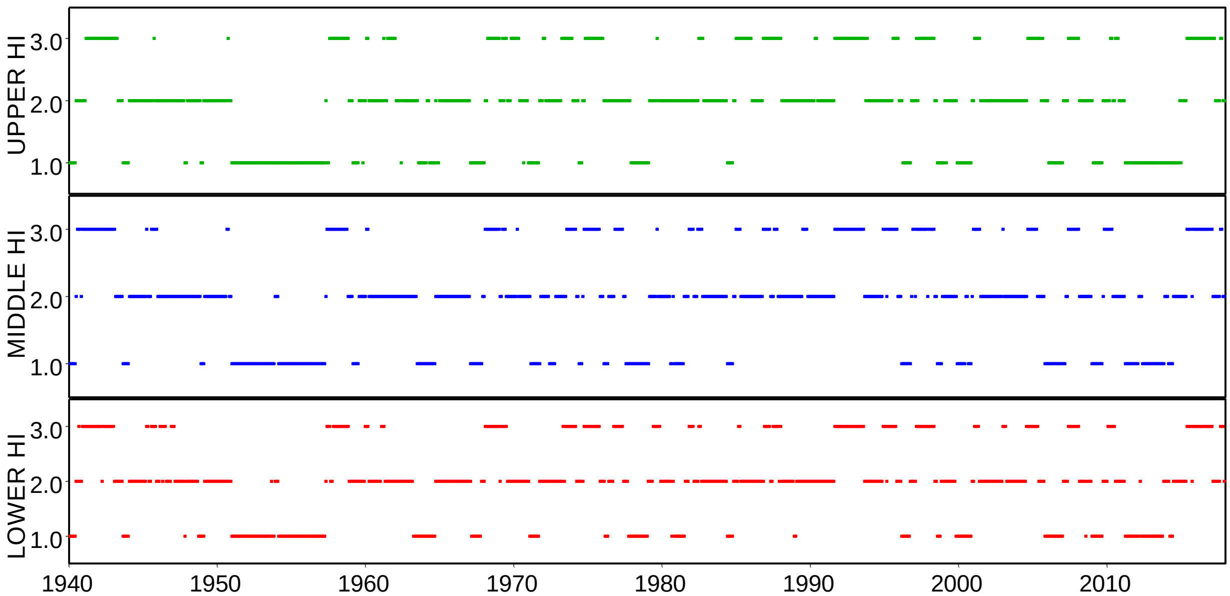

Figure 5.3 January 1940 through December 2017 Monthly *HI* Record Hydrologic Index Series for Upper, Middle, and Lower Brazos River Basin

Datasets Stored in the File BrazosPHDI.DSS

In addition to the Brazos WAM input files, Table 1.2 in Chapter 1 lists four other DSS files compiled for use in exploring river system hydrology in general as well as supporting development and future updates of the WAM input files. The organization of these supplemental DSS files are summarized in Chapter 9. The file BrazosPHDI.DSS contains the records listed in Table 5.7.

Table 5.7
DSS Pathnames for the File BrazosPHDI.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	PHDI	ZONE 4101	PHDI	31JAN1895-31DEC2017	1MON	HIGH PLAINS
2	PHDI	ZONE 4102	PHDI	31JAN1895-31DEC2017	1MON	LOW ROLLING PLAINS
3	PHDI	ZONE 4103	PHDI	31JAN1895-31DEC2017	1MON	NORTH CENTRAL
4	PHDI	ZONE 4104	PHDI	31JAN1895-31DEC2017	1MON	EAST TEXAS
5	PHDI	ZONE 4105	PHDI	31JAN1895-31DEC2017	1MON	TRANS PECOS
6	PHDI	ZONE 4106	PHDI	31JAN1895-31DEC2017	1MON	EDWARDS PLATEAU
7	PHDI	ZONE 4107	PHDI	31JAN1895-31DEC2017	1MON	SOUTH CENTRAL
8	PHDI	ZONE 4108	PHDI	31JAN1895-31DEC2017	1MON	UPPER COAST
9	PHDI	ZONE 4109	PHDI	31JAN1895-31DEC2017	1MON	SOUTHERN
10	PHDI	ZONE 4110	PHDI	31JAN1895-31DEC2017	1MON	LOWER VALLEY
11	LOWER BASIN	4103,4104,4106,4107,4108	PHDI	31JAN1895-31DEC2017	1MON	LOWER BASIN PHDI
12	MIDDLE BASIN	ZONE 4103	PHDI	31JAN1895-31DEC2017	1MON	MIDDLE BASIN PHDI
13	UPPER BASIN	ZONES 4101, 4102, 4103	PHDI	31JAN1895-31DEC2017	1MON	UPPER BASIN PHDI
14	BRAZOS	LOWER	HI	31JAN1940-31DEC2017	1MON	
15	BRAZOS	MIDDLE	HI	31JAN1940-31DEC2017	1MON	
16	BRAZOS	UPPER	HI	31JAN1940-31DEC2017	1MON	

The DSS file with filename BrazosPDHI.DSS was created in conjunction with compiling the PHDI sequences and associated *HI* record indices used with the *HC* records to define hydrologic conditions for the SB3 EFS. Pathnames for the DSS records are listed in Table 5.7.

The first ten DSS records contain the January 1895 through December 2017 monthly PHDI series for the ten climatic zones of Texas downloaded from the National Weather Service (NWS) National Climatic Data Center (NCDC) website. The ten climatic zones are listed in Table 5.4 with the weighting factors used to compute averages for the upper, middle, and lower Brazos River Basin. The 11th, 12th, and 13th records in the DSS file are the area-weight average 1895-2017 monthly series of PHDI quantities for the upper, middle, and lower Brazos River Basin. The PHDI quantities in the 11th, 12th, and 13th records listed in Table 5.7 are plotted in Figure 5.1.

The 14th, 15th, and 16th DSS record data series listed in Table 5.7 are the 1940-2017 *HI* record hydrologic indices for the upper, middle, and lower Brazos River Basin used for modeling SB3 environmental flow standards in the daily Brazos WAM. These *HI* records incorporated in the daily WAM hydrology input DSS file are plotted in Figure 5.2.

Modeling SB3 Environmental Flow Standards

Senate Bill 3 (SB3) environmental flow standards (EFS) are based on a flow regime that includes subsistence, base, and high pulse flows as explained in Chapter 4 of the *Reference Manual* [1] and illustrated by the Brazos EFS described on the preceding pages of this chapter. Hydrologic condition *HC*, environmental standard *ES*, pulse flow *PF*, and pulse flow supplemental options *PO* records are designed specifically to model *IF* record instream flow rights in the format of SB3 EFS. *HC* and *ES* input records are described in Chapter 3 of the *Users Manual* [2] and Chapter 4 of the *Reference Manual* [1]. *PF* and *PO* input records are covered in Chapter 4 of the *Users Manual* and Chapter 6 of the *Daily Manual*. An example of modeling SB3 environmental flow standards with *HC*, *ES*, and *PF* records is presented in Chapter 8 of the *Daily Manual* [4]. Hydrologic conditions are defined by *HC* records, optionally based on *HI* record indices.

Instream Flow Rights Defined by *IF*, *HC*, *ES*, and *PF* Records

HC and *ES* records are applicable for either a monthly *SIM/SIMD* simulation or a daily *SIMD* simulation. *PF* and *PO* records are applicable for only a daily *SIMD* simulation. *ES* records describe subsistence, base, and high flow components of environmental flow standards. *PF* and *PO* records model pulse flow components of environmental flow standards. *HC* records define hydrologic conditions for which alternative *ES* and *PF* record quantities are applicable.

The purpose of *HC*, *ES*, *PF*, and *PO* records is to control computation of a minimum instream flow target for each month of a monthly *SIM* or each day of a daily *SIMD* simulation. With these records employed, an *IF* record water right in a monthly *SIM* simulation input dataset consists of an *IF* record followed a *HC* record and a set of *ES* records. A set of *PF* and *PO* records can be added for a daily *SIMD* simulation.

IF, *HC*, and *ES* input records are described in Chapter 3 of the *Users Manual* [2]. *PF* and *PO* input records are covered in Chapter 4 of the *Users Manual*. The records replicated in Table 5.8 are inserted in the DAT file of the daily Brazos WAM to model the SB3 environmental flow standards. *IF*, *HC*, *ES*, and *PF* records are employed but *PO* records are not needed. With no pulse options *PO* records, defaults are activated for all of the parameters defined by *PO* record entries.

The *IF* records in Table 5.8 include the control point identifier of the EFS, priority of 20120301 (March 1, 2012), and water right identifier. The −9 for AMT in *IF* record field 3 signals that *HC*, *ES*, and *PF* records are being employed to model the instream flow right.

The identifier LOWER, MIDDLE, or UPPER in *HC* record field 2 references the relevant *HI* record in the hydrology input DSS file. The hydrologic condition (dry, average, wet) is defined by the hydrologic index (1, 2, or 3) read from the relevant (lower, middle, upper basin) hydrologic index *HI* record in the DSS file for the first month of the seasons defined in *HC* record fields 6 through 17. The M, J, and N on the *PF* records of Table 5.5 refer to updating the hydrologic index in March, July, and November for application throughout the seasons March-June (Spring), July-October (Summer), and November-February (Winter).

SF501 in *ES* record fields 2 and 3 refers to a subsistence flow limit with the 50% rule employed (EFS=SF50) for dry hydrologic conditions (ESHC=1). BASE1, BASE2, and BASE3 in *ES* record fields 2 and 3 refer to base flows (ESF=BASE) for dry, average, and wet hydrologic conditions (ESHC = 1, 2, 3). The twelve numbers in *ES* record fields 4 through 15 are the subsistence or base flow limits in cubic feet per second (cfs) from Table 5.2.

The high pulse flow specifications outlined in Table 5.3 are entered on *PF* records. Each *PF* record defines a set of high flow characteristics to be preserved in one or more high flow events initiated in the specified season if such events actually occur. Regulated flow is the *PF* record field 2 PVF option adopted for the Brazos WAM as well as the default recommended standard. Hydrologic condition 1, 2, or 3 (dry, average, wet) is specified in field 3 of each *PF* record. The trigger Q_P in cfs, volume limit in acre-feet, and duration in days from Table 5.3 are entered in *PF* record fields 4, 5, and 6. The target number of events (frequency) for each tracking period are set in *PF* field 7. The March-June (Spring), July-October (Summer), and November-February (Winter) tracking periods are defined in *PF* record fields 8-12.

PF record fields 12, 13, and 14 are left blank with defaults being activated. Regulated flow changes in the *SIM/SIMD* simulation as each water right is considered in the priority sequence computations. With the default flow option 1 (blank field 12), the final regulated flow at the end of the priority-sequence computations is used to determine the accumulated flow used with the volume termination criterion. The default target limit option 1 in *PF* record field 13 means that the computed target each day is limited to not exceed the trigger Q_P entered in *PF* field 4. The default target selection option 2 in *PF* record field 14 means that the *IF* record instream flow target computed each day is the maximum of the different computed intermediate component targets.

The set of *SIMD* DAT file input records reproduced as Table 5.8 control the computation of daily instream flow targets at the 19 control points representing the SB3 environmental flow standards. These instream flow targets are managed in the same manner as all water right targets within the *SIMD* simulation computations and output files. Options controlled by *IF* record field 3 and *PF* record field 15 create tables in the MSS and SMM message files that provide additional supplemental information that facilitates tracking the *HC*, *ES*, and *PF* record computations. These message file options are not activated in the dataset of Table 5.8.

Table 5.8
Instream Flow Rights that Model the EFS in the Daily Brazos WAM DAT File

```
**       1         2         3         4         5         6         7         8         9        10
**34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345
**     !       !       !       !       !       !       !       !       !       !       !       !       !
**
IFSFAS06     -9.        20120301                EFS-SFAS06
**
HC UPPER      HI       M   J   N     0.0     1.5     2.5     -9.
**
ES SF501      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE2      4.      4.      2.      2.      2.      2.      1.      1.      1.      1.      4.      4.
ES BASE3      9.      9.      5.      5.      5.      5.      3.      3.      3.      3.      9.      9.
**
PF     1    160.    720.  10   1   0   3   6
PF     2    160.    720.  10   2   0   3   6
PF     3    300.   1350.  11   1   0   3   6
PF     1    140.    560.   8   1   0   7  10
PF     2    140.    560.   8   2   0   7  10
PF     3    260.   1090.  10   1   0   7  10
**
IFDMAS09     -9.        20120301                EFS-DMAS09
**
HC UPPER      HI       M   J   N     0.0     1.5     2.5     -9.
**
ES SF501      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE2      4.      4.      3.      3.      3.      3.      2.      2.      2.      2.      4.      4.
ES BASE3     15.     15.      8.      8.      8.      8.      7.      7.      7.      7.     15.     15.
**
PF     1    280.   1270.  10   1   0   3   6
PF     2    280.   1270.  10   2   0   3   6
PF     3    570.   2600.  12   1   0   3   6
PF     1    230.    990.   9   1   0   7  10
PF     2    230.    990.   9   2   0   7  10
PF     3    480.   2160.  12   1   0   7  10
**
IFBRSE11     -9.        20120301                EFS-BRSE11
**
HC UPPER      HI       M   J   N     0.0     1.5     2.5     -9.
**
ES SF501      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1     10.     10.      7.      7.      7.      7.      4.      4.      4.      4.     10.     10.
ES BASE2     25.     25.     19.     19.     19.     19.     13.     13.     13.     13.     25.     25.
ES BASE3     46.     46.     35.     35.     35.     35.     32.     32.     32.     32.     46.     46.
**
PF     1    560.   2960.  10   1   0   3   6
PF     2    560.   2960.  10   2   0   3   6
PF     3   1040.   5870.  12   1   0   3   6
PF     1    370.   1870.   8   1   0   7  10
PF     2    370.   1870.   8   2   0   7  10
PF     3    800.   4290.  11   1   0   7  10   0   0   2   0   3
**
IFCFNU16     -9.        20120301                EFS-CFNU16
**
HC UPPER      HI       M   J   N     0.0     1.5     2.5     -9.
**
ES SF501      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1      5.      5.      3.      3.      3.      3.      1.      1.      1.      1.      5.      5.
ES BASE2      8.      8.      6.      6.      6.      6.      4.      4.      4.      4.      8.      8.
ES BASE3     13.     13.     12.     12.     12.     12.      9.      9.      9.      9.     13.     13.
**
PF     3     26.    160.   9   1   0  11   2
PF     1    180.    860.   9   1   0   3   6
```

Table 5.8 Continued
Instream Flow Rights that Model the EFS in the Daily Brazos WAM DAT File

```
PF     2    180.    860.   9   2   0   3   6
PF     3    590.   2800.  12   1   0   3   6
PF     1    100.    460.   8   1   0   7  10
PF     2    100.    460.   8   2   0   7  10
PF     3    390.   1890.  12   1   0   7  10
**
IFCON026     -9.        20120301               EFS- CON026
**
HC UPPER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1      7.      7.      4.      4.      4.      4.      1.      1.      1.      1.      7.      7.
ES BASE2     10.     10.      7.      7.      7.      7.      5.      5.      5.      5.     10.     10.
ES BASE3     16.     16.     15.     15.     15.     15.     11.     11.     11.     11.     16.     16.
**
PF     3     26.    158.   9   1   0  11   2
PF     1     18.     74.   2   1   0   3   6
PF     2     37.    148.   2   2   0   3   6
PF     3    355.   2054.   9   1   0   3   6
PF     1     18.     74.   2   1   0   7  10
PF     2     37.    148.   2   2   0   7  10
PF     3    170.    779.   5   1   0   7  10
**
IFBRSB23     -9.        20120301               EFS-BRSB23
**
HC UPPER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1     36.     36.     29.     29.     29.     29.     16.     16.     16.     16.     36.     36.
ES BASE2     73.     73.     60.     60.     60.     60.     46.     46.     46.     46.     73.     73.
ES BASE3    120.    120.    100.    100.    100.    100.     95.     95.     95.     95.    120.    120.
**
PF     1   1260.   7280.  10   1   0   3   6
PF     2   1260.   7280.  10   2   0   3   6
PF     3   2480.  15700.  13   1   0   3   6
PF     1    580.   3140.   8   1   0   7  10
PF     2    580.   3140.   8   2   0   7  10
PF     3   1180.   7050.  11   1   0   7  10
**
IFBRPP27     -9.        20120301               EFS-BRPP27
**
HCMIDDLE      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501     17.     17.     17.     17.     17.     17.     17.     17.     17.     17.     17.     17.
ES BASE1     40.     40.     39.     39.     39.     39.     40.     40.     40.     40.     40.     40.
ES BASE2     61.     61.     75.     75.     75.     75.     72.     72.     72.     72.     61.     61.
ES BASE3    100.    100.    120.    120.    120.    120.    120.    120.    120.    120.    100.    100.
**
PF   1 0    850.   3690.   5   2   0  11   2
PF   2 0    850.   3690.   5   4   0  11   2
PF     2   1390.   7180.   7   2   0  11   2
PF     3    850.   3690.   5   4   0  11   2
PF     3   1390.   7180.   7   3   0  11   2
PF     1   1400.   6600.   6   2   0   3   6
PF     2   1400.   6600.   6   4   0   3   6
PF     2   3370.  20200.  10   2   0   3   6
PF     3   1400.   6600.   6   4   0   3   6
PF     3   3370.  20200.  10   3   0   3   6
PF     1   1230.   5920.   6   2   0   7  10
PF     2   1230.   5920.   6   4   0   7  10
PF     2   2260.  13000.   9   2   0   7  10
PF     3   1230.   5920.   6   4   0   7  10
PF     3   2260.  13000.   9   3   0   7  10
```

Table 5.8 Continued
Instream Flow Rights that Model the EFS in the Daily Brazos WAM DAT File

```
**
IFBRGR30     -9.        20120301                EFS-BRGR30
**
HCMIDDLE      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501     16.      16.      16.     16.     16.     16.     16.     16.     16.     16.     16.     16.
ES BASE1     42.      42.      47.     47.     47.     47.     37.     37.     37.     37.     42.     42.
ES BASE2     77.      77.      92.     92.     92.     92.     70.     70.     70.     70.     77.     77.
ES BASE3    160.     160.     170.    170.    170.    170.    160.    160.    160.    160.    160.    160.
**
PF     1    930.   5400.   8   2   0  11   2
PF     2    930.   5400.   8   4   0  11   2
PF     2   1700.  10800.  10   2   0  11   2
PF     3    930.   5400.   8   4   0  11   2
PF     3   1700.  10800.  10   3   0  11   2
PF     1   2350.  14300.  10   2   0   3   6
PF     2   2350.  14300.  10   4   0   3   6
PF     2   6480.  46700.  14   2   0   3   6
PF     3   2350.  14300.  10   4   0   3   6
PF     3   6480.  46700.  14   3   0   3   6
PF     1   1320.   7830.   8   2   0   7  10
PF     2   1320.   7830.   8   4   0   7  10
PF     2   3090.  21200.  12   2   0   7  10
PF     3   1320.   7830.   8   4   0   7  10
PF     3   3090.  21200.  12   3   0   7  10
**
IFNBCL36     -9.        20120301                EFS-NBCL36
**
HC LOWER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501      1.       1.       1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1      5.       5.       7.      7.      7.      7.      3.      3.      3.      3.      5.      5.
ES BASE2     12.      12.      16.     16.     16.     16.      8.      8.      8.      8.     12.     12.
ES BASE3     25.      25.      33.     33.     33.     33.     17.     17.     17.     17.     25.     25.
**
PF     3    120.    750.  10   2   0  11   2
PF     1    710.   3490.  12   1   0   3   6
PF     2    710.   3490.  12   3   0   3   6
PF     3    710.   3490.  12   3   0   3   6
PF     3    130.    500.   6   2   0   7  10
**
IFBRWA41     -9.        20120301                EFS-BRWA41
**
HC LOWER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501     56.      56.      56.     56.     56.     56.     56.     56.     56.     56.     56.     56.
ES BASE1    120.     120.     150.    150.    150.    150.    140.    140.    140.    140.    120.    120.
ES BASE2    210.     210.     270.    270.    270.    270.    250.    250.    250.    250.    210.    210.
ES BASE3    480.     480.     690.    690.    690.    690.    590.    590.    590.    590.    480.    480.
**
PF     1   2320.  12400.   7   1   0  11   2
PF     2   2320.  12400.   7   3   0  11   2
PF     3   4180.  25700.   9   2   0  11   2
PF     1   5330.  32700.  10   1   0   3   6
PF     2   5330.  32700.  10   3   0   3   6
PF     3  13600. 102000.  14   2   0   3   6
PF     1   1980.  10500.   7   1   0   7  10
PF     2   1980.  10500.   7   3   0   7  10
PF     3   4160.  26400.  10   2   0   7  10
**
IFLEGT47     -9.        20120301                EFS-LEGT47
**
HC LOWER      HI       M   J   N      0.0     1.5     2.5     -9.
**
```

Table 5.8 Continued
Instream Flow Rights that Model the EFS in the Daily Brazos WAM DAT File

```
ES SF501      1.      1.       1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1      9.      9.      10.     10.     10.     10.      4.      4.      4.      4.      9.      9.
ES BASE2     20.     20.      24.     24.     24.     24.     12.     12.     12.     12.     20.     20.
ES BASE3     52.     52.      54.     54.     54.     54.     27.     27.     27.     27.     52.     52.
**
PF     3   100.    540.   6   2   0  11   2
PF     1   340.   1910.  10   1   0   3   6
PF     2   340.   1910.  10   3   0   3   6
PF     3   630.   4050.  13   2   0   3   6
PF     1    58.    220.   4   1   0   7  10
PF     2    58.    220.   4   3   0   7  10
PF     3   140.    600.   6   2   0   7  10
**
IFLAKE50     -9.        20120301                EFS-LAKE50
**
HC LOWER      HI      M   J   N      0.0     1.5     2.5     -9.
**
ES SF501     10.     10.      10.     10.     10.     10.     10.     10.     10.     10.     10.     10.
ES BASE1     18.     18.      21.     21.     21.     21.     16.     16.     16.     16.     18.     18.
ES BASE2     27.     27.      29.     29.     29.     29.     23.     23.     23.     23.     27.     27.
ES BASE3     39.     39.      43.     43.     43.     43.     32.     32.     32.     32.     39.     39.
**
PF     1    78.    430.   8   1   0  11   2
PF     2    78.    430.   8   3   0  11   2
PF     3   190.   1150.  11   2   0  11   2
PF     1   780.   4020.  13   1   0   3   6
PF     2   780.   4020.  13   3   0   3   6
PF     3  1310.   6860.  16   2   0   3   6
PF     1    77.    270.   4   1   0   7  10
PF     2    77.    270.   4   3   0   7  10
PF     3   190.    680.   6   2   0   7  10
**
IFLRLR53     -9.        20120301                EFS-LRLR53
**
HC LOWER      HI      M   J   N      0.0     1.5     2.5     -9.
**
ES SF501     55.     55.      55.     55.     55.     55.     55.     55.     55.     55.     55.     55.
ES BASE1     82.     82.      95.     95.     95.     95.     84.     84.     84.     84.     82.     82.
ES BASE2    110.    110.     150.    150.    150.    150.    120.    120.    120.    120.    110.    110.
ES BASE3    190.    190.     430.    430.    430.    430.    200.    200.    200.    200.    190.    190.
**
PF     1   520.   2350.   5   1   0  11   2
PF     2   520.   2350.   5   3   0  11   2
PF     3  1600.  11800.  11   2   0  11   2
PF     1  1420.   9760.  10   1   0   3   6
PF     2  1420.   9760.  10   3   0   3   6
PF     3  3290.  32200.  17   2   0   3   6
PF     1   430.   1560.   4   1   0   7  10
PF     2   430.   1560.   4   3   0   7  10
PF     3  1060.   5890.   8   2   0   7  10
**
IFLRCA58     -9.        20120301                EFS-LRCA58
**
HC LOWER      HI      M   J   N      0.0     1.5     2.5     -9.
**
ES SF501     32.     32.      32.     32.     32.     32.     32.     32.     32.     32.     32.     32.
ES BASE1    110.    110.     140.    140.    140.    140.     97.     97.     97.     97.    110.    110.
ES BASE2    190.    190.     310.    310.    310.    310.    160.    160.    160.    160.    190.    190.
ES BASE3    460.    460.     760.    760.    760.    760.    330.    330.    330.    330.    460.    460.
PF     1  1080.   6680.   8   1   0  11   2
PF     2  1080.   6680.   8   3   0  11   2
PF     3  2140.  14900.  10   2   0  11   2
PF     1  3200.  23900.  12   1   0   3   6
```

Table 5.8 Continued
Instream Flow Rights that Model the EFS in the Daily Brazos WAM DAT File

```
PF     2   3200.  23900.  12   3   0   3   6
PF     3   4790.  38400.  14   2   0   3   6
PF     1    560.  28600.   6   1   0   7  10
PF     2    560.  28600.   6   3   0   7  10
PF     3    990.  55500.   8   2   0   7  10
**
IFBRBR59     -9.        20120301                EFS-BRBR59
**
HC LOWER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501    300.    300.    300.    300.    300.    300.    300.    300.    300.    300.    300.    300.
ES BASE1    540.    540.    710.    710.    710.    710.    630.    630.    630.    630.    540.    540.
ES BASE2    860.    860.   1260.   1260.   1260.   1260.    920.    920.    920.    920.    860.    860.
ES BASE3   1760.   1760.   2460.   2460.   2460.   2460.   1470.   1470.   1470.   1470.   1760.   1760.
**
PF     1   3230.  21100.   7   1   0  11   2
PF     2   3230.  21100.   7   3   0  11   2
PF     3   5570.  41900.  10   2   0  11   2
PF     1   6050.  49000.  11   1   0   3   6
PF     2   6050.  49000.  11   3   0   3   6
PF     3  10400.  97000.  14   2   0   3   6
PF     1   2060.  12700.   7   1   0   7  10
PF     2   2060.  12700.   7   3   0   7  10
PF     3   2990.  20100.   8   2   0   7  10
**
IFNAEA66     -9.        20120301                EFS-NAEA66
**
HC LOWER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.      1.
ES BASE1      9.      9.     10.     10.     10.     10.      3.      3.      3.      3.      9.      9.
ES BASE2     14.     14.     19.     19.     19.     19.      8.      8.      8.      8.     14.     14.
ES BASE3     23.     23.     29.     29.     29.     29.     16.     16.     16.     16.     23.     23.
**
PF     1    260.   1610.   9   1   0  11   2
PF     2    260.   1610.   9   3   0  11   2
PF     3    800.   5440.  12   2   0  11   2
PF     1    720.   4590.  11   1   0   3   6
PF     2    720.   4590.  11   3   0   3   6
PF     3   1340.   8990.  13   2   0   3   6
PF     3     49.    220.   5   2   0   7  10
**
IFBRHE68     -9.        20120301                EFS-BRHE68
**
HC LOWER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501    510.    510.    510.    510.    510.    510.    510.    510.    510.    510.    510.    510.
ES BASE1    920.    920.   1130.   1130.   1130.   1130.    950.    950.    950.    950.    920.    920.
ES BASE2   1440.   1440.   1900.   1900.   1900.   1900.   1330.   1330.   1330.   1330.   1440.   1440.
ES BASE3   2890.   2890.   3440.   3440.   3440.   3440.   2050.   2050.   2050.   2050.   2890.   2890.
**
PF     1   5720.  49800.  10   1   0  11   2
PF     2   5720.  49800.  10   3   0  11   2
PF     3  11200. 125000.  15   2   0  11   2
PF     1   8530.  85000.  13   1   0   3   6
PF     2   8530.  85000.  13   3   0   3   6
PF     3  16800. 219000.  19   2   0   3   6
PF     1   2620.  17000.   7   1   0   7  10
PF     2   2620.  17000.   7   3   0   7  10
PF     3   5090.  40900.   9   2   0   7  10
**
```

Table 5.8 Continued
Instream Flow Rights that Model the EFS in the Daily Brazos WAM DAT File

```
**     !       !       !       !       !       !       !       !       !       !       !       !       !
**       1         2         3         4         5         6         7         8         9        10
**34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123 4
**
IFBRRI70     -9.        20120301                EFS-BRRI70
**
HC LOWER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501    550.    550.    550.    550.    550.    550.    550.    550.    550.    550.    550.    550.
ES BASE1    990.    990.   1190.   1190.   1190.   1190.    930.    930.    930.    930.    990.    990.
ES BASE2   1650.   1650.   2140.   2140.   2140.   2140.   1330.   1330.   1330.   1330.   1650.   1650.
ES BASE3   3310.   3310.   3980.   3980.   3980.   3980.   2190.   2190.   2190.   2190.   3310.   3310.
**
PF     1   6410.  60600.  11   1   0  11   2
PF     2   6410.  60600.  11   3   0  11   2
PF     3  12400. 150000.  16   2   0  11   2
PF     1   8930.  94000.  13   1   0   3   6
PF     2   8930.  94000.  13   3   0   3   6
PF     3  16300. 215000.  19   2   0   3   6
PF     1   2460.  16400.   6   1   0   7  10
PF     2   2460.  16400.   6   3   0   7  10
PF     3   5430.  46300.  10   2   0   7  10
**
IFBRRO72     -9.        20120301                EFS-BRRO72
**
HC LOWER      HI       M   J   N      0.0     1.5     2.5     -9.
**
ES SF501    430.    430.    430.    430.    430.    430.    430.    430.    430.    430.    430.    430.
ES BASE1   1140.   1140.   1250.   1250.   1250.   1250.    930.    930.    930.    930.   1140.   1140.
ES BASE2   2090.   2090.   2570.   2570.   2570.   2570.   1420.   1420.   1420.   1420.   2090.   2090.
ES BASE3   4700.   4700.   4740.   4740.   4740.   4740.   2630.   2630.   2630.   2630.   4700.   4700.
**
PF     1   9090.  94700.  12   1   0  11   2
PF     2   9090.  94700.  12   3   0  11   2
PF     3  13600. 168000.  16   2   0  11   2
PF     1   6580.  58500.  10   1   0   3   6
PF     2   6580.  58500.  10   3   0   3   6
PF     3  14200. 184000.  18   2   0   3   6
PF     1   2490.  14900.   6   1   0   7  10
PF     2   2490.  14900.   6   3   0   7  10
PF     3   4980.  39100.   9   2   0   7  10
**
**     !       !       !       !       !       !       !       !       !       !       !       !       !
```

Monthly WAM with Instream Flow Targets from the Daily WAM

A strategy for incorporating monthly instream flow targets computed in a daily *SIMD* simulation into the *SIM* input dataset for a monthly WAM is outlined on the last page of Chapter 6 of the *Daily Manual* [4]. The methodology is illustrated in an example in Chapter 8 of the *Daily Manual* [4]. Daily targets computed by *SIMD* are aggregated within *SIMD* to monthly targets which are included in the *SIMD* simulation results. These time series of monthly targets are converted to target series *TS* records incorporated in the *SIM/SIMD* hydrology input DSS file.

The *TS* records of monthly instream targets in acre-feet/month stored in the DSS file have the pathname identifiers listed in Table 5.9. The *TS* records in the DSS file are referenced by *TS* records in the DAT file which are replicated in Table 5.10. The instream flow rights in Table 5.10 model the environmental flow standards at the 19 sites.

Table 5.9
Pathnames for Target Series *TS* Records in Hydrology Input DSS File

Part A	Part B	Part C	Part D	Part E
BRAZOS	SFAS06	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	DMAS09	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRSE11	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	CFNU16	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	CON026	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRSB23	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRPP27	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRGR30	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	NBCL36	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRWA41	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	LEGT47	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	LAKE50	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	LRLR53	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	LRCA58	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRBR59	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	NAEA66	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRHE68	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRRI70	TS	01JJAN1940-01JAN2010	1MON
BRAZOS	BRRO72	TS	01JJAN1940-01JAN2010	1MON

A daily *SIMD* simulation was performed with the set of *IF*, *HC*, *ES*, and *PF* records replicated in Table 5.8 incorporated in the DAT file to control computation of daily instream flow targets for the EFS at the 19 USGS gaging stations (WAM control points). The daily instream flow targets in acre-feet/day were summed to monthly quantities in acre-feet/month, which are included in the simulation results DSS file. The DSS records of monthly targets were copied from the daily *SIMD* simulation results DSS output file to the *SIM/SIM* hydrology input DSS file and the pathnames were revised using HEC-DSSVue. The *TS* records in the monthly *SIM* DAT file replicated in Table 5.10 reference the DSS file target series employed by the *IF* record water rights.

Simulation results for both the daily and monthly simulations are presented in Chapter 10 along with a summary description of the overall modeling strategy including the methodology outlined here for modeling SB3 environmental flow standards. Daily and monthly instream flow targets and shortages associated with the SB3 EFS are presented and discussed. Chapter 10 also includes comparative analyses of simulation results from the monthly versus daily Brazos WAMs.

Table 5.10
Instream Flow Rights that Model the EFS in the Monthly Brazos WAM DAT File

```
IFSFAS06                20120301                EFS-SFAS06
TS      DSS
IFDMAS09                20120301                EFS-DMAS09
TS      DSS
IFBRSE11                20120301                EFS-BRSE11
TS      DSS
IFCFNU16                20120301                EFS-CFNU16
TS      DSS
IFCON026                20120301                EFS-CON026
TS      DSS
IFBRSB23                20120301                EFS-BRSB23
TS      DSS
IFBRPP27                20120301                EFS-BRPP27
TS      DSS
IFBRGR30                20120301                EFS-BRPP27
TS      DSS
IFNBCL36                20120301                EFS-NBCL36
TS      DSS
IFBRWA41                20120301                EFS-BRWA41
TS      DSS
IFLEGT47                20120301                EFS-LEGT47
TS      DSS
IFLAKE50                20120301                EFS-LAKE50
TS      DSS
IFLRLR53                20120301                EFS-LRCA53
TS      DSS
IFLRCA58                20120301                EFS-LRCA58
TS      DSS
IFBRBR59                20120301                EFS-BRBR59
TS      DSS
IFNAEA66                20120301                EFS-NAEA66
TS      DSS
IFBRHE68                20120301                EFS-BRHE68
TS      DSS
IFBRRI70                20120301                EFS-BRRI70
TS      DSS
IFBRRO72                20120301                EFS-BRRO72
TS      DSS
```

CHAPTER 6
DAILY STREAM FLOW HYDROGRAPHS

The 1940-2017 sequences of daily flows at 58 control points stored as *DF* records in the Brazos WAM hydrology input DSS file were developed in two steps as follows.

1. Initial 1940-2017 pattern hydrographs of daily mean flow rates in cfs at the 58 control points were developed as described in this chapter and stored as *DF* records in a DSS file. Some of the 1940-2017 sequences reflect combinations of flows from different sources and/or sites.

2. Daily flow volumes in acre-feet/day at the 58 sites were computed with *SIMD* by combining monthly naturalized flow volumes with the initial daily flow pattern hydrographs in cfs from the first step described above. These final *DF* record daily flows represent 1940-2017 daily naturalized flow volumes, rather than just flow patterns, and have units of acre-feet/day.

The WRAP daily simulation model *SIMD* disaggregates monthly naturalized flow volumes to daily volumes in proportion to the flows in the daily pattern hydrographs while preserving the monthly volumes [4]. Although monthly and daily flow volumes in a *SIMD* simulation are in units of acre-feet, flow rates in cfs can be used for the flow sequences defining patterns since only relative, not absolute, quantities are relevant. However, the final daily flows adopted for the Brazos WAM pattern hydrographs are daily naturalized flow volumes in acre-feet/day as noted above.

In addition to the Brazos WAM input files, Table 1.2 in Chapter 1 lists four other DSS files compiled for use in exploring river system hydrology in general as well as supporting development and future updates of the WAM input files. The organization of these supplemental DSS files are summarized in Chapter 9. The DSS file with filename BrazosDailyFlows.DSS was created in conjunction with compiling, analyzing, and verifying daily simulation *SIMD* daily flow pattern hydrographs and contains five datasets of daily flow sequences described in the present Chapter 6.

Disaggregation of Monthly Naturalized Flows to Daily

The disaggregation of monthly naturalized flow volumes in acre-feet/month to daily volumes in acre-feet/day at the over 3,800 control points in the Brazos WAM is controlled by the input parameters (Table 6.1) on the *JO* and *JU* records found in the DAT file and *DC* records in the DIF file along with the 58 daily flow pattern hydrographs stored on *DF* records in the DSS file.

INEV option 6 in *JO* record field 2 specifies that the naturalized monthly flows on *IN* records at the primary control points are read from the DSS hydrology input file along with other time series input data. The blank *JU* record field 3 results in the default DFFILE option 1 of reading the *DF* record daily flow pattern hydrographs from the DSS file. The *DF* records in the DAT file lists the 58 control point identifiers for the *DF* records read from the DSS file.

DFMETH option 1 in *JU* record field 2 sets uniform as the default for distributing monthly naturalized flows to daily. This default is applied at any and all control points for which another flow distribution option is not specified. Flow disaggregation DFMETHOD(cp) option 4 is applied at most of the control points in the Brazos WAM as specified by the three DIF file *DC* records shown in Table 6.1. Option 4 is applied to all control points located above the Brazos River outlet and the two stream outlets in the coastal basin (control points BRGM73, SJBC3, and SJGMC4).

Table 6.1
SIMD DAT and DIF File Input Parameters that Control Naturalized Flow Disaggregation

DAT File

```
JO      6
JU      1

DF         227901  509431  515531  515631  515731  515831  515931  516031  516131
DF         516231  516331  516431  516531  AQAQ34  BGNE71
DF         BRAQ33  BRBR59  BRDE29  BRGR30  BRHB42  BRHE68  BRPP27  BRRI70  BRRO72
DF         BRSB23  BRSE11  BRWA41  CBALC2  CFFG18  CFNU16
DF         CLPEC1  CON070  CON095  CON102  CON129  CON137  CON145  CON147  CON231
DF         DMAS09  DMJU08  EYDB61  GAGE56  GALA57  LAKE50
DF         LEBE49  LEGT47  LRCA58  LRLR53  NABR67  NAEA66  NBCL36  NBVM37  PAGR31
DF         RWPL01  SFAS06  SGGE55  YCSO62
```

DIF File

```
DCBRGM73   2   4
DCSJGBC3   2   4  CLPEC1
DCSJGMC4   2   4  CBALC2
```

The three *DC* records in the DIF file are assigned to control points BRGM73 which is the Brazos River outlet to the Gulf of Mexico and SJGBC3 and SJGMC4 which are outlets of San Jacinto-Brazos coastal basin streams. Disaggregation DFMETHOD(cp) option 4 in *DC* record field 4 is based on daily flow pattern hydrographs input on *DF* records stored in the DSS input file. Monthly volumes are distributed to daily volumes in proportion to daily flows from *DF* record pattern hydrographs while maintaining the monthly volumes.

REPEAT option 2 in field 3 of the three *DC* records repeats the DSS file *DF* record daily flow pattern hydrographs input for 58 control points for disaggregating flows at over 3,800 control points. The automated procedure in *SIMD* for repeating daily flows at multiple control points is described on page 28 of Chapter 2 of the *Daily Manual* [4]. The automated procedure consists of using flows at the nearest downstream control point if available, otherwise finding flows at the nearest upstream control point, and lastly if necessary using flows from another tributary.

Alternative Datasets of Daily Flows

The *SIMD* input DCF file for the original 2012 and 2013 developmental versions of the daily Brazos WAM [11, 12] included daily flow pattern hydrographs for 44 control points. The May 2019 updated and refined dataset documented here includes the daily flows at the original 44 sites plus 14 additional control points for a total of 58 control points. The earlier developmental versions of the daily Brazos WAM have a 1940-1997, 1940-2011, or 1940-2012 hydrologic period-of-analysis. The present update has a 1940-2017 period-of-analysis. The new *SIMD* input dataset of daily flows is stored in a hydrology DSS file rather than in the old text-format DCF file.

The daily flow pattern hydrographs are comprised of 1940-1997 unregulated flows from a USACE modeling system and observed flows from USGS gages. Data and methods were reviewed and the daily flow dataset was both refined and extended in the present update. Daily flows for

1998-2012 were assigned in the earlier (2012) daily WAM by repeating USACE flows for 1940-1954 or other 15-year period. USGS gaged flows are used for the 1998-2017 extension period in the 2019 update, instead of repeating sub-sets of the 1940-1997 USACE flows. Gaps in USGS gage records are filled in using flows recorded at other gage sites. Daily flow pattern hydrographs are added in the new dataset at 14 additional control points by adopting 1940-2017 gaged flows.

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

The USACE Fort Worth District employs a daily modeling system designed to support operations of federal multiple-purpose reservoirs, particularly flood control operations. The modeling system includes incremental unregulated flows that are accumulated to obtain total regulated flows at each control point. Unregulated daily flows from the USACE modeling system are analogous to WAM monthly naturalized flows. USACE unregulated flows are similarly developed by adjusting gaged flows to remove the effects of major reservoirs and water users but include routing in the adjustments and focus on flood flows at and below the USACE reservoirs.

The 24 reservoirs in Texas owned and operated by the USACE Fort Worth District include eight reservoirs in the Trinity River Basin and nine reservoirs in the Brazos River Basin. Daily unregulated flows for the Trinity and Brazos River Basins from the USACE modeling system were obtained from the USACE Fort Worth District for use in the daily WAMs. The unregulated daily flows for the Brazos and Trinity Basins cover periods of 1940-1997 and 1940-2009, respectively.

The 1940-1997 unregulated daily flows from the USACE modeling system at 44 sites were obtained from the USACE in 2010 for use as daily pattern hydrographs [15]. The unregulated flows at the 37 sites listed in Table 6.2 were used as daily WAM pattern hydrographs. Flows at BRRO72 were computed at TAMU based on flows at BRRI70. The sites of the daily flows are at or near and are assigned to the WAM control points listed in Table 6.2. Locations are shown in the map of Figure 6.1. The Figure 6.2 schematic shows the connectivity of the Brazos WAM control points assigned to the sites of the USACE unregulated daily flow data.

Original Daily Flow Pattern Hydrographs

The *SIMD* input DCF file in the previous daily Brazos WAM [15, 16] included 1940-2012 daily flow pattern hydrographs at a total of 44 control points. Unregulated flows from the USACE modeling system were adopted directly for 37 control points. Daily flows at one other control point (BRRO72) were computed from USACE unregulated flows at control point BRRI70. Flows during a 15-year sub-period of 1940-1997 were repeated to cover the 1998-2012 extension. USGS gaged flows were adopted for six other control points located in the upper basin.

Control point BRRO72 is the USGS gaging station on the Brazos River at Rosharon. The USACE did not provide unregulated flows for this site. USACE unregulated flows were provided for control point BRRI70 which is the gage on the Brazos River at Richmond located upstream of BRRO72. In the original daily WAM input dataset, the daily flows at control point BRRO72 were computed by routing the flows at BRRI70 with a lag of 0.53 days and attenuation of 1.00 day developed using the WRAP routing parameter calibration procedure. However, observed gaged flows are used for BRRO72 in the updated/refined dataset.

Table 6.2
USACE Unregulated Flow Sites and Corresponding Assigned WAM Control Points

River	Location	WAM Control Point	Drainage Area (sq miles)	Distance to Outlet (miles)
Brazos River	Possum Kingdom Dam Outflow	515531	14,030	706
Brazos River	Granbury Dam Outflow	515631	16,181	559
Brazos River	Whitney Dam Outflow	515731	17,690	462
Aquilla Creek	Aquilla Dam Outflow	515831	254	458
Aquilla Creek	Above confluence with Brazos	AQAQ34	307	453
North Bosque River	Upper North Bosque River	227901	710	490
Bosque River	Waco Dam Outflow	509431	1,655	428
Leon River	Proctor Dam Outflow	515931	1,280	639
Leon River	Belton Dam Outflow	516031	3,568	442
Lampasas River	Stillhouse Hollow Dam Outflow	516131	1,313	441
SF San Gabriel Riv	Georgetown gage on South Fork	SGGE55	132	430
San Gabriel River	Georgetown Dam Outflow	516231	247	432
San Gabriel River	Granger Dam Outflow	516331	726	399
Yequa Creek	Somerville Dam Outflow	516431	1,008	271
Navasota River	Limestone Dam Outflow	516531	675	351
Brazos River	Dennis Gage	BRDE29	15,733	605
Brazos River	Glen Rose Gage	BRGR30	16,320	527
Brazos River	Mouth Aquilla Creek, Elm Mott	CON070	18,313	434
North Bosque River	Clifton Gage	NBCL36	977	468
Brazos River	Waco Gage	BRWA41	20,065	418
Brazos River	Highbank Gage	BRHB42	20,900	358
Leon River	Gatesville Gage	LEGT47	2,379	519
Lampasas River	Mouth of Salado Creek	CON095	1,511	426
Little River	Little River Gage	LRLR53	5,266	419
San Gabriel River	Georgetown Gage	GAGE56	404	427
San Gabriel River	Mouth of Brushy Creek	CON102	1,357	373
Little River	Cameron Gage	LRCA58	7,100	357
Brazos River	Bryan Gage	BRBR59	30,016	290
Yequa Creek	Near confluence with Brazos Riv	CON129	1,302	257
Brazos River	Mouth Navasota R, Washington	CON147	33,930	234
Navasota River	Easterly Gage	NAEA66	936	334
Navasota River	Mill Creek confluence	CON137	1,295	320
Navasota River	Bryan Gage	NABR67	1,427	300
Navasota River	Gibbons Creek confluence	CON145	2,066	261
Navasota River	Big Creek Mouth, near Brazos R	CON231	2,241	240
Brazos River	Hempstead Gage	BRHE68	34,374	202
Brazos River	Richmond Gage	BRRI70	35,454	97

Many of the USACE flow sites are USGS gages that are at the same locations as WAM control points. In other cases, the USACE flows are assigned to the nearest or most reasonable

WAM control point. Locations of the control points are shown in Figures 6.1 and 6.2. The WAM control point assignments for the USACE unregulated flows have not been changed in the update/refinement study reported here. The original developmental daily Brazos WAM [11, 12] also included daily pattern hydrographs consisting of observed flows at six USGS gaging stations in the upper basin which are the sites of primary control points SFAS06, DMAS09, BRSE11, CFNU16, CFFG18, and BRSB23. These control points are included in Tables 2.8, 5.1, and 6.1 and Figure 2.14.

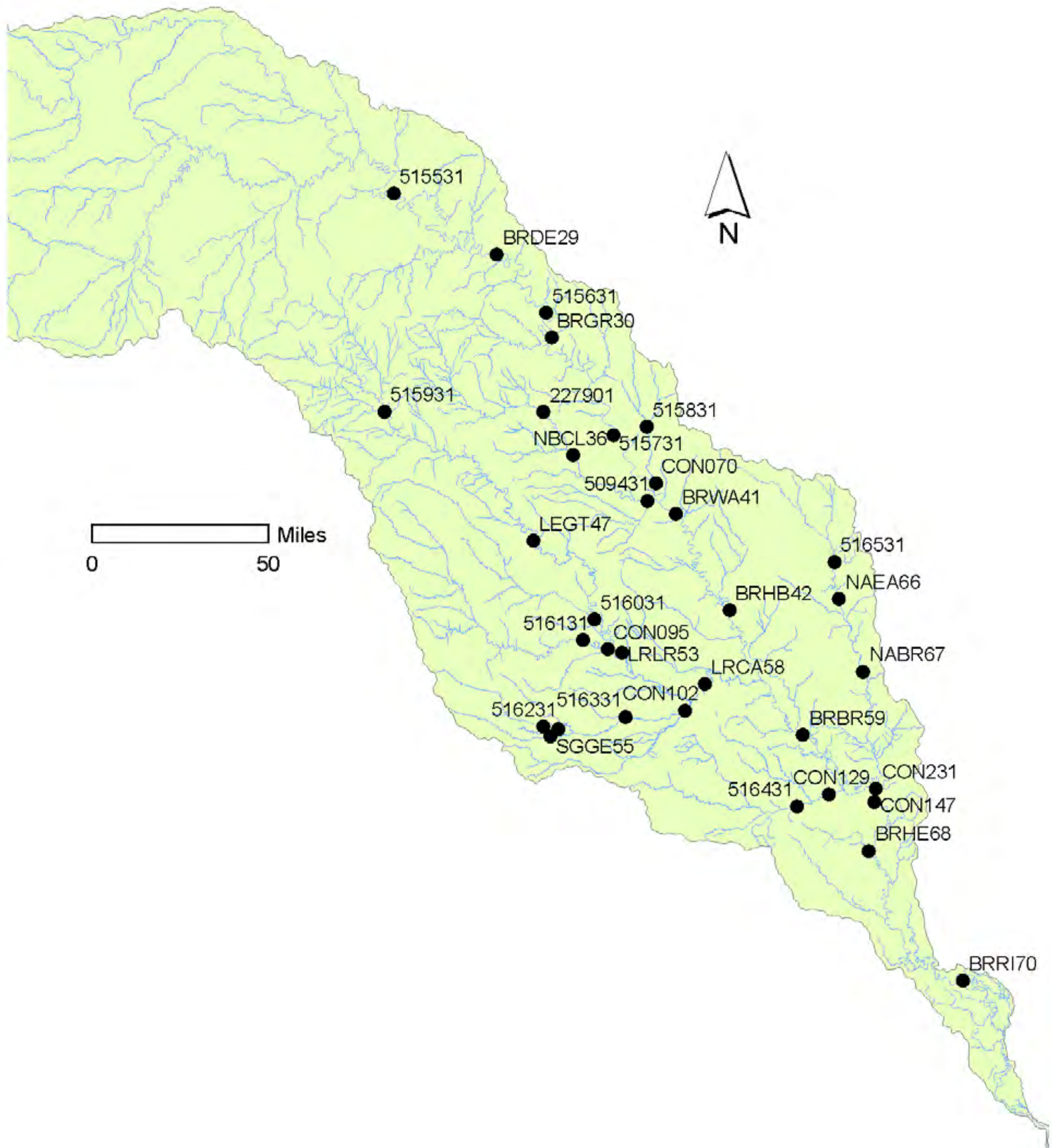

Figure 6.1 Brazos WAM Control Points with USACE Unregulated Flow Data

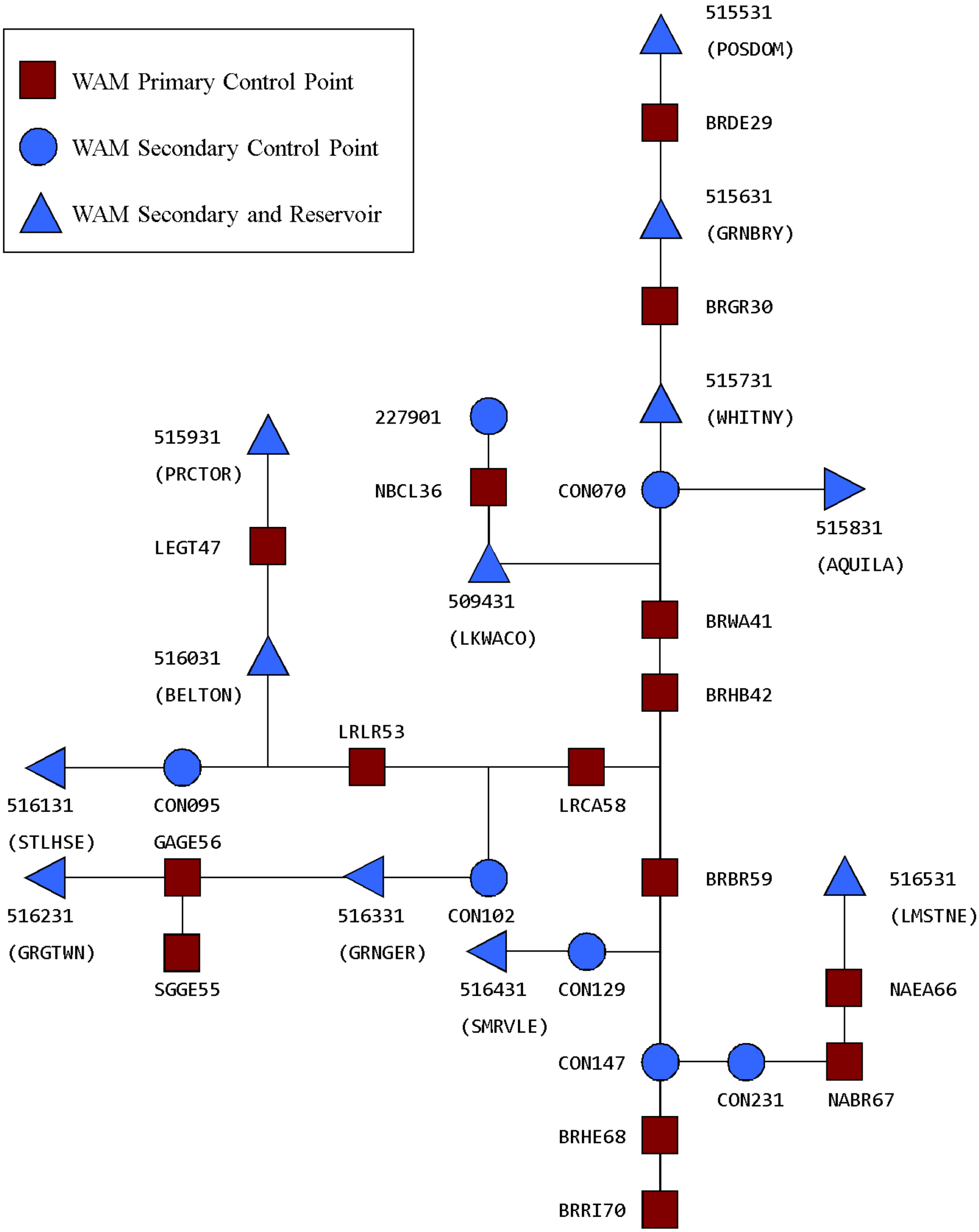

Figure 6.2 Connectivity of WAM Control Points Representing Sites of USACE Flow Data
(Schematic is not to scale.)

SWAT and HAWQS Watershed Rainfall-Runoff Modeling System

A concept that was explored but not adopted is to synthesize daily flow hydrographs from observed daily rainfall data and parameters representing the characteristics of the watershed. Daily flows can be used as *DF* record daily pattern hydrographs and/or aggregated to monthly totals to extend *IN* record monthly naturalized flows. SWAT was selected as the most appropriate of the various available watershed models for this type of application. Early in the TCEQ WAM System development process, application of SWAT for distributing monthly naturalized flows from gaged to ungaged controlled points had been investigated [29]. SWAT had been combined with the Brazos WAM during 2002-2004 [30] in an attempt to analyze the potential impacts of climate change on monthly naturalized flows.

The Soil and Water Assessment Tool (SWAT) developed by the USDA Agricultural Research Service and Texas A&M AgriLife Research Service computes daily stream flow and water quality constituent loads at stream sites that result from inputted observed or stochastically generated daily rainfall based on parameters reflecting the hydrologic characteristics of the watersheds. SWAT software and documentation are available at http://swat.tamu.edu/ .

The feasibility of employing the generalized SWAT watershed rainfall-runoff model to develop daily flow hydrographs was also investigated in conjunction with developing and updating the hydrology for the *SIM*/*SIMD* input datasets [28]. The conclusion of the investigation was that adoption of SWAT for developing the *SIMD* daily pattern hydrographs was not warranted. SWAT watershed-runoff modeling is not highly accurate, particularly in modeling low flows. Excessive days with zero flow tend to be generated. Limitations on the availability of rainfall data and the time and effort required to compile watershed data and apply the model were also found to be key issues.

The Hydrologic and Water Quality System (HAWQS) is a web-based interactive water quantity and quality modeling system that employs SWAT as its core modeling engine. A Beta version of HAWQS was released in June 2016. HAWQS was developed and is maintained by the Texas A&M University Spatial Sciences Laboratory under the sponsorship of the U.S. Environmental Protection Agency. HAWQS software, documentation, and online information are accessible at https://epahawqs.tamu.edu/ . The user creates a project for a modeling scenario and changes variables and inputs using web interfaces. To run the simulation, HAWQS connects with the latest version of the SWAT simulation model to process the inputs, data and other information. SWAT finishes processing and generates outputs, and HAWQS stores outputs centrally. Users can view results through a web interface, save results, and run additional scenarios.

SWAT and/or HAWQS potentially provide an alternative approach for generating daily flow pattern hydrographs for input as *DF* record daily flows to the WRAP daily simulation model *SIMD*. SWAT generated daily flows could be aggregated to monthly totals for use in extending *IN* record monthly naturalized flows. Key issues include (1) the expertise and effort required to compile rainfall and watershed parameter input data for SWAT, perform parameter calibration studies, and to perform the watershed rainfall-runoff simulations and (2) the approximations and inaccuracies inherent in watershed modeling. HAWQS is designed to simplify application of SWAT but introduces significant additional approximations.

Daily Flow Datasets Stored in the File BrazosDailyFlows.DSS

The DSS file with filename BrazosDailyFlows.DSS containing the following daily flow hydrographs was created along with developing the *DF* record daily flow pattern hydrographs incorporated in the *SIMD* hydrology input file. Control point LRCA58 at the USGS gaging station on the Little River at Cameron is used in Table 6.3 to illustrate the pathnames adopted for the DSS data records in each of the five datasets. The fourth dataset consists of daily flow volumes in acre-feet, and the other four datasets consist of mean daily flows in cubic feet per second (cfs). The DSS file contains the following five datasets, with a total of 285 daily flow sequences. Counts of DSS records of flow sequences are shown below in parenthesis.

1. Period-of-record observed daily flows at 74 USGS gages obtained from the USGS NWIS website that serve as 70 of the 77 WAM primary control points (74 records).
2. The 1940-1997 USACE unregulated daily flows at the 37 sites listed in Table 6.5 (37 records).
3. An initial version in cfs of the 1940-2018 pattern hydrograph daily flows at the selected 58 control points that were developed by selecting between and combining flows from the two preceding datasets of USGS observed flows and USACE unregulated flows (58 records).
4. 1940-2017 daily naturalized flow volumes at the 58 control points in acre-feet/day computed within the *SIMD* simulation by disaggregating monthly flow volumes to daily. These are the flows adopted as the *DF* record daily flow pattern hydrographs incorporated in the *SIMD* hydrology DSS input file (58 records).
5. Daily naturalized flows in cfs at the 58 control points derived by converting the preceding dataset from volumes in acre-feet to flow means in cfs for consistency with the other datasets.

Table 6.3
DSS Pathnames for the File BrazosDailyFlows.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	LITTLE RV	CAMERON, TX	USGS DAILY CFS	01JAN1916-01JAN2018	1DAY	LRCA58
2	USACE UNREGULATED	LITTLE RIVER, CAMERON	USACE DAILY CFS	01JAN1940-01JAN1997	1DAY	LRCA58
3	BRAZOS CFS	LRCA58	FLOW – CFS	01JAN1940-01JAN2016	1DAY	LRCA58
4	BRAZOS	LRCA58	FLOW – ACRE-FEET	01JAN1910-01JAN1990	1DAY	LRCA58
5	NATURALIZED CFS	LRCA58	FLOW – CFS	01JAN1910-01JAN2010	1DAY	LRCA58

The first dataset consists of period-of-record daily flows in cfs at 74 gages downloaded from the NWIS website maintained by the USGS. The 74 gages include 70 gages at the primary control points listed in Table 2.8 for which gaged flows are available and the four additional gages listed in Table 2.9. The flows at the four additional gages are used to extend the records of four of 70 gaged control points. The same daily dataset is listed first in both Tables 6.3 and 7.1 and included in both the files BrazosDailyFlows.DSS and BrazosMonthlyFlows.DSS.

The second dataset in the daily DSS file of Table 6.3 consists of the 1940-1997 daily unregulated flows in cfs at 37 sites generated by the USACE modeling system. The 37 sites listed in Table 6.2 include 16 of the WAM primary control points and 21 WAM secondary control points.

The third dataset consists of 1940-2017 daily pattern hydrographs at 58 control points in cfs that can be inserted in the *SIMD* hydrology input DSS file for use within the *SIMD* simulation in disaggregating monthly naturalized flows to daily. The 1940-2017 sequences reflect combinations of USACE unregulated and USGS observed flows and in some cases combinations of flows from different sites. The daily pattern flows in cfs were converted to daily naturalized flow volumes in acre-feet as described in the next paragraph.

The fourth dataset in the file BrazosDailyFlows.DSS is the final adopted *DF* record daily flows in the *SIMD* input file BrazosHYD.DSS. The 1940-2017 daily naturalized flow volumes in acre-feet at the 58 control points were computed in a *SIMD* simulation using the third dataset described in the preceding paragraph as the *SIMD* daily flow pattern hydrographs read from the hydrology input DSS file. The fourth dataset then replaced the third dataset in the *SIMD* input file.

The fifth dataset also consists of daily naturalized flows at the 58 control points computed by *SIMD*. However, the daily flow volumes in acre-feet in the *SIMD* simulation results are converted within *HEC-DSSVue* to daily means in cfs, by multiplying by 0.504166667, for consistency in comparing with the other datasets contained in the file BrazosDailyFlows.DSS.

Relevant WAM Control Points and USGS Gaging Stations

WAM primary control points are defined as those with monthly naturalized flows stored in a *SIM* or *SIMD* input file. Secondary control points are sites at which monthly flows are synthesized within the monthly *SIM* or daily *SIMD* simulation. The *SIMD* input dataset for the daily Brazos WAM includes daily flow pattern hydrographs at 37 primary control points and 21 secondary control points, which are used within the *SIMD* simulation to disaggregate monthly flows to daily at over 3,700 other control points as well as at these 58 control points.

The 77 primary control points are listed in Table 2.8 and shown on the schematic of Figure 2.13 and map of 2.14 of Chapter 2. The periods-of-record of the 72 control points with recorded daily flows from USGS gages and the number of days within the period-of-record with missing data are also tabulated in Table 2.8. The primary control points that are relevant in the development of the daily flow pattern hydrographs are reproduced as Table 6.4, which includes 40 of the 77 control points in Table 2.8 plus three of the four gages in Table 2.9 of Chapter 2.

Daily flows covering different periods-of-record at two gages are combined to compile daily flows at each of control points SHGR26, BRHB42, BRBR59, and NABR67 included in Tables 2.8 and 2.9. SHGR26 is not included in the 58 control points with pattern hydrographs. The extra USGS gages for BRHB42, BRBR59, and NABR67, which are included in the 58 control points with pattern hydrographs, are included in Table 6.4. The flows adopted here for each of these three control points were compiled by combining two gage records.

The last two columns of Table 6.4 show the period-of-record for each of the gages and the number of days during the periods-of-record with no data. The 1,734 days of missing data at gage 08080500 (DAMS09) are all before July 1939. The 8,005 days with no data at control point PAGR31 are before June 1947. The missing data at LRLR53 and BRRI70 occur before August 1962 and October 1923, respectively.

Table 6.4
Control Points with Gages Relevant in the Compilation of Daily Flow Pattern Hydrographs

WAM CP ID	Stream	Nearest City	USGS Gage No.	Watershed Area (square miles)	USGS Period of Record	Missing Days
RWPL01	Running Water Draw	Plainview	08080700	295	1939–present	10,166
SFAS06	Salt Fork Brazos River	Aspermont	08082000	2,504	1924–present	5,058
DMJU08	Double Mountain Fork	Justiceburg	08079600	265	1961–present	5
DMAS09	Double Mountain Fork	Aspermont	08080500	1,891	1923–present	1,734
BRSE11	Brazos River	Seymour	08082500	5,996	1923–present	0
CFNU16	Clear Fork Brazos	Nugent	08084000	2,236	1924–present	2
CFFG18	Clear Fork Brazos	Fort Griffin	08085500	4,031	1924–present	0
BRSB23	Brazos River	South Bend	08088000	13,171	1938–present	0
BRPP27	Brazos River	Palo Pinto	08089000	14,309	1924–present	0
BRDE29	Brazos River	Dennis	08090800	15,733	1968–present	0
BRGR30	Brazos River	Glen Rose	08091000	16,320	1923–present	0
PAGR31	Paluxy River	Glen Rose	08091500	411	1924–present	8,005
BRAQ33	Brazos River	Aquilla	08093100	17,746	1938–present	1
AQAQ34	Aquilla Creek	Aquilla	08093500	307	1939–2001	0
NBCL36	North Bosque River	Clifton	08095000	977	1923–present	0
NBVM37	North Bosque River	Valley Mills	08095200	1,158	1959–present	1,025
BRWA41	Brazos River	Waco	08096500	20,065	1898–present	0
BRHB42	Brazos River	Highbank	08098290	20,900	1965–present	2
Additional gage for BRHB42		Marlin	08097500	20,645	1938-1951	0
LEGT47	Leon River	Gatesville	08100500	2,379	1950–present	0
COPI48	Cowhouse Creek	Pidcoke	08101000	455	1950-present	8
LEBE49	Leon River	Belton	08102500	3,579	1923–present	0
LAKE50	Lampasas River	Kempner	08103800	817	1962–present	0
LRLR53	Little River	Little River	08104500	5,266	1923–present	3,470
SGGE55	South Fork San Gabriel	Georgetown	08104900	132	1967–present	0
GAGE56	San Gabriel River	Georgetown	08105000	404	1924–1987	7,526
GALA57	San Gabriel River	Laneport	08105700	737	1965–present	3
LRCA58	Little River	Cameron	08106500	7,100	1916–present	36,373
BRBR59	Brazos River	Bryan	08109000	30,016	1899–1993	0
Additional gage for BRBR59		SH 21 Bryan	08108700	29,483	1993-present	0
MYDB60	Middle Yequa Creek	Dime Box	08109700	235	1962-present	0
EYDB61	East Yegua Creek	Dime Box	08109800	239	1962–present	0
YCSO62	Yegua Creek	Somerville	08110000	1,011	1924–1991	6,210
DCLY63	Davidson Creek	Lyons	08110100	195	1962-present	0
NAEA66	Navasota River	Easterly	08110500	936	1924–present	0
NABR67	Navasota River	Bryan	08111000	1,427	1951–1997	801
Additional gage for NABR67		OSR Bryan	08110800	1,287	1997-present	0
BRHE68	Brazos River	Hempstead	08111500	34,374	1938–present	0
BRRI70	Brazos River	Richmond	08114000	35,454	1903–present	5,936
BGNE71	Big Creek	Needville	08115000	46	1947–present	640
BRRO72	Brazos River	Rosharon	08116650	35,775	1967–present	1,302
CLPEC1	Clear Creek	Pearland	08077000	38.8	1944–1994	2,339
CBALC2	Chocolate Bayou	Alvin	08078000	87.7	1959–present	1

Daily Flow Pattern Hydrographs

Unregulated daily flows for January 1940 through December 1997 from the USACE modeling system are adopted for the 16 primary and 21 secondary control points listed in Table 6.5. The USACE unregulated flows cover the period 1940-1997 at these 37 control points. Observed flows from USGS gages are adopted for January 1998 through December 2017. The 1940-1997 USACE unregulated flows and 1998-2017 USGS gaged flows were combined using the tabular edit feature of *HEC-DSSVue*. Only relative, not absolute, magnitudes of daily flows within each month are relevant in the pattern hydrographs. Thus, months of daily flows from two or more different sources or sites can be combined to develop a complete 1940-2017 sequence.

Selection of Control Points and Gaging Stations

The control point of the 1998-2017 gaged flows is indicated in the last column of Table 6.5. For the 16 primary control points located at USGS gage sites, the observed flows at the site are adopted to the extent that the gage record covers January 1, 1998 through December 31, 2017. Interpolation is applied to fill in one to several days of missing data. For gage sites with significant periods of missing data during 1998-2017, observed flows from another gage are adopted. In this case, the source gage site is listed in the last column of Table 6.4. There are no gages at the 21 secondary control points listed in Table 6.4. Observed 1998-2017 flows at the gage sites listed in the last column are employed at these control points.

Judgement was applied in selecting nearby gages for filling in missing data that have relatively unregulated watersheds if possible. For several of the daily pattern flow control points located below dams, source sites upstream of the lake were selected as being more representative of natural unregulated flow conditions. Watershed area was also considered. Sites with smaller drainage areas tend to have greater flow variability than sites with larger drainage areas.

Daily flows for 1998-2017 at the control points listed in the first column of Table 6.5 are supplied by gaged flows at the control points listed in the last column. A single USGS gage site was adopted for each WAM control point where feasible, but multiple gage sites are combined if needed. The 1998-2017 flows at control point 509431 are assigned as the gaged flows at control point NBVM37, with missing data filled in from NBCL36. Flows at control point 516031 are the summation of flows at control points COPI48 and LEGT47. Flows at control points 516431 and CON129 are the summation of flows at MYDB60, EYDB61, and DCLY63.

Observed flows are employed for the 1940-2017 daily pattern hydrographs stored in the *SIMD* hydrology input DSS file for the 21 gaged primary control points listed in Table 6.6. In cases of missing data during 1940-2017, USACE unregulated and/or USGS gaged flows from another site are used to fill in the periods of missing observed data. The sources of daily flow data for filling in periods of missing recorded data are listed in the last column of Tables 6.5 and 6.6.

Judgement was applied in selecting source gages (last column of tables) for filling in missing data at the control points listed in the first column that are located reasonably nearby with shared or adjacent watersheds of similar size but relatively unregulated without reservoirs. Missing data at CLPEPC1 are filled with flows at CBALC2 to the extent available, then with flows from YCSO62. Flows at CBALC2 are completed similarly with flows from CLPEC1 and then YCSO62.

Table 6.5
37 Control Points with 1940-1997 USACE Unregulated Flows

Control Point	Stream	DA (sq mile)	1998-2017 Flows
	16 Primary (Gaged) Control Points		
BRDE29	Brazos River	15,733	–
BRGR30	Brazos River	16,320	–
AQAQ34	Aquilla Creek	307	PAGR31
NBCL36	North Bosque River	977	–
BRWA41	Brazos River	20,065	–
BRHB42	Brazos River	20,900	–
LEGT47	Leon River	2,379	–
LRLR53	Little River	5,266	–
SGGE55	San Gabriel River	132	–
GAGE56	SF San Gabriel River	404	SGGE55
LRCA58	Little River	7,100	–
BRBR59	Brazos River	30,016	gage 08108700
NAEA66	Navasota River	936	–
NABR67	Navasota River	1,427	gage 08110800
BRHE68	Brazos River	34,374	–
BRRI70	Brazos River	35,454	–
	21 Secondary (Ungaged) Control Points		
515531	Brazos River	14,030	BRSB23
515631	Brazos River	16,181	BRDE29
515731	Brazos River	17,690	BRAQ33
515831	Aquilla Creek	254	PAGR31
227901	North Bosque River	710	NBCL36
509431	Bosque River	1,655	NBVM37, NBCL36
515931	Leon River	1,280	PAGR31
516031	Leon River	3,568	COPI48+LEGT47
516131	Lampasas River	1,313	LAKE50
516231	San Gabriel River	247	SGGE55
516331	San Gabriel River	726	GALA57
516431	Yequa Creek	1,008	MYDB60+EYDB61+DCLY63
516531	Navasota River	675	NAEA66
CON070	Brazos River	18,313	BRAQ33
CON095	Lampasas River	1,511	LRLR53
CON102	San Gabriel River	1,357	LRCA58
CON129	Yequa Creek	1,302	MYDB60+EYDB61+DCLY63
CON137	Mill Creek	1,295	NABR67
CON145	Gibbons Creek	2,066	NABR67
CON147	Brazos River	33,930	BRHE68
CON231	Navasota River	2,241	NABR67

Table 6.6
21 Primary Control Points with Gaged Flows Adopted for 1940-2017 Daily Pattern Flows

WAM CP ID	Stream	Nearest City	Watershed Area (sq miles)	USGS Period of Record	Missing Days	Filling in Missing Data
RWPL01	Running Water Draw	Plainview	295	1939–present	10,166	DMJU08
SFAS06	Salt Fork Brazos River	Aspermont	2,504	1924–present	5,058	–
DMJU08	Double Mountain Fork	Justiceburg	265	1961–present	5	DMAS09
DMAS09	Double Mountain Fork	Aspermont	1,891	1923–present	1,734	–
BRSE11	Brazos River	Seymour	5,996	1923–present	2	–
CFNU16	Clear Fork Brazos	Nugent	2,236	1924–present	3	–
CFFG18	Clear Fork Brazos	Fort Griffin	4,031	1924–present	0	–
BRSB23	Brazos River	South Bend	13,171	1938–present	0	–
BRPP27	Brazos River	Palo Pinto	14,309	1924–present	0	–
PAGR31	Paluxy River	Glen Rose	411	1924–present	8,005	NBCL36
BRAQ33	Brazos River	Aquilla	17,746	1938–present	1	–
NBVM37	North Bosque River	Valley Mills	1,158	1959–present	1,025	NBCL36
LEBE49	Leon River	Belton	3,579	1923–present	0	–
LAKE50	Lampasas River	Kempner	817	1962–present	0	LAYO51
GALA57	San Gabriel River	Laneport	737	1965–present	3	GAGE56
EYDB61	East Yegua Creek	Dime Box	239	1962–present	0	YCSO62
YCSO62	Yegua Creek	Somerville	1,011	1924–present	6,210	EYDB61
BGNE71	Big Creek	Needville	46	1947–present	640	YCSO62
BRRO72	Brazos River	Rosharon	35,775	1967–present	1,302	BRRI70
CLPEC1	Clear Creek	Pearland	38.8	1944–1994	2,339	CBALC2, YCSO62
CBALC2	Chocolate Bayou	Alvin	87.7	1959–present	1	CLPEC1, YCSO62

Data Compilation and Manipulation Methods

The first dataset listed in Tables 6.3 and 7.1 consists of period-of-record, as of December 13, 2018, daily flows in cfs at 74 USGS gaging stations representing 70 WAM control points that were downloaded from the USGS NWIS website using the Hydrologic Engineering Center (HEC) Statistical Software Program (SSP), which stored the flow sequences in a DSS file. Both HEC-DSSVue and HEC-SSP have similar features for downloading flow data from the USGS NWIS website. However, the NWIS data download feature in the current version of HEC-DSSVue is not currently functioning due to changes made by the USGS in the NWIS website. Thus, the flows were downloaded from the NWIS using HEC-SSP into a DSS file accessed by HEC-DSSVue.

Datasets compiled for the daily Brazos WAM at different times over the past two years were updated again in December 2018 in order to have the latest data. The USGS often revises provisional data recorded over the most recent past several months. Thus, updates include correction of provisional data as well as extension of the period-of-record.

Simple linear interpolation was applied if one day or a small number of days have no flows recorded in the gage record. For gages with significant periods with no recorded data, the last column of Tables 6.5 and 6.6 shows the control point location from which gaged daily flows are adopted for the control point listed in the first column. If gaged daily flows are available at the control point listed in the first column for the entire period 1998-2017 (Table 6.5) or 1940-2017 (Table 6.6), these flows are adopted without needing an alternative source site, and thus the last column of the tables is blank. HEC-DSSVue tabular editor features for finding and filling in days of missing data were employed.

Two or three gages are cited in the last column of Tables 6.5 and 6.6 for several of the control points listed in column 1. Two control points separated by commas, such as "CLPEC1, YCSO62", means that flows are provided by the first control point listed to the extent available and then remaining gaps are filled in from the second control point listed. Summations such as MYDB60+EYDB61+DCLY63 mean that the flows at the multiple control points are added each day. Flows were combined within HEC-DSSVue using mathematical options accessed through the tools feature.

The daily flow in cfs at many of the control points reflect combinations of different sub-periods at two or more sites to cover the entire 1940-2017 hydrologic period-of-analysis. These flow sequences would function fine as *SIMD* pattern hydrographs. However, these daily flows are combined with the WAM monthly naturalized flows to obtain 1940-2017 daily naturalized flows in acre-feet that are adopted for the *SIMD* hydrology input. *SIMD* was executed with the initial pattern hydrograph, and the computed daily naturalized flow volumes were transferred from the simulation results DSS file to the hydrology input DSS file. Thus, both the monthly naturalized flow volumes and daily flow patterns are represented in the adopted *DF* record flows.

CHAPTER 7
MONTHLY NATURALIZED FLOWS

The Brazos WAM hydrology input dataset contains monthly naturalized flows at the 77 control points listed in Table 2.8 that are located at the sites shown in Figures 2.13 and 2.14. Monthly naturalized flows at over 3,700 secondary control points are synthesized during the *SIM* or *SIMD* simulation based on the flows at the 77 primary control points and information provided on *CP* records in the DAT file and *FD* and *WP* records in the flow distribution DIS file. Flow distribution option 6 based on drainage area ratios and channel loss factors is employed for synthesizing flows at most of the secondary control points in the Brazos WAM.

The original Brazos WAM has a hydrologic period-of-analysis of January 1940 through December 1997 which has been extended through December 2017 as outlined in Chapters 7 and 8. The present Chapter 7 describes monthly naturalized streamflows. Chapter 8 covers 1940-2017 sequences of monthly reservoir net evaporation less preciptation rates.

The 1940-2017 sequences of monthly naturalized flow at 77 control points are composed of the three following subsequences as described in this chapter.

1. 1940-1997 sequences at 77 control points from the original WAM [8, 9] with minor refinements made recently by Freese and Nichols, Inc. [10].
2. 1998-2015 sequences at 73 control points developed by Freese and Nichols for the Brazos River Authority [10] in conjunction with submission to the TCEQ of a system operations permit application and water management plan [11, 12, 13, 14]. This dataset includes all 73 primary control points in the Brazos River Basin but excludes the four control points located in the San Jacinto-Brazos coastal basin.
3. 2016-2017 sequences at 77 control points and 1998-2017 sequences at 4 control points developed in conjunction with the daily Brazos WAM documented by this report based on observed flows and flows synthesized with a hydrologic model.

Data files accompanying this report are listed in Table 1.2 on page 5. Additional relevant monthly flow hydrographs stored in the file BrazosMonthlyFlows.DSS are discussed in the present Chapter 7 as well as the *IN* record naturalized monthly flows in the file BrazosHYD.DSS.

Original 1940-1997 Monthly Naturalized Flows

Development of the original hydrology dataset is documented by the 2001 WAM Reports [8, 9]. The original sequences of monthly naturalized flows for 1940-1997 at 72 of the 77 primary control points were developed by adjusting actual observed flows recorded at USGS gaging stations. Naturalized flows at two of the primary control points were developed by adjusting gaged releases from reservoirs, Buffalo Springs Lake near Lubbock and Lake Graham near Graham. The other three primary control points represent basin outlets.

Naturalized flows were developed by adjusting actual observed flows recorded at USGS gaging stations to remove the effects of human activities as follows.

Naturalized Flow = Historical Gaged Flow + Upstream Diversions – Upstream Return Flows + Changes in Upstream Reservoir Storage + Upstream Reservoir Evaporation

Historical gaged flows were determined using available USGS stream flow data. For many control point locations, USGS flow data were not available for the full 1940-1997 period-of-analysis. Missing data were estimated based on relationships with other primary control points that had flow data covering the relevant period of concern [8]. Channel loss factors were included in the adjustment computations for upstream activities.

Upstream diversions were estimated using a variety of methods for municipal, industrial, and agricultural water rights. For municipal water rights, water use records from the Texas Natural Resource Conservation Commission (TNRRC, later renamed TCEQ) were used to determine historical diversions. Gaps in the available data were filled in by contacting individual water right holders or making estimates on a per capita basis using population data. Water use estimates for industrial and agricultural water rights were made using historical water use patterns for individual rights or rights with similar uses and diversion amounts. Historical water use was estimated to be zero for water rights for which sound estimates could not be determined.

Historical return flows were estimated for municipal and industrial users and neglected for agricultural users. TNRCC return flow data was available for municipal and industrial sites for the period from 1978 to 1996. Return flow data for the remaining time period was determined using records from individual users or estimates based on information from individual users.

Historical changes in reservoir storage were determined using USGS data, information from alternative sources, or estimates of storage content changes. Historical reservoir evaporation was estimated by multiplying the net evaporation rate by the average reservoir surface area. The net evaporation rate was computed by subtracting precipitation from evaporation using TWDB data. Values of evaporation and precipitation for each reservoir were computed using the sum of weighted values from adjacent TWDB quadrangles.

Hydrology Dataset Developed by Freese and Nichols for the Brazos River Authority

As previously noted on pages 21-23 of Chapter 2, Freese and Nichols (FN), Inc. developed an updated monthly Brazos WAM in conjunction with the Brazos River Authority (BRA) system operations permit and associated water management plan [10, 11, 12, 13, 14]. The hydrologic period-of-analysis was updated to extend through December 2015 and the original 1940-1997 flows were refined. The 2017 update report [10] documents the changes to the original WAM hydrology dataset documented by the original 2001 report [9].

The methods employed to convert 1998-2015 observed flows at USGS gaging stations to WAM monthly naturalized flows were essentially the same as those used in developing the original WAM dataset, though smaller reservoirs, diversions, and return flows considered originally [9] were omitted in the update [10]. The process for naturalizing the 1998-2015 flows included adjustments for: diversions by water rights authorized for more than 1,000 acre-feet/year; reservoirs with capacity of 10,000 acre-feet or greater; and return flows larger than 2 million gallons per day. The 73 primary control points in the Brazos River Basin are included in the hydrology update. The four control points in the San Jacinto-Brazos coastal basin are not included.

The naturalized flow update also included minor refinements to the flow adjustment computations for the original 1940-1997 naturalized flows and evaporation-precipitation rates at several sites. However, these computational improvements were concluded to have only minimal impacts on water availability simulation results.

Hydrologic Model Relating Monthly Naturalized Flows to Precipitation and Evaporation

A WRAP program *HYD* methodology described in Chapters 5 and 7 of the *Hydrology Manual* [5] was employed during 2012 to extend the naturalized flows to cover 1998-2011 as described in detail in the 2012 Brazos WAM hydrology extension report [18]. The update of the Brazos WAM during 2012 was the first application of the new *HYD* hydrologic model.

The *HYD* flow extension model is a physically relevant regression model with numerous parameters to be calibrated [5]. Calibration of the hydrologic model is complex and requires significant time and expertise. However, after the flow extension model has been calibrated for each individual control point, the extension of naturalized flows is performed quickly. Naturalized flows can be extended easily as more years of precipitation and evaporation data accumulate. The model is designed to replicate the statistical characteristics of the naturalized flows over a series of many months rather than focus on accuracy in particular individual months.

The work during 2018 documented by this present report included extending the flows from January 1998 through December 2017 at all 77 primary control points using the previously calibrated model parameters determined based on 1940-1997 hydrology. A complete set of 1998-2017 monthly naturalized flows was synthesized using the WRAP program *HYD* hydrologic model, but only a selected subset of these flows were actually adopted for incorporation in the WAM. Comparative analyses of the extended flows and observed flows were performed. Based on these analyses, the flows extended using the hydrologic model were adopted at some control points for some periods, but actual observed flows were used instead of the synthesized flows in some cases. The selection of flows from alternative sources is outlined later in this chapter.

The *HYD* watershed rainfall-streamflow model extends monthly naturalized flows based on relating naturalized flow sequences to corresponding monthly precipitation and reservoir evaporation rate sequences from Texas Water Development Board (TWDB) databases. The TWDB maintains datasets of monthly precipitation and evaporation depths for the 92 one degree latitude by one degree longitude quadrangles shown in Figure 8.1. The *HYD* flow extension model has been calibrated for each of the 77 primary control points listed in Table 2.8 using the original naturalized flows along with concurrent TWDB precipitation and evaporation depths for relevant quadrangles [18]. The calibrated flow extension model is employed to compute naturalized flows for the period from January 1998 through December 2017 using 1998-2017 TWDB precipitation and evaporation depths as input.

Program *HYD* consists of various routines designed to facilitate developing and updating net evaporation-precipitation rates and naturalized flows included in *SIM* simulation input datasets. The *HYD* methodology referenced here is described in detail in Chapters 4 and 7 of the *Hydrology Manual* [5]. The hydrologic model is essentially a physically relevant regression model with numerous parameters to be calibrated (regressed). Complex optimization algorithms are automated within *HYD* to perform the iterative search for optimal parameter values. However, after the model has been calibrated for each relevant control point, the extension of naturalized flows is quick and easy. With the model calibration completed, flows can be further extended each year in the future as the TWDB continues to update the precipitation and evaporation datasets. The same TWDB datasets are used to extend both the naturalized flows and the net evaporation-precipitation rates.

A DSS file with 1940-2017 monthly naturalized flows at the 77 primary control points was created by executing the WRAP program *HYD* with the following input files.

HIN file controlling the 1997-2017 naturalized flow extension.
FLO file from Brazos WAM with 1940-1997 monthly naturalized flows.
Evaporation.EEE file with TWDB statewide 1940-2017 evaporation data.
Precipitation.PPP file with TWDB statewide 1940-2017 precipitation data.

The *HYD* input HIN file contains the values for the parameters of the previously calibrated hydrologic models for each of the 77 control points and all other input data required for the flow synthesis computations [13]. The resulting DSS record dataset, with renamed pathnames, is included in the DSS file BrazosMonthlyFlows.DSS.

Observed Flows at USGS Gaging Stations and WAM Control Points

Seventy-seven primary control points with locations shown in Figures 2.13 and 2.14 are listed in Table 2.8. Seventy-two of the 77 primary control points listed in Table 2.8 are located at USGS gaging stations with periods-of-record that include all or a portion of 1940-1997. Fifty of the USGS gages listed in Table 2.8 have periods-of-record that include 1998-2017. Twenty-seven of the gages in Table 2.8 have been discontinued and are no longer operated. Records for four of the gages in Table 2.8 are combined with the gages listed in Table 2.9 to compile longer periods-of-record.

Primary control point BRGM73 represents the outlet of the Brazos River which has no gage. Primary control points SJGBC3 and SJGMC4 represent the outlets of Clear Creek and Chocolate Bayou in the Brazos-San Jacinto coastal basin which have no gage. Primary control points CLPEC1 and CBALC2 with periods-of-record of 1944-1994 and 1959-present, respectively, are the only control points in the coastal basin with stream flow gage records.

Observed daily flows are discussed in Chapter 1 and used for daily pattern hydrographs as discussed in Chapter 6. The DSS files described in the next section contain recorded daily and aggregated monthly flows for 74 USGS gages. Daily mean flow rates in cfs are downloaded from the USGS NWIS website and aggregated to monthly volumes in acre-feet using *HEC-DSSVue*.

Seventy-two of the 77 primary control points listed in Table 2.8 are at USGS gages, four of which have gaps during 1940-2017 filled in with flows from the four gages in Table 2.8 in compiling the daily flow pattern hydrographs described in Chapter 6. Two of the 72 gages (WRSP02 and NBHI35) have been deactivated by the USGS and removed from the NWIS website. Of the 77 primary control points, the original USGS gages at the sites of the following four control points are no longer not found in the USGS NWIS and thus are not included in the first dataset described in the next section and listed in Table 7.1: WRSP02, BSLU07, GHGH24, and NBHI35.

Stream Flow Datasets Stored in the File BrazosMonthlyFlows.DSS

The DSS file prepared in conjunction with analyzing, synthesizing, and verifying monthly flows has the filename BrazosMonthlyFlows.DSS and contains the following eight datasets, which contain a total of 567 data sequences, referred to in parenthesis below as DSS data records.

1. Period-of-record observed daily flows in cfs at 70 of the 77 control points listed in Table 2.8 and the four gages in Table 2.9 obtained from the USGS NWIS website (74 records).
2. Monthly means in cfs of the period-of-record daily observed flows at the 74 USGS gages included in the daily flow dataset described above (74 records).
3. Monthly summations in acre-feet/month of the period-of-record daily observed flows at the 74 gaged control points included in the original daily flow dataset described above (74 records).
4. Monthly summations in acre-feet/month of 1940-1997 daily unregulated flows from the USACE Fort Worth District modeling system at 16 primary and 21 secondary control points, which are listed in Table 6.2 (37 records).
5. 1940-2017 monthly naturalized flow volumes in acre-feet/month at the 77 primary control points composed of the original 1940-1997 monthly naturalized flows and 1998-2017 extensions synthesized using the hydrologic modeling feature of the WRAP program *HYD* that relates naturalized flows to precipitation and evaporation (77 records).
6. 1940-1997 monthly naturalized flow volumes in acre-feet/month at the 77 primary control points from the official TCEQ Bwam3 Brazos WAM last updated 11/3/2017 (77 records).
7. 1940-2015 monthly naturalized flow volumes in acre-feet/month at the 77 primary control points from the BRA Brazos WAM last updated 5/8/2017 (77 records).
8. Final adopted 1940-2017 monthly naturalized flows at the 77 WAM primary control points compiled as described in the last section of this chapter. These *IN* records are included in the daily Brazos WAM hydrology input file BrazosHYD.DSS (77 records).

Control point LRCA58 at the USGS gaging station on the Little River near Cameron is used in Table 7.1 to illustrate the pathnames adopted for the DSS data records in each of these eight datasets. Pathname Part B and/or Part F are used for control point identifiers. The DSS file contains records for each of the relevant WAM control points.

Table 7.1
DSS Pathnames for the File BrazosMonthlyFlows.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	LITTLE RV	CAMERON, TX	USGS DAILY CFS	01JAN1916-01JAN2018	1DAY	LRCA58
2	LITTLE RV	CAMERON, TX	USGS MONTHLY MEANS CFS	01JAN1910-01JAN2010	1MON	LRCA58
3	LITTLE RV	CAMERON, TX	USGS MONTHLY VOLUME AC-FT	01JAN1910-01JAN2010	1MON	LRCA58
4	USACE UNREGULATED	LITTLE RIVER, CAMERON	FLOW USACE ACRE-FEET	01JAN1910-01JAN1990	1MON	LRCA58
5	WAM & 1998-2017 HYD	LRCA58	NATURALIZED ACRE-FEET	01JAN1940-01JAN2010	1MON	LRCA58
6	TCEQ BWAM3 1940-1997	LRCA58	IN	01JAN1940-01JAN1990	1MON	
7	BRA 1940-2015	LRCA58	IN	01JAN1940-01JAN2010	1MON	
8	BRAZOS	LRCA58	IN	01JAN1940-01JAN2010	1MON	

The first dataset consists of period-of-record, as of December 13, 2018, daily flows in cubic feet per second (cfs) at 74 USGS gaging stations representing 70 WAM control points that were downloaded from the U.S. Geological Survey (USGS) National Water Information System (NWIS) website using the Hydrologic Engineering Center (HEC) Statistical Software Program (SSP). Parts A and B of the pathname indicate the gage site location (Little River near Cameron). Parts C and E indicate the type of data (USGS daily flows in cfs), and Part D shows the range covered by the data blocks, which encompasses the period-of-record covered by the daily observed flows. The WAM control point identifier (LRCA58) is recorded in Part F.

The second dataset was created within *HEC-DSSVue* by converting the period-of-record observed flow daily means in cfs at the 74 USGS gages representing 70 primary control points stored in the first dataset to monthly means in cfs. The following *HEC-DSSVue* option path was employed: Tools – Math Functions – Time Functions – Min/Max/Avg/…over period – Average for Period – 1MON.

The third dataset was created within *HEC-DSSVue* by converting the daily flow means in cfs in the first dataset to monthly volumes in acre-feet using. the following *HEC-DSSVue* option: Tools – Math Functions – Time Functions – Min/Max/Avg/ – Volume for Period – 1MON.

The fourth dataset consists of monthly summations of the USACE 1940-1997 daily unregulated flows, described in Chapter 6, at 37 locations of which 16 sites are USGS gage sites at WAM primary control points. The daily flows were summed to monthly volumes within *HEC-DSSVue*. The beginning date for the monthly flow sequences was changed from 24:00 hours (midnight) on January 1, 1940 to 24:00 hours on December 31, 1939 using the following *HEC-DSSVue* option path: Tools – Math Functions – Time Functions – Shift in Time – Shift to date/time.

The fifth dataset consists of 1940-2017 monthly naturalized flows at the 77 WAM primary control points. The original naturalized flows are adopted without change for 1940-1997. The WRAP program *HYD* hydrologic model that relates naturalized flows to precipitation and evaporation was applied to extend the flows through 1998-2017. Pathnames for the 77 records of 1940-2017 monthly naturalized flows at the 77 primary control points are assigned as indicated in Table 7.1, which shows only control point LRCA58.

The sixth dataset consists of the final 1940-2017 monthly naturalized flows at the 77 primary control points adopted for the official TCEQ Brazos WAM which has flow file Bwam3.FLO which was last updated by the TCEQ on November 3, 2017.

The seventh dataset is from the FLO file dated May 8, 2017 of the WAM dataset compiled by the consulting firm Freese and Nichols (FN) in support of the Brazos River Authority (BRA) system operations permit and associated water management plan. The hydrologic period-of-analysis was updated by BRA/FN to extend through December 2015 and the original 1940-1997 flows were refined as noted earlier in this chapter.

The eighth dataset consists of the final naturalized 1940-2017 monthly flows at 77 control points adopted for the daily Brazos WAM. These are the *IN* records in the hydrology input file BrazosHYD.DSS. These final *IN* record flow sequences were developed by combining monthly flow sequences from the third, fifth, and sixth datasets as described in the next section.

Adopted Monthly Naturalized Flows at the 77 Primary Control Points

The previously discussed FN/BRA hydrology dataset compiled by Freese and Nichols (FN) for the Brazos River Authority (BRA) system operations permit and associated water management plan [10, 11, 12, 13, 14] was adopted for the daily Brazos WAM documented here. The monthly naturalized flows and evaporation-precipitation depths stored in FLO and EVA files in the FN/BRA dataset cover a hydrologic period-of-analysis of 1940-2015. The FN/BRA hydrology dataset is modified as follows in conjunction with developing the daily Brazos WAM.

1. The FLO and EVA files are converted to DSS records in a DSS file.
2. Control points CLPEC1, CBALC2, SJGB3, and SJGMC4 are located in the coastal basin and have zeros on the *IN* records for all months during 1998-2015 in the FN/BRA FLO file. The 1998-2017 naturalized flows for these control points are compiled using observed flows and *HYD* synthesized flows.
3. The 2016-2017 naturalized monthly flows for all 77 primary control points are added to the dataset using observed flows and *HYD* synthesized flows.
4. The evaporation-precipitation rates are likewise extended as described in Chapter 8.

The 77 primary control points are listed in Table 7.2. The last four control points listed in Table 7.2 are located in the San Jacinto-Brazos coastal basin. Control point CBALC2 is located at a USGS gaging station with a complete record of observed flows from 1959 to the present. Observed flows are adopted as the 1998-2017 monthly naturalized flows for control point CBALC2. Control points CLPEC1, SJGBC3, and SJGMC4 have no record of observed flows during 1998-2017. Sequences of 1998-2017 monthly naturalized flows synthesized with the WRAP program *HYD* hydrologic model are adopted for these three coastal basin control points.

The other 73 control points listed in Table 7.1 are located in the Brazos River Basin. The naturalized monthly flows at these 73 control points are extended over the period from January 2015 through December 2017 with either *HYD* synthesized flows or USGS gaged flows. Naturalized flows for 2015-2017 consist of *HYD* synthesized flows for 45 of the 73 control points and USGS gaged flows are adopted for the other 28 sites in the Brazos River Basin as indicated in the last column of Table 7.1. The Edit – Tabular Edit feature of *HEC-DSSVue* was used to combine portions of the data records from the different flow datasets to create the final monthly flow dataset.

Monthly naturalized flows for 1998-2017 for the 77 Brazos WAM primary control points were computed using the previously calibrated *HYD* hydrologic model with 1998-2017 monthly quadrangle precipitation and evaporation depths from the TWDB database. These flows can be combined with the original 1940-1997 naturalized flows or FN/BRA 1998-2015 naturalized flows.

HEC-DSSVue facilitates convenient comparative analyses of observed flows recorded at gages, naturalized flows computed by adjusting observed flows, and *HYD* synthesized 1940-1997 and 1998-2017 flow sequences. Choices between the available alternative flow extension data were supported by these analyses. USGS gaged flows are adopted for sites with relatively small unregulated watersheds. Gaged flows at some sites are identical or almost identical to WAM naturalized and USACE unregulated flows. The 2015-2017 flows synthesized with the *HYD* hydrologic model are adopted for control points with no gages or with large watersheds and flows regulated by large dams. Twenty-six control points have no recorded flows during 1998-2017.

Table 7.2
Sources of 2016-2017 Naturalized Monthly Flows at the 77 Primary Control Points

WAM CP ID	Stream	Watershed Area (sq. miles)	Gage Period of Record	2016-2017 Extension
RWPL01	Running Water Draw	295	1939–present	Gaged
WRSP02	White River Reservoir	689	1964-1976	HYD
DUGI03	Duck Creek	300	1964-1989	HYD
SFPE04	Salt Fork Brazos River	2,007	1950–1986	HYD
CRJA05	Croton Creek	293	1959–1986	HYD
SFAS06	Salt Fork Brazos River	2,504	1924–present	Gaged
BSLU07	Buffalo Spring Lake	245	reservoir releases	HYD
DMJU08	Double Mountain Fork	265	1961–present	Gaged
DMAS09	Double Mountain Fork	1,891	1923–present	Gaged
NCKN10	North Croton Creek	250	1965–1986	HYD
BRSE11	Brazos River	5,996	1923–present	Gaged
MSMN12	Millers Creek	106	1963–present	Gaged
CFRO13	Clear Fork Brazos	266	1962–present	Gaged
CFHA14	Clear Fork Brazos	1,456	1967–1989	HYD
MUHA15	Mulberry Creek	208	1967–1989	HYD
CFNU16	Clear Fork Brazos	2,236	1924–present	HYD
CAST17	California Creek	476	1962–present	Gaged
CFFG18	Clear Fork Brazos	4,031	1924–present	Gaged
HCAL19	Hubbard Creek	612	1966–present	Gaged
BSBR20	Big Sandy Creek	289	1962–present	Gaged
HCBR21	Hubbard Creek	1,092	1955–1986	HYD
CFEL22	Clear Fork Brazos	5,738	1915–1982	HYD
BRSB23	Brazos River	13,171	1938–present	Gaged
GHGH24	Lake Graham	224	reservoir releases	HYD
CCIV25	Big Cedar Creek	97	1964–1989	HYD
SHGR26	Brazos River	14,030	1976–1994	HYD
BRPP27	Brazos River	14,309	1924–present	HYD
PPSA28	Palo Pinto Creek	574	1924–1976	HYD
BRDE29	Brazos River	15,733	1968–present	HYD
BRGR30	Brazos River	16,320	1923–present	HYD
PAGR31	Paluxy River	411	1924–present	Gaged
NRBL32	Nolan River	282	1947–present	Gaged
BRAQ33	Brazos River	17,746	1938–present	HYD
AQAQ34	Aquilla Creek	307	1939–2001	HYD
NBHI35	North Bosque River	360	1994–2003	HYD
NBCL36	North Bosque River	977	1923–2008	HYD
NBVM37	North Bosque River	1,158	1959–present	Gaged
MBMG38	Middle Bosque River	77	1959–present	Gaged
HGCR39	Hog Creek	181	1959–present	HYD
BOWA40	Bosque River	1,660	1959–1982	HYD

Table 7.2 Continued
Sources of 1998-2017 Naturalized Monthly Flows at the 77 Primary Control Points

WAM CP ID	Stream	Watershed Area (sq. miles)	Gage Period of Record	2016-2017 Extension
BRWA41	Brazos River	20,065	1898–present	HYD
BRHB42	Brazos River	20,900	1965–present	HYD
LEDL43	Leon River	267	1960–present	Gaged
SADL44	Sabana River	476	1960–present	Gaged
LEHS45	Leon River	1,283	1939–present	HYD
LEHM46	Leon River	1,928	1925–present	HYD
LEGT47	Leon River	2,379	1950–present	HYD
COPI48	Cowhouse Creek	455	1950–present	Gaged
LEBE49	Leon River	3,579	1923–present	HYD
LAKE50	Lampasas River	817	1962–present	Gaged
LAYO51	Lampasas River	1,240	1924–1980	HYD
LABE52	Lampasas River	1,321	1963–present	HYD
LRLR53	Little River	5,266	1923–present	HYD
NGGE54	North Fork San Gabriel	248	1968–present	HYD
SGGE55	South Fork San Gabriel	132	1967–present	Gaged
GAGE56	San Gabriel River	404	1924–1987	HYD
GALA57	San Gabriel River	737	1965–present	HYD
LRCA58	Little River	7,100	1916–present	HYD
BRBR59	Brazos River	30,016	1899–1993	HYD
MYDB60	Middle Yegua Creek	235	1962–present	Gaged
EYDB61	East Yegua Creek	239	1962–present	Gaged
YCSO62	Yegua Creek	1,011	1924–1991	HYD
DCLY63	Davidson Creek	195	1962–present	Gaged
NAGR64	Navasota River	240	1978–present	Gaged
BGFR65	Big Creek	97	1978–present	Gaged
NAEA66	Navasota River	936	1924–present	Gaged
NABR67	Navasota River	1,427	1951–1997	HYD
BRHE68	Brazos River	34,374	1938–present	HYD
MCBL69	Mill Creek	377	1963–1993	HYD
BRRI70	Brazos River	35,454	1903–present	HYD
BGNE71	Big Creek	46	1947–present	Gaged
BRRO72	Brazos River	35,775	1967–present	HYD
BRGM73	Brazos River	36,027	–	HYD
Control Points in Coastal Basin with 1998-2017 Flow Extensions				
CLPEC1	Clear Creek	38.8	1944–1994	HYD
CBALC2	Chocolate Bayou	87.7	1959–present	Gaged
SJGBC3	Coastal Basin	415	–	HYD
SJGMC4	Coastal Basin	1,004	–	HYD

The period from January 2016 through December 2017 is generally characterized by abundant precipitation and higher than normal stream flows in the Brazos River system and adjoining river basins. Naturalized monthly flows tend to be closer to actual observed flows during periods of above normal flow than during droughts. Flood control operations of USACE reservoirs greatly affect daily flows below the dams during floods but the effects on flood flows greatly diminish with monthly aggregations of daily flows.

CHAPTER 8
EVAPORATION, PRECIPITATION, AND NET EVAPORATION-PRECIPITATION RATES

The primary final product of the compilations documented in this chapter is a dataset of sixty-seven 1940-2017 sequences of monthly net reservoir evaporation less precipitation depths in feet stored as *EV* records in the daily Brazos WAM hydrology input DSS file. However, the compilation also includes 1940-2017 monthly precipitation depths and 1954-2017 reservoir evaporation depths in inches that are relevant to extending the *EV* record net evaporation-precipitation depths. Four sets of *EV* record net evaporation-precipitation rates are covered: (1) the original WAM 1940-1997 *EV* records, (2) the updated 1940-2015 hydrology dataset compiled by Freese and Nichols, Inc. for studies supporting the Brazos River Authority systems operation permit application, (3) a 1940-2017 updated hydrology dataset extended using the WRAP program *HYD* hydrologic model, and (4) the final *EV* records adopted for the daily Brazos WAM.

Texas Water Development Board Evaporation and Precipitation Database

Datasets of monthly precipitation depths and reservoir surface evaporation depths in inches along with explanation of methods employed in compiling the data are available at the following Texas Water Development Board (TWDB) website.

https://www.twdb.texas.gov/surfacewater/conditions/evaporation/index.asp

These data were used to develop the original net evaporation-precipitation input files for the TCEQ WAM system. TWDB precipitation and evaporation datasets for the quadrangles delineated in Figure 8.1 were used in compiling the Brazos WAM datasets discussed in this chapter.

A total of 168 one-degree quadrangles with areas varying from 3,000 to 4,000 square miles encompass adjacent surrounding land area along with all of Texas. Complete records of monthly precipitation from 1940 and evaporation from 1954 to near the present are available for the 92 quadrangles that encompass the state. The datasets include an additional 76 quadrangles located outside of Texas, but there are periods of missing data for these quadrangles. The 168 one-degree quadrangles define a grid with 12 rows and 14 columns. The three or four digit quadrangle identifiers consist of the row and column numbers.

The TWDB databases of monthly precipitation and evaporation rates are based on daily precipitation and pan evaporation rates measured at gages in Texas and neighboring states. The number of gage stations varies from year to year. In 2017, the TWDB compiled data measured at 86 evaporation stations and more than 3,000 precipitation stations. The National Weather Service (NWS) and TWDB administer climatic data collection programs with data being collected by volunteer partners that include various public and private entities such as reservoir operators. The NWS data are available from the National Climatic Data Center.

Daily precipitation and evaporation depths in inches are summed to monthly quantities. The TWDB computer-based data compilation system applies Thiessen polygon networks to spatially average the precipitation and evaporation rates by one-degree quadrangle. Sets of 12 monthly pan coefficients are used to convert pan evaporation measurements to estimates of lake surface evaporation rates.

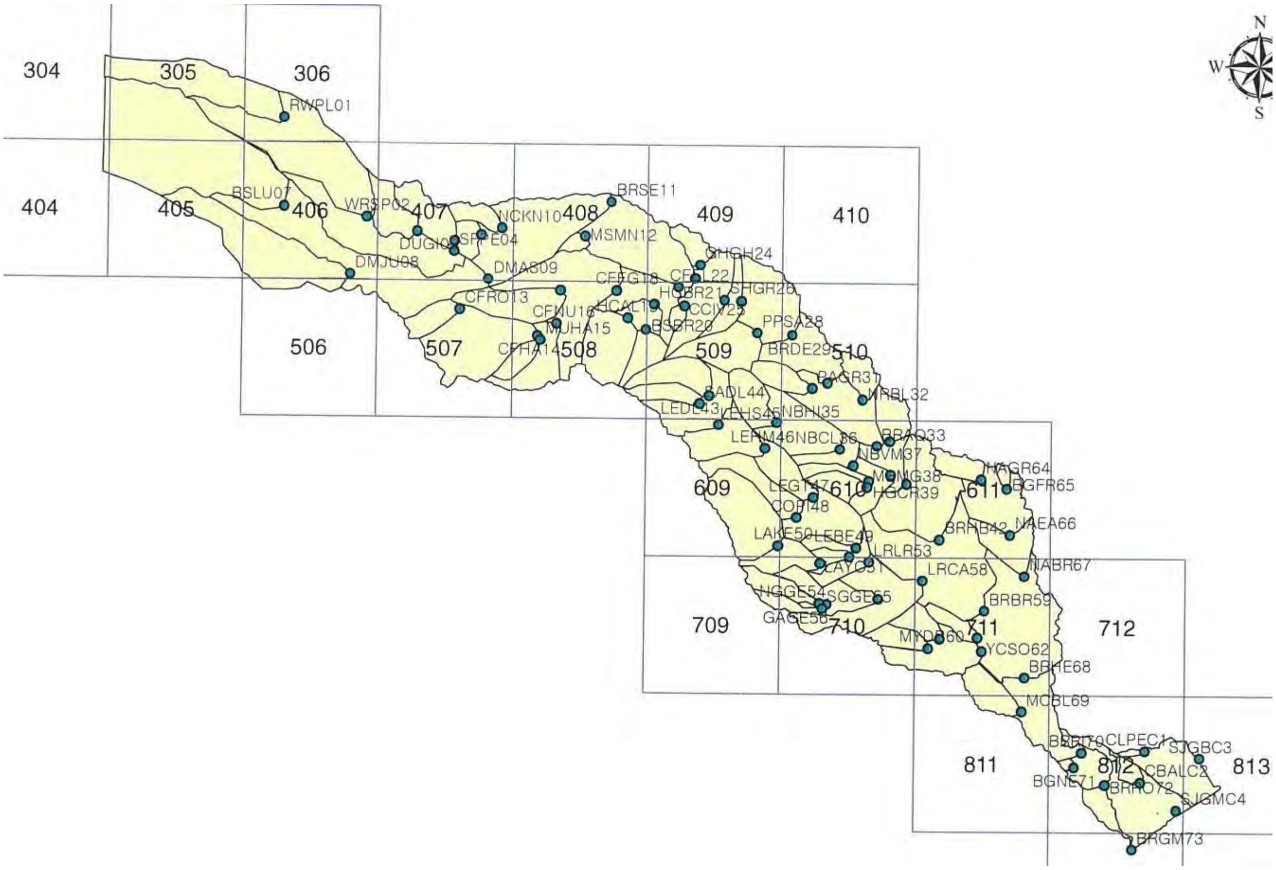

Figure 8.1 Brazos River Basin and San Jacinto-Brazos Coastal Basin quadrangles, primary control points, and control point watersheds

The data for the quadrangles of Figure 8.1 are stored in the file BrazosEvapPrecip.DSS described later in this chapter. The great temporal and spatial variability of precipitation and evaporation is illustrated by Figures 8.2-8.4 created with HEC-DSSVue. Mean monthly 1940-2017 precipitation depths in inches/month for quadrangle 610 are plotted in Figure 8.2. Mean monthly 1954-2017 reservoir evaporation depths in inches/month for quadrangle 610 are plotted in Figure 8.3. Quadrangle 610 is located in the central Brazos River Basin as indicated by Figure 8.1.

Mean annual precipitation and evaporation in inches/year for quads 406 and 812 are plotted in Figures 8.4 and 8.5. Monthly depths were summed to annual depths within HEC-DSSVue. Figure 8.5 also includes a plot of basin total annual precipitation computed within HEC-DSSVue by averaging depths for 20 quads that encompass the basin. Quad 406 is illustrative of the dry upper Brazos River Basin. Quad 812 in the extreme lower basin represents the wettest region.

Original Net Evaporation-Precipitation Depths

The original Brazos WAM EVA file contains *EV* records with January 1940 through December 1997 sequences of monthly net reservoir surface evaporation-precipitation depths at the 67 control points listed in Table 8.1, none of which are the primary control points listed in Table 2.8. The locations of the control points are indicated in Table 8.1 either by the quadrangle identifier of the evaporation-precipitation data or by a major reservoir with its control point identifier assigned to the net evaporation data. The approximately 700 reservoirs in the Brazos WAM dataset are each assigned sequences of monthly net evaporation-precipitation depths in feet/month read from *EV* records that are connected to one of the control points listed in Table 8.1.

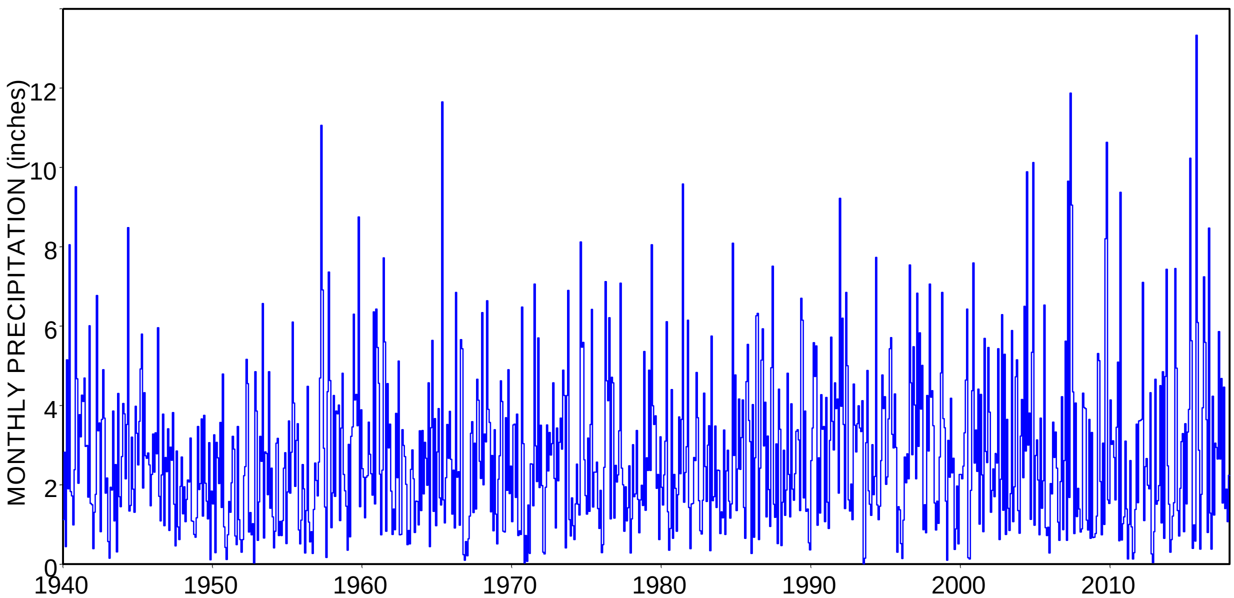

Figure 8.2 January 1940 – December 2017 Monthly Precipitation Depth for Quadrangle 610

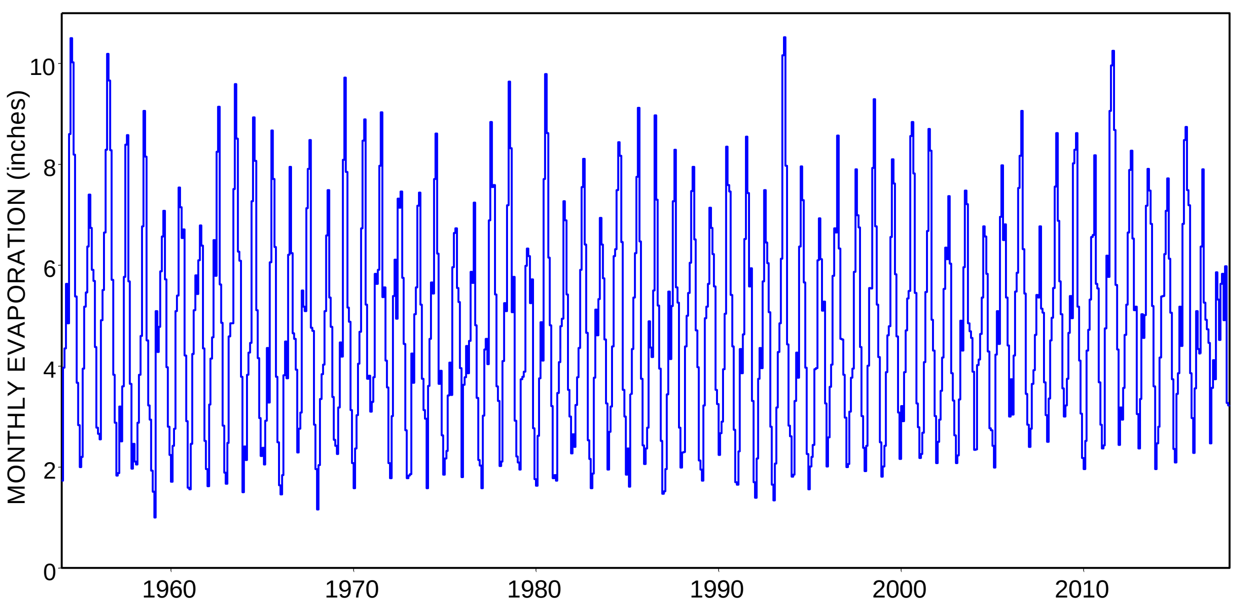

Figure 8.3 January 1954 – December 2017 Monthly Evaporation Depth for Quadrangle 610

The first 20 control points listed in Table 8.1 serve as location identifiers for the one degree quadrangles that cover the Brazos River Basin, which are shown on the Figure 8.1 map. The DSS or EVA file evaporation-precipitation depths are applied to multiple reservoirs located within each of these 20 quadrangles. The other control points in Table 8.1 are locations of large reservoirs.

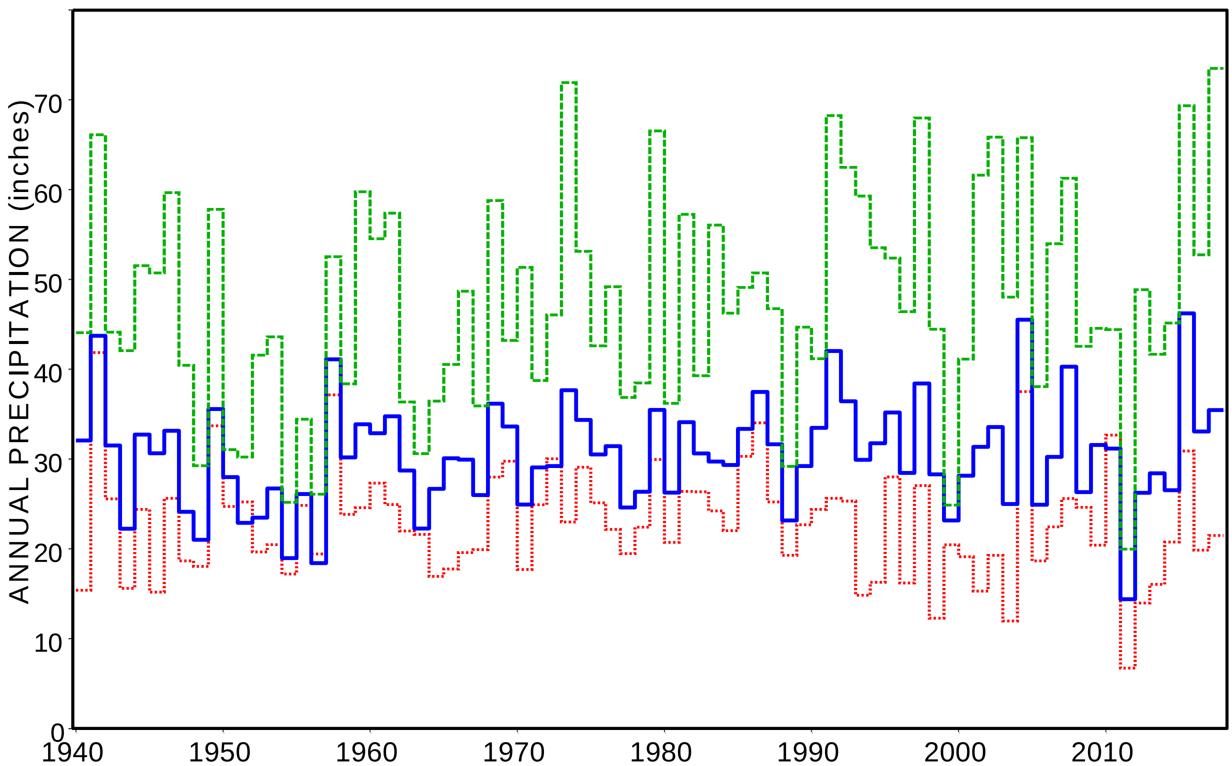

Figure 8.4 Mean Annual Precipitation for Quad 406 (green dashed), Quad 812 (red dotted), and 20 Quads Encompassing the Entire Brazos Basin and Coastal Basin (blue solid)

The Brazos WAM dataset was developed during 1997-2001 by Freese and Nichols, Inc. and HDR Engineering, Inc. under contract with the TCEQ [8, 9]. The 1940-1997 monthly net evaporation less precipitation depths were compiled as *EV* records stored in an EVA file. Observed data at precipitation gages and evaporation pans maintained near the ten reservoirs listed in Table 8.2 were obtained from the National Climatic Data Center and used in developing the WAM input for these reservoirs, supplemented with TWDB quadrangle data for periods of incomplete or missing records. TWDB quadrangle data were adopted for the numerous other reservoirs.

A weighted average for adjoining quadrangles was applied for reservoir sites extending into more than one quadrangle. The equations in Table 8.3 are from the 2001 WAM report [9]. The equations shown in Table 8.3 were used for 39 of the reservoirs that have water surfaces located in either two or four adjacent quadrangles. These equations assign net evaporation-precipitation depths to these 39 reservoirs as a weighted-average of net evaporation-precipitation depths for the quadrangles.

Eight other reservoirs are each assigned evaporation-precipitation rates for only one quadrangle as follows: Allen Creek (quadrangle 813), Brazoria (812), Bryan Utilities (711), Eagle Nest (812), Marlin (611), Post (406), Sandow Mine (710), and William Harris (quadrangle 812). As indicate in Table 8.4, these eight reservoirs, like the other reservoirs, are assigned their individual control point identifiers. Net evaporation-precipitation rate sequences are repeated in the hydrology input data for both the quadrangles and reservoirs listed in Table 8.1.

Table 8.1
Control Points Assigned to Reservoir Net Evaporation-Precipitation Depth Input

Control Point	Quadrangle
366631	305
368131	306
370431	405
368931	406
341131	407
341331	408
344801	409
371431	506
372031	507
413331	508
220131	509
227031	510
225331	609
228731	610
406331	611
299231	710
375931	711
531531	712
401041	812
516841	813

Control Point	Reservoir
414231	Abilene
4146P1	Alan Henry
527231	Alcoa
292531	Allen Creek
515831	Aquilla
293631	Belton
532842	Brazoria
526831	Bryan Utilities
370631	Buffalo Springs
530131	Camp Creek
421131	Cisco
421431	Daniel
344031	Davis
549231	Eagle Nest
416131	Fort Phantom Hill
516231	Georgetown
531131	Gibbons Creek
345831	Graham
515631	Granbury
516331	Granger
421331	Hubbard Creek
415031	Kirby
434531	Lake Creek
347031	Leon

Control Point	Reservoir
516531	Limestone
435533	Marlin City
528731	Mexia
344431	Millers Creek
403931	Mineral Wells
403131	Lake Palo Pinto
410631	Pat Cleburne
515531	Possum Kingdom
371131	Post
515931	Proctor
554032	Sandow Mine
532531	Smithers
516431	Somerville
409731	Squaw Creek
417931	Stamford
516131	Stillhouse Hollow
413031	Sweetwater
434231	Tradinghouse
529831	Twin oaks
231531	Waco
369331	White River
515731	Whitney
532841	William Harris

Table 8.2
Evaporation and Precipitation Stations Used by HDR for Ten Reservoirs

Reservoir	Evaporation Station	Beginning of Record	Precipitation Station	Beginning of record
Abilene	none		Lake Abilene	1960
Whitney	Whitney Dam	1952	Whitney Dam	1948
Waco	Waco Dam	1963	Waco Airport	1880
Proctor	Proctor Reservoir	1961	Proctor Reservoir	1961
Belton	Belton Dam	1962	Belton Dam	1962
Stillhouse	Stillhouse Dam	1962	Stillhouse Dam	1961
Georgetown	Georgetown Lake	1977	Georgetown Lake	1977
Granger	Granger Dam	1977	Granger Dam	1977
Somerville	Somerville Dam	1963	Somerville Dam	1963
Smithers	Thompsons 3	1956	Thompsons 3	1956

Table 8.3
Equations for Averaging Net Evaporation-Precipitation Depths
for Major Reservoirs Lying in Multiple Quadrangles

	Reservoir	Quadrangle Weighting Equation
1	White River	0.589*(406)+0.411*(407)
2	Buffalo Springs	0.097*(305)+0.115*(306)+0.170*(405)+0.618*(406)
3	Alan Henry	0.097*(406)+0.115*(407)+0.170*(506)+0.618*(507)
4	Davis	0.267*(407)+0.733*(408)
5	Sweetwater	0.633*(507)+0.158*(508)+0.114*(607)+0.094*(608)
6	Abilene	0.277*(507)+0.364*(508)+0.175*(607)+0.184*(608)
7	Kirby	0.193*(507)+0.550*(508)+0.116*(607)+0.141*(608)
8	Fort Phantom Hill	0.103*(407)+0.126*(408)+0.168*(507)+0.602*(508)
9	Stamford	0.188*(407)+0.339*(408)+0.176*(507)+0.297*(508)
10	Cisco	0.188*(407)+0.339*(408)+0.176*(507)+0.297*(508)
11	Hubbard	0.194*(408)+0.194*(409)+0.299*(508)+0.313*(509)
12	Daniel	0.142*(408)+0.158*(409)+0.255*(508)+0.446*(509)
13	Millers Creek	0.707*(408)+0.118*(409)+0.098*(508)+0.076*(509)
14	Graham	0.193*(408)+0.410*(409)+0.159*(508)+0.237*(509)
15	Possum Kingdom	0.386*(409)+0.614*(509)
16	Palo Pinto	0.137*(409)+0.108*(410)+0.586*(509)+0.170*(510)
17	Mineral Wells	0.206*(409)+0.195*(410)+0.312*(509)+0.287*(510)
18	Squaw Creek	0.218*(509)+0.468*(510)+0.142*(609)+0.173*(610)
19	Granbury	0.199*(509)+0.556*(510)+0.112*(609)+0.132*(610)
20	Pat Cleburne	0.577*(510)+0.154*(511)+0.157*(610)+0.112*(611)
21	Whitney	0.296*(510)+0.169*(511)+0.355*(610)+0.180*(611)
22	Aquilla	0.262*(510)+0.196*(511)+0.321*(610)+0.221*(611)
23	Waco	0.138*(510)+0.119*(511)+0.528*(610)+0.215*(611)
24	Tradinghouse	0.480*(610)+0.520*(611)
25	Lake Creek	0.480*(610)+0.520*(611)
26	Leon	0.266*(508)+0.42*(509)+0.15*(608)+0.165*(609)
27	Proctor	0.511*(509)+0.489*(609)
28	Belton	0.171*(609)+0.421*(610)+0.151*(709)+0.257*(710)
29	Stillhouse Hollow	0.175*(609)+0.329*(610)+0.168*(709)+0.329*(710)
30	Georgetown	0.128*(609)+0.158*(610)+0.200*(709)+0.514*(710)
31	Granger	0.157*(610)+0.117*(611)+0.557*(710)+0.169*(711)
32	Alcoa	0.153*(610)+0.146*(611)+0.391*(710)+0.309*(711)
33	Somerville	0.150*(710)+0.592*(711)+0.108*(811)+0.150*(811)
34	Mexia	0.064*(510)+0.086*(511)+0.094*(610)+0.755*(611)
35	Limestone	0.655*(611)+0.143*(612)+0.113*(711)+0.089*(712)
36	Twin Oaks	0.724*(611)+0.276*(711)
37	Camp Creek	0.338*(611)+0.197*(612)+0.284*(711)+0.182*(712)
38	Gibbons Creek	0.168*(611)+0.162*(612)+0.359*(711)+0.310*(712)
39	Smithers	0.144*(811)+0.856*(812)

The *JD* record for the Brazos WAM has an entry of −1 for the parameter EPADJ, which activates a methodology for adjusting the net evaporation-precipitation depths read from the input file during the *SIM/SIMD* simulation to account for runoff from the land area covered by the reservoir. The issue addressed is that all of the rain falling on the reservoir water surface contributes to the reservoir but a portion of the rain is also reflected in the naturalized flows. The automated adjustment technique activated by EPADJ is explained in the *Reference Manual* [1].

Updated Hydrology Dataset for Brazos River Authority System Operations Permit and Water Management Plan

Freese and Nichols, Inc. developed an updated monthly Brazos WAM in conjunction with the Brazos River Authority (BRA) system operations permit and associated water management plan [10, 11, 12, 13, 14] as discussed in Chapters 2 and 7. The hydrologic period-of-analysis was updated to extend through December 2015 and the original 1940-1997 evaporation-precipitation rates were refined using the same basic methods used in compiling the original WAM dataset during 2000-2001. The 2017 update report [10] documents the improvements to the original WAM hydrology dataset [9]. The FN/BRA monthly evaporation-precipitation rates as well as monthly naturalized flows are adopted for the daily Brazos WAM for the period 1940-2015. The WRAP program *HYD* 2016-2017 extension of the period-of-analysis is discussed in the next section.

Extension of the *EV* Records Using WRAP-HYD and HEC-DSSVue

The *SIM* and *SIMD* hydrology input file with filename BrazosHYD.DSS created as explained in this report includes sixty-seven 1940-2017 sequences of monthly net reservoir evaporation less precipitation depths in feet stored as *EV* records. The 1940-2015 *EV* records from the updated EVA file developed by FN for the BRA are adopted without change, other than conversion from EVA file to DSS file format. Program *HYD* is employed to extend the data sequences to cover 2016-2017. The datasets are combined within HEC-DSSVue.

Original TCEQ WAM 1940-1997 and *HYD* Extended 1998-2017 Hydrology

The statewide TWDB precipitation and evaporation depth datasets are converted at Texas A&M University to *HYD* input files with filenames Precipitation.PPP and Evaporation.EEE. The WRAP program *HYD* consists of an assortment of routines designed to facilitate developing and updating the monthly naturalized flows net evaporation-precipitation rates and included in the *SIM/SIMD* simulation input datasets. The *HYD* methodology described in Chapters 4 and 7 of the *Hydrology Manual* [5] was employed previously to extend the naturalized flows and evaporation-precipitation rates to cover 1998-2012 and again in 2018 to extend the hydrology to cover 1998-2017. The extension of naturalized flows is covered in the preceding Chapter 7. The 2016-2017 evaporation-precipitation rates were adopted for the daily Brazos WAM as discussed here.

A DSS or EVA file with 1940-2017 net evaporation-precipitation rates is created by executing the WRAP program *HYD* with the following input files.

HIN file controlling the 1998-2017 evaporation-precipitation update.
EVA file from Brazos WAM with 1940-1997 evaporation-precipitation rates.
Evaporation.EEE file with TWDB statewide 1940-2017 evaporation data.
Precipitation.PPP file with TWDB statewide 1940-2017 precipitation data.

The *HYD* input HIN file (filename extension HIN) contains the information presented in Tables 8.1, 8.2, and 8.3. The HYD methodology is designed to replicate the methods employed to develop the original 1940-1997 evaporation-precipitation dataset as closely as possible in extending the sequences through 1998-2017.

Creation of the program *HYD* input HIN file required significant time and effort [18]. However, continuing future updates of the WAM net evaporation-precipitation simulation input data using the same HIN file can be readily performed after updating the Evaporation.EEE and Precipitation.PPP files each year after the TWDB completes the annual update of the quadrangle precipitation and evaporation databases.

DSS File with Filename BrazosEvapPrecip.DSS

A DSS file with filename BrazosEvapPrecip.DSS was created to store, display, analyze, compare, and combine the precipitation, evaporation, and net evaporation-precipitation datasets for the Brazos River Basin discussed in this chapter. The file has a total of 335 records, which includes records for each of the 67 control points listed in Table 8.1 in each of the following five sets of records.

1. Sixty-seven 1954-2017 sequences of monthly reservoir evaporation depths in inches derived from the TWDB database that include individual quads and weighted averages for multiple quads as defined in Tables 8.1 and 8.3.
2. Sixty-seven 1940-2017 sequences of monthly precipitation depths in inches derived from the TWDB database in the same manner as the evaporation depths noted above.
3. Sixty-seven 1940-2015 sequences of monthly net evaporation-precipitation depths in feet from the FN/BRA EVA file compiled in conjunction with the system operations permit..
4. Sixty-seven 1940-2017 sequences of monthly net evaporation-precipitation depths in feet that consist of the 1940-1997 quantities from the original Brazos WAM EVA file extended through 1998-2017 employing the program *HYD*.
5. The final adopted *EV* records consisting of 1940-2015 quantities from the third dataset combined with 2016-2017 quantities from the fourth dataset.

Table 8.4
DSS Pathnames for the File BrazosEvapPrecip.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	BRAZOS EVAPORATION	228731	EVAPORATION (INCHES)	31JAN1954-31DEC2017	1MON	INCHES
2	BRAZOS PRECIPITATION	228731	PRECIPITATION (INCHES)	31JAN1940-31DEC2017	1MON	INCHES
3	BWAM3 AND HYD	228731	EV	31JAN1940-31DEC2017	1MON	FEET
4	BWAM3 BRA&FN	228731	EV	31JAN1940-31DEC2017	1MON	FEET
5	BRAZOS	228731	EV	31JAN1940-31DEC2017	1MON	

The pathnames adopted for the DSS records are listed in Table 8.4. The record for control point 366631 is adopted as an example in Table 8.4 for each of the five sets of 67 records. As indicated in Table 8.1, the control point identifier 228731 is assigned to data sequences for quadrangle 610 in the TWDB database.

The TWDB maintains datasets of monthly precipitation and evaporation depths for the 92 one degree latitude by one degree longitude quadrangles that cover the state of Texas. The quads that encompass the Brazos River Basin are shown in Figure 8.1. This map of the Brazos River Basin and San Jacinto-Brazos Coastal Basin shows the following information: quadrangles for the evaporation-precipitation data, 77 primary naturalized flow control points, and delineation of watersheds above the primary control points. The first 20 control points listed in Table 8.1 serve as location identifiers for relevant one degree quadrangles. The DSS or EVA file evaporation-precipitation depths are applied to multiple reservoirs located within each of these 20 quads. The other 47 control points in Table 8.1 are locations of large reservoirs. A weighted average of quantities for adjoining quads was applied for reservoir sites extending into more than one quad.

Final Adopted Net Evaporation-Precipitation *EV* Records

The net evaporation minus precipitation depths in the last dataset of Table 8.4 is the set of *EV* records that are incorporated in the *SIM* and *SIMD* hydrology input file BrazosHYD.DSS. These final adopted *EV* records consisting of 1940-2015 quantities from FN/BRA EVA file combined with 2016-2017 quantities synthesized with the WRAP program *HYD*. The datasets were combined within the HEC-DSSVue tabular editor.

The *EV* records assigned the WAM control point identifiers 368931, 228731, and 401041 are plotted in Figures 8.5, 8.6, and 8.7. Control point identifiers 368931, 228731, and 401041 represent TWDB database quadrangles 406, 610, and 812 in the upper, middle, and lower Brazos River Basin as indicated by Figure 8.1 and Table 8.1.

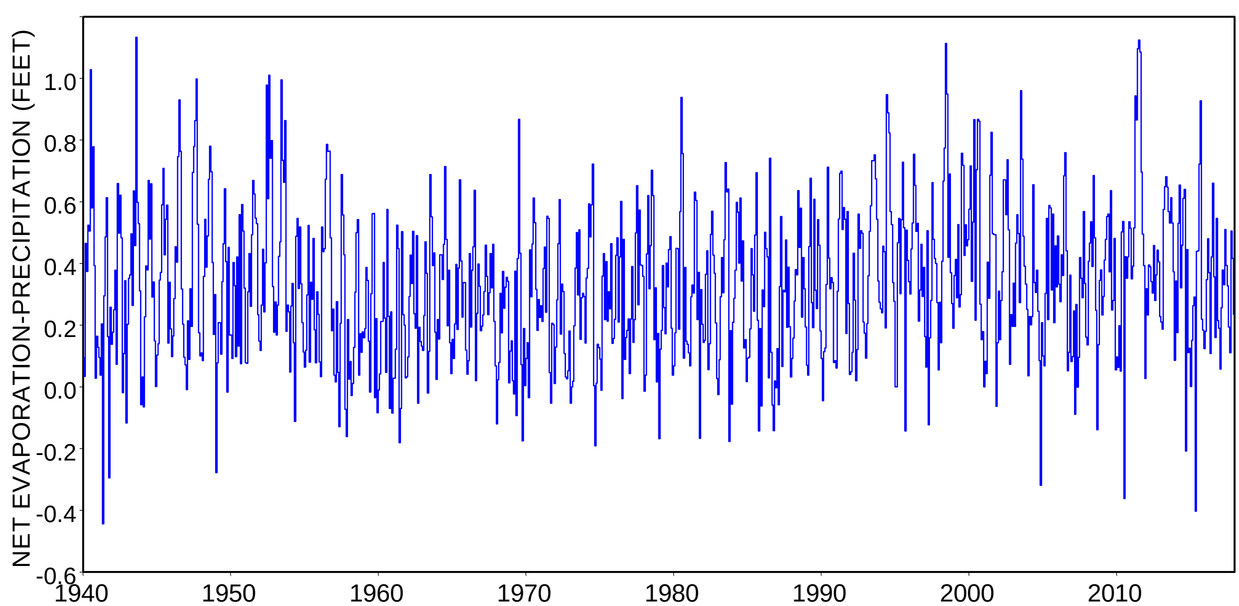

Figure 8.5 Control Point 368931 (Quad 406) 1940-2017 Monthly
Net Evaporation Less Precipitation Depths (feet)

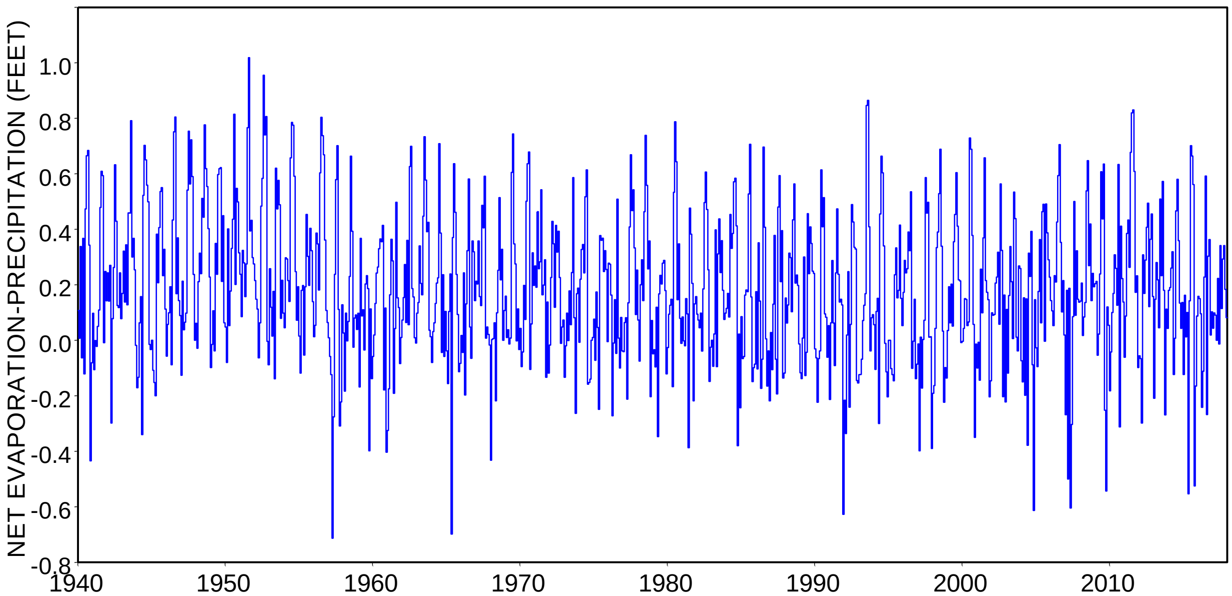

Figure 8.6 Control Point 22873 (Quad 610) 1940-2017 Monthly
Net Evaporation-Precipitation Depths (feet)

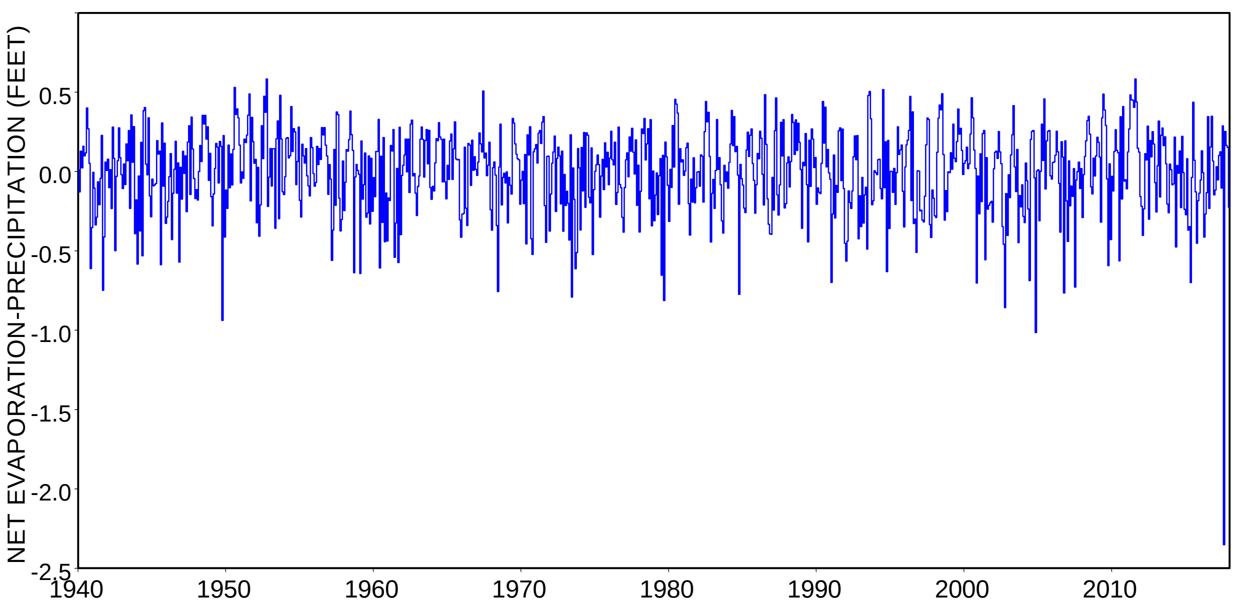

Figure 8.7 Control Point 401041 (Quad 812) 1940-2017 Monthly
Net Evaporation Less Precipitation Depths (feet)

The flooding associated with Hurricane Harvey is evident in Figure 8.7. Quadrangle 812 has an observed mean precipitation of 33.53 inches and evaporation of 5.31 inches during August 2017 for a net evaporation-precipitation of −28.22 inches or −2.35 feet.

CHAPTER 9
ORGANIZATION AND CONTENTS OF DATA STORAGE SYSTEM (DSS) FILES

This report is accompanied by the following six DSS files. The first four files were used to compile, synthesize, and evaluate the time series data described in the preceding chapters of this report. The fifth file is the hydrology input file read by *SIMD* and *SIM*. The sixth file listed below contains *SIMD* and *SIM* simulation results discussed in Chapter 10. The present Chapter 9 summarizes the organizational structure and contents of these six DSS files.

1. A file with filename BrazosPHDI.DSS contains the sequences of Palmer hydrologic drought index (PHDI) quantities and associated *HI* record hydrologic indices described in Chapter 5 used to define hydrologic conditions for the SB3 environmental flow standards.
2. A file with filename BrazosDailyFlows.DSS contains datasets described in Chapter 6 compiled in the process of developing and analyzing daily flow sequences to be adopted as the daily flow pattern hydrographs used in disaggregating monthly naturalized flows to daily.
3. A file with filename BrazosMonthlyFlows.DSS contains data compiled in the process of analyzing and synthesizing the monthly naturalized flow sequences covered in Chapter 7.
4. A file with filename BrazosEvapPrecip.DSS contains monthly precipitation rates and reservoir evaporation rates and net reservoir evaporation less precipitation rates discussed in Chapter 8.
5. The file with filename BrazosHYD.DSS is the hydrology input file read by *SIM* and *SIMD.* It contains the adopted sequences of *EV* record evaporation-precipitation depths, *IN* record monthly naturalized flows, and *DF* record daily flows from the three preceding DSS files. This file also contains hydrologic index *HI* records and *TS* records of instream flow targets used with the SB3 environmental flow standards.
6. A file with filename BrazosSimulationResults.DSS contains the results from the daily *SIMD* and monthly *SIM* simulations labeled D7 and M3 in Chapter 10.

WRAP applications of the Hydrologic Engineering Center (HEC) Data Storage System (DSS) and the *HEC-DSSVue Visual Utility Engine* component of the HEC-DSS are explained in the new Chapter 6 added to the *WRAP Users Manual* [2]. The public domain *HEC-DSSVue* software and *User's Manual* are readily available free-of-charge from the USACE Hydrologic Engineering Center website. The *HEC-DSSVue User's Manual* explains in great detail all of the features and extensive optional capabilities provided by the software. However, the *WRAP Users Manual* introduces *HEC-DSSVue* to the extent necessary to create, manipulate, display, and analyze the DSS files created and employed in conjunction with this Brazos WAM Report.

HEC-DSSVue was employed to create the first five DSS files listed above, as discussed in Chapters 1, 5, 6, 7, and 8. *SIM/SIMD* created the sixth DSS file, which is a simulation results output file, as discussed in Chapter 10. The DSS files are designed to serve as appendices to this report, allowing readers to compare, explore, and later update the datasets using *HEC-DSSVue*. *HEC-DSSVue* was used to create all of the time series plots presented in this report. Thousands of additional similar plots of data from the six DSS files can be created by interested readers of this report. The datasets can also be further tabulated, compared, combined, and manipulated in the tabular editor. Statistical analyses and mathematical operations can be performed. DSS records can be conveniently searched, grouped, adjusted, copied, renamed, and otherwise managed.

Hydrologic Indices in File *BrazosPHDI.DSS* of Chapter 5

The DSS file with filename BrazosPDHI.DSS was created in the process of compiling the Palmer Hydrologic Drought Index (PHDI) sequences and associated hydrologic index *HI* record indices used with the hydrologic condition *HC* records to define hydrologic conditions for the SB3 environmental flow standards (EFS) as explained in Chapter 5 of this report. Time series data are stored in a DSS file as DSS records identified by pathnames with parts A, B, C, D, E, and F, as explained in Chapter 6 of the *WRAP Users Manual* [2]. Pathnames for the sixteen time series data records in the hydrologic index file are listed in Table 5.7 of Chapter 5 and Table 9.1 below.

Table 9.1
DSS Pathnames for the File BrazosPDHI.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	PHDI	ZONE 4101	PHDI	31JAN1895-31DEC2017	1MON	HIGH PLAINS
2	PHDI	ZONE 4102	PHDI	31JAN1895-31DEC2017	1MON	LOW ROLLING PLAINS
3	PHDI	ZONE 4103	PHDI	31JAN1895-31DEC2017	1MON	North Central
4	PHDI	ZONE 4104	PHDI	31JAN1895-31DEC2017	1MON	East Texas
5	PHDI	ZONE 4105	PHDI	31JAN1895-31DEC2017	1MON	Trans Pecos
6	PHDI	ZONE 4106	PHDI	31JAN1895-31DEC2017	1MON	Edwards Plateau
7	PHDI	ZONE 4107	PHDI	31JAN1895-31DEC2017	1MON	South Central
8	PHDI	ZONE 4108	PHDI	31JAN1895-31DEC2017	1MON	Upper Basin
9	PHDI	ZONE 4109	PHDI	31JAN1895-31DEC2017	1MON	Low Rolling Plains
10	PHDI	ZONE 4110	PHDI	31JAN1895-31DEC2017	1MON	North Central
11	LOWER BASIN		PHDI	31JAN1895-31DEC2017	1MON	
12	MIDDLE BASIN		PHDI	31JAN1895-31DEC2017	1MON	
13	UPPER BASIN		PHDI	31JAN1895-31DEC2017	1MON	
14	Brazos	LOWER	HI	31JAN1940-31DEC2017	1MON	
15	Brazos	MIDDLE	HI	31JAN1940-31DEC2017	1MON	
16	Brazos	UPPER	HI	31JAN1940-31DEC2017	1MON	

The first ten DSS records contain the dimensionless January 1895 through December 2017 monthly Palmer Hydrologic Drought Index (PHDI) series for the ten climatic zones of Texas downloaded from the National Weather Service (NWS) National Climatic Data Center (NCDC) website. The 11th, 12th, and 13th records listed in Table 6.1 are area-weighted average 1895-2017 monthly series of PHDI quantities for the upper, middle, and lower Brazos River Basin. These PHDI sequences for the lower, middle, and upper basin are plotted in Figure 5.1 of Chapter 5.

The 14th, 15th, and 16th DSS record data series are the 1940-2017 *HI* record hydrologic indices for the upper, middle, and lower Brazos River Basin used for modeling SB3 environmental flow standards in the daily Brazos WAM. These *HI* records incorporated in the daily WAM hydrology input DSS file are plotted in Figure 5.2. The *HI* records contain a hydrologic condition parameter with values of 1, 2, or 3 indicating dry, average, or wet hydrologic conditions for each month of the 1940-2017 hydrologic period-of-analysis. Three sets of *HI* records are provided, one for each of the three regions of the Brazos River Basin (lower, middle, and upper). Identifiers LOWER, MIDDLE, and UPPER on the *HI* records are treated in S*IMD* as control point identifiers defined by DAT file *CP* and *HI* records and referenced by DAT file *HC* records.

Daily Stream Flows in File *BrazosDailyFlows.DSS* of Chapter 6

The DSS file with filename BrazosDailyFlows.DSS was created in conjunction with compiling, analyzing, synthesizing, and verifying daily simulation *SIMD* daily flow pattern hydrographs and contains the following five datasets of daily flow sequences as described in Chapter 6. Control point BRWA41 at the USGS gaging station on the Brazos River at Waco is used in Table 9.2 to illustrate the pathnames adopted for the DSS data records in each of the five datasets. The fourth dataset consists of daily flow volumes in acre-feet, and the other four datasets consist of mean daily flows in cubic feet per second (cfs). The DSS file contains five datasets with a total of 285 daily flow sequences stored as 285 DSS records.

Table 9.2
DSS Pathnames for the File BrazosDailyFlows.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	LITTLE RV	CAMERON, TX	USGS DAILY CFS	01JAN1916-01JAN2018	1DAY	BRWA41
2	USACE UNREGULATED	LITTLE RIVER, CAMERON	USACE DAILY CFS	01JAN1940-01JAN1997	1DAY	BRWA41
3	BRAZOS CFS	LRCA58	FLOW – CFS	01JAN1940-01JAN2016	1DAY	BRWA41
4	BRAZOS	LRCA58	FLOW – ACRE-FEET	01JAN1910-01JAN1990	1DAY	BRWA41
5	NATURALIZED CFS	LRCA58	FLOW – CFS	01JAN1910-01JAN2010	1DAY	BRWA41

1. The period-of-record observed daily flows at 74 USGS gages were downloaded from the USGS NWIS website The 74 gages include 70 gages at the primary control points listed in Table 2.8 for which gaged flows are available and the four additional gages listed in Table 2.9 that are used to extend the records of four of 70 gaged control points. The same daily flow dataset is listed first in both of the Tables 9.2 and 9.3 and included in both of the files BrazosDailyFlows.DSS and BrazosMonthlyFlows.DSS. (74 records, one for each of 74 USGS gaging stations)
2. The 1940-1997 unregulated daily flows for the 37 sites listed in Table 6.5 were generated by the modeling system maintained by the USACE Fort Worth District. The 37 sites include 16 of the WAM primary control points and 21 WAM secondary control points. (37 records)
3. An initial version in cfs of the 1940-2017 pattern hydrograph daily flows at the selected 58 control points listed in Tables 6.5 and 6.6 that was developed by selecting between and combining flows from the two preceding datasets of USGS observed flows and USACE unregulated flows. (58 records, one for each of 58 selected WAM control points)
4. The flows adopted as the final *DF* record daily flow pattern hydrographs incorporated in the *SIMD* hydrology DSS input file. These are 1940-2017 daily naturalized flow volumes at the 58 control points in acre-feet/day were computed within a *SIMD* simulation by disaggregating monthly flow volumes to daily using the preceding third dataset for pattern flows. (58 records)
5. Daily naturalized flows in cfs at the 58 control points were derived within HEC-DSSVue by converting the preceding fourth dataset from daily volumes in acre-feet to daily mean flow rates in cfs for consistency with the first three datasets in file BrazosDailyFlows.DSS.
(58 records, one for each of 58 selected control points listed in Tables 6.5 and 6.6)

Monthly Stream Flows in File *BrazosMonthlyFlows.DSS* of Chapter 7

The DSS file with the filename BrazosMonthlyFlows.DSS was constructed along with compiling, analyzing, synthesizing, and verifying the *IN* record monthly naturalized flows for the daily Brazos WAM hydrology input dataset as described in Chapter 7. Control point BRWA41 at the USGS gaging station on the Brazos River at Waco is used in Table 9.3 to illustrate the pathnames adopted for the DSS records in each of the eight datasets in this file. The eight datasets listed below contain a total of 567 flow sequences stored as 567 DSS records.

Table 9.3
DSS Pathnames for the File BrazosMonthlyFlows.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	BRAZOS RV	WACO, TX	USGS DAILY CFS	01JAN1916-01JAN2018	1DAY	BRWA41
2	BRAZOS RV	WACO, TX	USGS MONTHLY MEANS CFS	01JAN1910-01JAN2010	1MON	BRWA41
3	BRAZOS RV	WACO, TX	USGS MONTHLY VOLUME AC-FT	01JAN1910-01JAN2010	1MON	BRWA41
4	USACE UNREGULATED	BRAZOS RIVER, WACO	FLOW USACE ACRE-FEET	01JAN1910-01JAN1990	1MON	BRWA41
5	WAM & 1998-2017 HYD	BRWA41	NATURALIZED ACRE-FEET	01JAN1910-01JAN2010	1MON	BRWA41
6	TCEQ BWAM3 1940-1997	BRWA41	IN	01JAN1910-01JAN1990	1MON	
7	BRA 1940-2015	BRWA41	IN	01JAN1910-01JAN2010	1MON	
8	BRAZOS	BRWA41	IN	01JAN1910-01JAN2010	1MON	

1. The same dataset of period-of-record observed daily flows in cfs at 70 of the 77 control points listed in Table 2.8 and the four gages in Table 2.9 is listed first in both Tables 9.2 and 9.3 and included in both the daily and monthly flow files. The daily observed flows are included in the monthly file because the second and third datasets are derived directly therefrom. (74 records).
2. Monthly means in cfs of the period-of-record daily observed flows at the 74 USGS gages included in the daily flow dataset described above. (74 records, one for each of 74 gages).
3. Monthly summations in acre-feet/month of the period-of-record daily observed flows at the 74 gaged control points included in the original daily flow dataset described above. (74 records)
4. Monthly summations in acre-feet/month of 1940-1997 daily unregulated flows from the USACE Fort Worth District modeling system at the 37 control points Table 6.2. (37 records)
5. 1940-2017 monthly naturalized flow volumes in acre-feet/month at the 77 primary control points composed of the original 1940-1997 monthly naturalized flows and 1998-2017 extensions synthesized using the hydrologic modeling feature of the WRAP program *HYD* that relates naturalized flows to precipitation and evaporation. (77 records)
6. 1940-1997 monthly naturalized flow volumes in acre-feet/month at the 77 primary control points from the official TCEQ Bwam3 Brazos WAM last updated 11/3/2017. (77 records)
7. 1940-2015 monthly naturalized flow volumes in acre-feet/month at the 77 primary control points from the BRA Brazos WAM last updated 5/8/2017. (77 records)
8. Final adopted 1940-2017 monthly naturalized flows at the 77 WAM primary control points compiled as described in the Chapter 7. These *IN* records are included in the daily Brazos WAM hydrology input file BrazosHYD.DSS. (77 records, one for each primary control point)

Monthly Evaporation and Precipitation in File *BrazosEvapPrecip.DSS* of Chapter 8

The DSS file prepared in conjunction with compilation of net reservoir evaporation less precipitation depths has the filename BrazosEvapPrecip.DSS and contains the following datasets, which are discussed in greater detail in Chapter 8. Control point 366631 (quadrangle 305, Figure 8.1) defined in Table 8.1 is used in Table 9.4 to illustrate the pathnames adopted for the DSS data records in each dataset. The file has a total of 355 records, which includes records for each of the 67 control points listed in Table 8.1 in each of the following five sets of records.

Table 9.4
DSS Pathnames for the File BrazosEvapPrecip.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	BRAZOS EVAPORATION	366631	EVAPORATION (INCHES)	31JAN1940-31DEC2017	1MON	INCHES
2	BRAZOS PRECIPITATION	366631	PRECIPITATION (INCHES)	31JAN1940-31DEC2017	1MON	INCHES
3	BWAM3 BRA&FN	366631	EV	31JAN1940-31DEC2015	1MON	FEET
4	BWAM3 AND HYD	366631	EV	31JAN1940-31DEC2017	1MON	FEET
5	BRAZOS	366631	EV	31JAN1940-31DEC2017	1MON	

1. TWDB 1954-2017 monthly reservoir evaporation depths in inches that include individual quads and weighted averages for multiple quads as defined in Tables 8.1 and 8.3. (67 records)
2. TWDB 1940-2017 monthly precipitation depths in inches compiled in the same manner as the evaporation depths noted above. (67 records)
3. 1940-2015 monthly net evaporation-precipitation depths in feet from the FN/BRA EVA file compiled in conjunction with the BRA system operations permit. (67 records)
4. Sequences of 1940-2017 monthly net evaporation-precipitation depths in feet that consist of the 1940-1997 quantities from the original Brazos WAM EVA file extended through 1998-2017 employing the program *HYD*. (67 records)
5. The final adopted *EV* records consisting of 1940-2015 quantities from the third dataset combined with 2016-2017 quantities from the fourth dataset. (67 records)

SIM and *SIMD* Hydrology Input File *BrazosHYD.DSS*

The *SIM* and *SIMD* hydrology input file with filename BrazosHYD.DSS contains:

3 hydrologic index *HI* records for the lower, middle, and upper Brazos River Basin
58 daily flow *DF* records for 58 control points
77 naturalized flow *IN* records for 77 control points
67 evaporation-precipitation *EV* records assigned 67 control point identifiers
19 target series *TS* records for 19 SB3 environmental flow standard instream flow rights

The *HI*, *DF*, *IN*, and *EV* records in the BrazosHYD.DSS file are copied from the DSS files described in Chapters 5, 6, 7, and 8 and the preceding sections of this chapter. The *TS* records were added from the results of a *SIMD* simulation as described in Chapters 5 and 10. The pathnames for the 224 DSS records in the hydrology input file are illustrated in Table 9.5 by listing the pathname for one record from each type of the five types of data records.

Table 9.5
DSS Pathnames for *SIM/SIMD* Hydrology Input File BrazosHYD.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	BRAZOS	MIDDLE	HI	01JAN1940-01JAN2010	1MON	
2	BRAZOS	BRWA41	DF	01JAN1940-01JAN2016	1DAY	
3	BRAZOS	BRWA41	IN	01JAN1940-01JAN2010	1MON	
4	BRAZOS	366631	EV	01JAN1940-01JAN2010	1MON	
5	BRAZOS	BRWA41	TS	01JAN1940-01JAN2010	1MON	

DSS pathname conventions for the *SIM/SIMD* hydrology input file and simulation results output file are described in Chapter 5 of the *WRAP Users Manual*. The following standard format for the pathnames for the *SIM* and *SIMD* hydrology input file is generally required.

Part A is the filename root of the hydrology input file.

Part B is the WAM control point identifier.

Part C differentiates between daily flows (DF), monthly flows (IN), and monthly net evaporation-precipitation depths (EV), hydrologic indices (HI), and target series (TS) by the standard identifiers DF, IN, EV. HI, and TS.

Part D is either the start date or the range of the data blocks.

Part E is 1DAY for daily data or 1MON for monthly data.

Part F is blank in the pathnames of *SIM/SIMD* hydrology input records.

The DSS files described in the preceding sections of this chapter are designed to be read, displayed, and manipulated only with HEC-DSSVue. Pathname parts D and E are fixed but the other parts can be renamed using the HEC-DSSVue editor. Since file BrazosHYD.DSS is read by *SIM* and *SIMD*, as wells as HEC-DSSVue, the pathname parts must conform to the conventions outlined above.

<u>***SIM* and *SIMD* Simulation Results File *BrazosSimulationResults.DSS***</u>

Simulations D7 and M3 in Chapter 10 reflect the final proposed Brazos WAM. Results of these simulations are stored in a file with filename *BrazosSimulationResults.DSS*. The pathnames have ″SIMD DAILY SIMULATION″ or ″SIM MONTHLY SIMULATION″ inserted in part A.

The 13 types of output files that may be created by *SIM* and *SIMD* are described in the *Reference* and *Users Manuals* [1, 2]. The 1940-2017 times series of monthly simulation results are stored in OUT and SUB files read by *TABLES* and/or a single DSS file read by *HEC-DSSVue*. *SIM/SIMD* OUT, SUB, and DSS files and the programs *TABLES* and *HEC-DSSVue* were all employed in the simulation study presented in the Chapter 10. However, the remainder of the present chapter focuses on the organization and format of the DSS output file.

Input records at the beginning of the DAT file that control the selection of information to include in the simulation results output files discussed in Chapter 10 are replicated in Table 9.6. Pathnames for DSS records in the *SIM* and/or *SIMD* output DSS are illustrated in Table 9.7.

Table 9.6
SIMD DAT File Input Records Controlling Simulation Results Output Files

```
**      1       2       3       4       5       6       7       8
**345678901234567890123456789012345678901234567890123456789012345678901234567
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!
JD    78    1940       1       0       0              4              -1      13
JO     6                  1                          1                       3
JT     0   0   0   0   0   0   0   0   0   0   0   0
JU     1   1   0   0   0   0   0
OF     0   0   2   7       0   0                               Brazos
OFV    1   2   3  15  16   9  31
**
C2         SFAS06  DMAS09  BRSE11  CFNU16  CON026  BRSB23  BRPP27  BRGR30  NBCL36  BRWA41
C2         LEGT47  LAKE50  LRLR53  LRCA58  BRBR59  NAEA66  BRHE68  BRRI70  BRRO72
C2         515731  509431
R2         AQUILA  PRCTOR  BELTON  STLHSE  GRGTWN  GRNGER  SMRVLE
R2         POSDOM  GRNBRY  LMSTNE  ALLENS  ALANHN  HUBBRD
```

Table 9.7
DSS Pathnames for *SIM/SIMD* Simulation Results Output File Brazos.DSS

	Part A	Part B	Part C	Part D / range	Part E	Part F
1	BRAZOS	BRRI70	IFS-CP	01JAN1940-01JAN2010	1MON	CP
2	BRAZOS	BRRI70	IFS-CP	01JAN1940-01JAN2017	1DAY	CP DAILY
3	BRAZOS	BRRI70	IFT-CP	01JAN1940-01JAN2010	1MON	CP
4	BRAZOS	BRRI70	IFT-CP	01JAN1940-01JAN2017	1DAY	CP DAILY
5	BRAZOS	BRRI70	NAT-CP	01JAN1940-01JAN2010	1MON	CP
6	BRAZOS	BRRI70	NAT-CP	01JAN1940-01JAN2017	1DAY	CP DAILY
7	BRAZOS	BRRI70	REG-CP	01JAN1940-01JAN2010	1MON	CP
8	BRAZOS	BRRI70	REG-CP	01JAN1940-01JAN2017	1DAY	CP DAILY
9	BRAZOS	BRRI70	UNA-CP	01JAN1940-01JAN2010	1MON	CP
10	BRAZOS	BRRI70	UNA-CP	01JAN1940-01JAN2017	1DAY	CP DAILY
11	BRAZOS	516431	STO-RE	01JAN1940-01JAN2010	1MON	SMRVLE
12	BRAZOS	516431	STO-RE	01JAN1940-01JAN2017	1DAY	SMRVLE

The simulation study results presented in Chapter 10 focus on 1940-2017 daily and monthly stream flows and instream flow targets at the 19 SB3 EFS sites and reservoir storage contents of 15 large reservoirs. Total storage volumes in Whitney and Waco Reservoirs are recorded on control point output records since these two reservoirs are simulated as multiple-owner (multiple-component) reservoirs. WRAP provides considerable flexibility in organizing massive simulation results through various options for user selection of results to include in output files.

SIM and *SIMD* simulation results are recorded in the OUT, CRM, SUB, and/or DSS output files in the form of the three types of time series output records: (1) water right output records for *WR* and *IF* record rights, (2) control point output records, and (3) reservoir output records. The selection of water rights, control points, and reservoirs for which data are included in the output files is controlled by input parameters OUTCP and OUTWR on the *JD* record, OUTCP2 and

OUTWR2 on the *JT* record, and *CO*, *C2*, *WO*, *W2*, *GO*, *G2*, *RO*, and *R2* records as explained in the *Users Manual* [2]. The *JD* and *JT* record parameters are used to specify all or selected type groups of water rights and control points. Selecting all water rights or these particular groups may include very large numbers of water rights and/or control points. The *CO*, *WO*, *GO*, and *RO* records are used to list individual water rights, water right groups, control points, and reservoirs for which to include monthly output data records in the OUT, CRM, SUB, and/or DSS output files. The *C2*, *W2*, *G2*, and *R2* records are the daily versions of these output data selection records.

If both monthly and daily output records are included in a *SIMD* output DSS file, the *C2*, *W2*, *G2*, and *R2* records specify output for both monthly and daily quantities. DSS(3) option 2 selected in *OF* record field 4 (column 16) in Table 9.6 instruct *SIMD* to record both daily and monthly simulation results in the DSS output file.

The *OF* record explanation on pages 45-47 of Chapter 3 of the *Users Manual* includes a table listing 42 time series variables that are included in *SIM* and *SIMD* output files. These simulation results variables are defined in detail in Chapter 5 of the *Reference Manual*. The OUT, CRM, and SUB files include all of the variables for each of the selected water rights, control points, or reservoirs. However, *OF* record options allow the DSS file to be limited to user-selected simulation results variables for each of the specified water rights, control points, or reservoirs. The *OFV* record selection of variables 1, 2, 3, 15, 16, 27, and 28 in Table 9.6 specifies inclusion of the following variables in the simulation results DSS output file: naturalized flows (NAT), regulated flows (REG), unappropriated flows (UNA), instream flow targets (IFT), and instream flow shortages (IFS) at each of the 19 specified control points, reservoir storage (STO) at two control points, and reservoir storage (STO) at 13 other reservoirs. Since Whitney and Waco Reservoirs are modeled as multiple-owner reservoirs with multiple components, the control points 515731 and 509431 storage is recorded in the output file to have the total rather than component storage.

The *SIMD* input DAT file records in Table 9.6 create a DSS file with 232 DSS records with pathnames illustrated by Table 9.7. DSS pathname conventions are described in Chapter 6 of the *Users Manual*. The Brazos River at Richmond control point, with identifier BRRI7, is used in Table 9.7 as an example of pathname format. Somerville Reservoir, with reservoir identifier SMRVLE and control point identifier 516431, illustrates the format of the pathnames for the reservoir output records. The 232 DSS records include 116 records with daily time series simulation results and 116 records with the corresponding monthly aggregates of the daily data. The DSS file contains the following daily simulation results and corresponding monthly data.

naturalized stream flow (NAT-CP) at 21 control points
regulated stream flow (REG-CP) at 21 control points
unappropriated stream flow (UNA-CP) at 21 control points
instream flow targets (IFT-CP) at 19 control points
instream flow shortages (IFS-CP) at 19 control points
Whitney and Waco reservoir storage (STO-CP) at control points 515731 and 509431
reservoir storage volumes (STO-RE) for 13 reservoirs

The simulation results from *SIMD* simulation D7 described in Chapter 10 are copied to the file *BrazosSimulationResults.DSS* with pathname part F renamed "*Daily SIMD*" for identification. Likewise, the results of the monthly *SIM* simulation M3 is copied to the same DSS file with pathname part F renamed "*Monthly SIM*".

CHAPTER 10
SIMULATION RESULTS

The effects on *SIMD* and *SIM* simulation results of different components of the daily WAM input dataset are explored in Chapter 10. The chapter progresses step-by-step through the modeling process covering the following modeling features in sequential order.

1. Conversion of the monthly WAM to daily to better reflect stream flow variability.
2. Addition of routing and forecasting to the daily WAM.
3. Addition of flood control operations of the nine USACE reservoirs.
4. Addition of the Senate Bill 3 (SB3) environmental flow standards (EFS) at the 19 sites to the daily WAM.
5. Addition of SB3 EFS at the 19 sites to the monthly WAM based on monthly summations of daily instream flow targets derived from the daily WAM.

Comparative analyses of the results of alternative monthly *SIM* and daily *SIMD* simulations, with different features activated, focus on the SB3 EFS instream flow targets and shortages; naturalized, regulated, and appropriated flows at the 19 EFS control points; and reservoir storage in 15 large reservoirs. Simulation results plots, tabulations, and statistics are explored directly within HEC-DSSVue. Selected statistical frequency analysis metrics and time series plots are copied from HEC-DSSVue into the chapter. The Chapter 10 comparative analyses address the following topics.

- Variability characteristics of daily versus monthly naturalized stream flows.
- Effects of negative incremental flow adjustment options and other related options.
- Daily simulations with and without routing, forecasting, flood control operations, and Senate Bill 3 (SB3) environmental flow standards (EFS).
- Monthly versus daily simulations with and without SB3 EFS.

Daily and Monthly Brazos WAM

The January 2019 version of the authorized use scenario (run 3) Brazos WAM dataset documented by this report consists of the following set of *SIMD* and/or *SIM* input files, which are described in the preceding.

Brazos3D.DAT – The daily DAT file contains disaggregation, routing, forecasting, flood control, and SB3 environmental flow standard features described in Chapters 3, 4, and 5 of this report added to the original monthly DAT file described in Chapter 2.

Brazos3M.DAT – The monthly DAT file models SB3 environmental flow standards with *IF* and *TS* records that reference instream flow targets in the DSS hydrology input file that were derived from a daily *SIMD* simulation.

Brazos.DIS – Parameters governing distribution of monthly naturalized flows from primary to secondary control points are the same for both daily and monthly simulations.

Brazos.DIF The daily input DIF file contains three *DC* records controlling disaggregation of monthly naturalized flows to daily and 58 *RT* records with routing parameters.

BrazosHYD.DSS – The same hydrology input file containing *IN*, *EV*, *DF*, *HI*, and *TS* records is employed for both daily and monthly simulations.

Complexity of the Brazos WAM

The *SIM* or *SIMD* message MSS file includes a summary table of system components reflecting counts of input records. The MSS file table for a *SIMD* daily simulation includes additional information regarding daily parameters. The MSS file table for a daily simulation with the forecast period set at 15 days is replicated as Table 10.1.

Table 10.1
Model Component Counts from Message MSS File for Daily *SIMD* Simulation

```
*******************************************************
  System components counted from input file:
    3845 control points (CP records)
      77 primary control points (INMETHOD=1)
      67 control points with evap input (CPEV=blank)
     680 reservoirs
     141 instream flow rights (IF records)
    1668 all water rights except IF rights (WR records)
      16 system water rights
     122 sets of water use coefficients (UC records)
      49 storage-area tables (SV/SA records)
       3 flood storage-outflow tables (FV/FQ records)
       6 drought indices (DI records)
     159 flow switches (FS records)
    1800 dual simulation rights
    3152 FD records in the DIS file
       4 maximum upstream gaged cpts on FD records
*******************************************************
  Daily simulation information:
      58 control points with daily flows input in hydrology DSS file.
     464 control points form the longest flow path to the outlet.
      66 control points have routing coefficients in the DIF file.
      20 control points form the longest routing chain to the outlet.
      46 forecast days are required for the longest routing chain
         with normal flow parameters.
      33 forecast days are required for the longest routing chain
         with flood flow parameters.
      15 future time steps are covered during the forecast simulation.
*******************************************************
```

The size and complexity of the Brazos WAM are illustrated by the MSS file counts shown in Table 10.1. Monthly and daily versions of the WAM both have 3,845 control points, 1,676 *WR* record water rights, and 141 *IF* record instream flow rights including the 19 SB3 EFS. The longest flow path from the most upstream control point to the outlet is composed of 463 consecutive sub-reaches defined by 464 control points with a total travel (lag) time of 46 days for normal flow conditions and 33 days for high flow conditions computed by adding the lags from the DIF file.

Computer execution times vary with different computers and selections of simulation results to include in the output files. However, examples of execution times on the same desktop computer for alternative simulations with only a DSS output file (no OUT or SUB files) are as follows: original monthly WAM (12 seconds), daily WAM with no forecasting (11.0 minutes), 15 day forecast period

(2.6 hours), and 30 day forecast period (5.9 hours). The 1940-2017 period-of-analysis consists of 936 months or 28,490 days. For a daily simulation with forecasting, the simulation is repeated for each day of the 15-day, 30-day, other forecast period as the simulation progresses through each of the 28,490 simulation days.

Monthly *SIM* simulation results output can be massive if not limited by output options. Daily *SIMD* simulation results can be much more massive than monthly *SIM* results if not carefully controlled. Execution of *SIMD* may terminate if the SUB file becomes too large. The DSS output file is much more efficient than the optional SUB file is storing extremely large datasets. Options activated on input records in the DAT file to control simulation results output are described in the last section of the preceding Chapter 9.

The following complexities are fundamental to the discussions of this chapter. Monthly stream flow is extremely variable. Within-month daily variability is also great. The monthly *SIM* and daily *SIMD* simulation algorithms for determining the amount of stream flow available to each water right is based on the minimum of the flow at the control point of the water right and all downstream control points. With forecasting, water availability depends on flows at downstream control points in future days. Flow variability may result in over constraining flow availability.

Switching Between Daily and Monthly Simulations

A monthly simulation can be performed with *SIM* with a DAT file containing input records for a daily simulation, such as the file Brazos3D.DAT. *SIM* skips over daily input records in the DAT file, does not read the DIF file, and ignores the *DF* records in the DSS time series input file. However, *SIMD* has no option for skipping over daily-only records in the DAT file. *SIMD* can perform a monthly simulation if and only if no daily-only records are included in the input dataset.

Conversion of the monthly Brazos WAM to daily is described in Chapters 3, 4, 5, and 6. Converting the daily Brazos WAM back to monthly is outlined as follows.

1. The appropriate negative incremental flow option is selected in DAT file *JD* record field 10.
2. *JT*, *JU*, and *DF* records, *FR* and associated *WS*, *FV* and *FQ*, and *FF* and associated *DI/IS/IP* records are relevant only for a daily simulation. *SIM* skips over these daily-only records in the DAT file. These records must be removed to perform a monthly simulation with *SIMD*.
3. The DIF file is not used in a monthly simulation.
4. The 19 SB3 EFS are modeled in the daily simulation DAT file with the *IF*, *HC*, *ES*, and *PF* records shown in Table 5.5. The SB3 EFS are modeled in the monthly simulation DAT file with the instream flow *IF* and target series *TS* records listed in Tables 5.6 and 5.7.
5. Whitney and Waco Reservoirs are modeled in both the monthly and daily WAMs as multiple-owner reservoirs represented by multiple components. The entries of 2 and -1 for input parameters IEAR and SA in *WS* record fields 9 and 10 connects the flood control pool with the following *EA* records and corresponding *SV/SA* records. Flood control component reservoirs WTNYFC and WACOFC are removed for the monthly DAT file.

```
EA      1       2  WHITNY     BRA  CORWHT  WTNYFC
EA      2       2  LKWACO   WACO2   WACO4   WACO5  WACOFC
```

Alternative Simulations

Results from the variations of monthly and daily simulations defined in Tables 10.2 and 10.3 are employed in Chapter 10 to explore modeling features.

Table 10.2
Three Monthly *SIM* and Nine Daily *SIMD* Simulations

M1, M2 - M1 is a monthly *SIM* simulation with the base WAM dataset reflected in Table 2.4 and the first column of Table 2.5. M2 switches ADJINC option 5 to option 4. Otherwise M1 and M2 are identical. The monthly WAM is described in Chapter 2.

D1, D2 - Daily *SIMD* simulations without forecasting, routing, flood control operations, and SB3 EFS. Simulations D1 and D2 are used to compare ADJINC options 4 and 7.

D3, D4 - Daily *SIMD* simulations with forecasting and routing but without flood control and SB3 EFS. Routing and forecasting are described in Chapter 3. Simulations D3 and D4 employ forecast periods of 15 days versus 30 days with no other differences.

D5, D6, D7, D8 - Daily *SIMD* simulations with flood control and SB3 EFS. Flood control operations and SB3 EFS are described in Chapters 4 and 5, respectively.
D5 has no routing and no forecasting. D6 has both routing and 15 day forecasting.
D7 has routing but no forecasting. D8 switches D7 SB3 EFS priorities to 99999999.

D9 - Simulation D9 is identical to simulation D7 except the SB3 EFS are removed.

M3 - Monthly *SIM* simulation with the SB3 environmental flow standards described in Chapter 5 modeled by adding *IF* and *TS* records derived from daily simulation D7 to the M1 monthly WAM dataset. These records are replicated in Tables 5.9 and 5.10.

Table 10.3
Features of Twelve Alternative Simulations

Simulation	Time Step	ADJINC Option	Lag Routing	Flow Forecast	Flood Control	SB3 EFS	SB3 EFS Priority
M1	month	5	no	no	no	no	-
M2	month	4	no	no	no	no	-
D1	day	4	no	no	no	no	-
D2	day	7	no	no	no	no	-
D3	day	7	yes	15 days	no	no	-
D4	day	7	yes	30 days	no	no	-
D5	day	4	no	no	yes	yes	20120301
D6	day	7	yes	15 days	yes	yes	20120301
D7	day	4	yes	no	yes	yes	20120301
D8	day	4	yes	no	yes	yes	99999999
D9	day	4	yes	no	yes	no	-
M3	month	5	no	no	no	yes	20120301

Simulations are performed with-versus-without routing and/or forecasting, reservoir operations for flood control, and SB3 EFS. The effects of negative incremental flow adjustments ADJINC options 4, 5, and 7 are compared. Simulation M1 employs the original base monthly WAM. SB3 EFS are added in the final simulation M3 using monthly summations of daily instream flow targets derived from simulation D7. Simulation has routing but does not include forecasting.

All of the simulations employ the same hydrology input DSS file with the filename BrazosHYD.DSS. The naturalized flows are identically the same in all simulations. Only monthly naturalized flows are employed in the three monthly simulations labeled M1, M2, and M3. The monthly flows are disaggregated to daily in the daily simulations labeled D1, D2, D3, D4, D5, D6, D7, and D8 based on daily pattern hydrographs. Daily simulations results include both daily time series quantities and monthly summations or end-of-month values of the daily quantities.

Selected Control Points and Reservoirs for the Analyses Presented in this Chapter

The discussions in this chapter focus on the 19 control points and 15 reservoirs listed in Tables 10.4 and 10.5. The Senate Bill 3 (SB3) environmental flow standards (EFS) are located at the sites listed in Table 10.4. The locations of these sites are shown in Figure 5.1. The simulation results selected for presentation in this chapter include naturalized, regulated, and appropriated flows and SB3 EFS instream flow targets and shortages at these 19 control points.

Table 10.4
Control Points for the 19 SB3 Environmental Flow Standards

WAM CP ID	Stream	Nearest City	USGS Gage No.	Watershed Area (square miles)
SFAS06	Salt Fork Brazos River	Aspermont	08082000	2,504
DMAS09	Double Mountain Fork	Aspermont	08080500	1,891
BRSE11	Brazos River	Seymour	08082500	5,996
CFNU16	Clear Fork Brazos	Nugent	08084000	2,236
CON026	Clear Fork Brazos	Lueders	08084200	2,542
BRSB23	Brazos River	South Bend	08088000	13,171
BRPP27	Brazos River	Palo Pinto	08089000	14,309
BRGR30	Brazos River	Glen Rose	08091000	16,320
NBCL36	North Bosque River	Clifton	08095000	977
BRWA41	Brazos River	Waco	08096500	20,065
LEGT47	Leon River	Gatesville	08100500	2,379
LAKE50	Lampasas River	Kempner	08103800	817
LRLR53	Little River	Little River	08104500	5,266
LRCA58	Little River	Cameron	08106500	7,100
BRBR59	Brazos River	Bryan	08109000	30,016
NAEA66	Navasota River	Easterly	08110500	936
BRHE68	Brazos River	Hempstead	08111500	34,374
BRRI70	Brazos River	Richmond	08114000	35,454
BRRO72	Brazos River	Rosharon	08116650	35,775

Table 10.5
Reservoirs Included in Simulation Results Analyses of Chapter 10

Reservoir	Stream	Reservoir Identifier	Control Point ID	Storage Capacity Conservation (acre-feet)	Storage Capacity Flood Control (acre-feet)	Storage Capacity Total (acre-feet)
Whitney	Brazos River	multiple *	515731	636,100	1,363,400	1,999,500
Waco	Bosque River	multiple *	509431	206,562	519,840	726,400
Aquilla	Aquilla Creek	AQUILA	515831	52,400	93,600	146,000
Proctor	Leon River	PRCTOR	515931	59,400	314,800	374,200
Belton	Leon River	BELTON	516031	457,600	640,000	1,097,600
Stillhouse Hollow	Lampasas River	STLHSE	516131	235,700	394,700	630,400
Georgetown	San Gabriel	GRGTWN	516231	37,100	93,700	130,800
Granger	San Gabriel	GRNGER	516331	65,500	178,500	244,000
Somerville	Yequa Creek	SMRVLE	516431	160,110	347,290	507,400
Possum Kingdom	Brazos River	POSDOM	515531	724,739	–	724,739
Granbury	Brazos River	GRNBRY	515631	155,000	–	155,000
Limestone	Navasota River	LMSTNE	516531	225,400	–	225,400
Allen's Creek	Allen's Creek	ALLENS	292531	145,533	–	145,533
Alan Henry	Double Mountain	ALANHN	4146P1	115,937	–	115,937
Hubbard Creek	Hubbard Creek	HUBBRD	421331	317,750	–	317,750
Total Storage Capacity				3,594,830	3,945,830	7,540,660

* *Whitney Reservoir is modeled as four component reservoirs with identifiers WHITNY, BRA, CORWHT, and WTNYFC. Waco Reservoir is modeled as five component reservoirs with identifiers LKWACO, WACO2, WACO4, WACO5, and WACOFC.*

The 16 largest reservoirs in the Brazos River Basin are listed in Tables 2.1 and 2.6. Their locations are shown in Figures 2.2, 2.3, 2.13, and 5.1. The 16 largest reservoirs include Squaw Creek Reservoir which is omitted from the list of 15 reservoirs of Table 10.5. Squaw Creek is a constant-level cooling water reservoir for an electric power plant. Squaw Creek is excluded from the list of reservoirs with simulation results presented in Chapter 10 because it is operated and modeled very differently than the other 15 reservoirs, which are operated with fluctuating storage contents.

The 673 reservoirs in the authorized use Brazos WAM contain conservation storage capacities totaling 4,746,330 acre-feet. The total conservation storage capacity of 3,594,830 acre-feet in the 15 reservoirs listed in Table 10.5 represents 74.7 percent of this total conservation capacity. The count of 680 reservoirs in Table 10.1 includes nine component reservoirs used to model Whitney and Waco Reservoirs. The nine USACE reservoirs listed in Table 10.5 contain all of the controlled (gated) flood control storage capacity in the Brazos River Basin. There are no reservoirs with capacities of more than 5,000 acre-feet in the San Jacinto-Brazos coastal basin.

About 39.1 percent of the total annual volume of permitted diversions in the Brazos authorized use WAM are supplied by these 15 reservoirs. Most of the remaining diversion rights are supplied by the numerous other reservoirs. Run-of-river diversion rights represent only a small portion of the total annual volume of permitted diversions.

Stream Flows at the Gage Sites and Storage Contents of the Reservoirs

Reservoir storage contents provide a meaningful metric for assessing the effects of the different aspects of the simulation on water availability for supplying existing water rights. Unappropriated stream flows represent the additional stream flow still available after supplying all existing water rights. Unappropriated flows are extremely variable and thus additional reservoir storage is required to convert unappropriated stream flows to reasonably reliable water supplies. The summary metrics tabulated in Tables 10.6, 10.7, and 10.8 are relevant to the discussions that follow later throughout the remainder of this chapter and the next chapter.

Average regulated and unappropriated flows during the 1940-2017 period-of-analysis at each of the 19 control points listed in Table 10.4 are computed in the 11 simulations defined in Tables 10.2 and 10.3 in acre-feet and tabulated in units of cfs in Tables 10.6 and 10.7 for comparison. Mean observed and naturalized flows are included in the second and third columns of the two tables. The periods-of-record for the USGS gages at control points BRSB23, NBCL36, LEGT47, LAKE50, LRLR53, BRBR59, and BRRO72 do not include all of the period 1940-2017. Gaged flow means for the 11 other control points are for the entire 1940-2017 period-of-analysis.

All of the simulations have the same naturalized flows. Means of the monthly naturalized flows computed with the *TABLES* 2FRE record CFS option are tabulated in the third column of Table 10.6. The third column of Table 10.7 shows the means of daily naturalized flows. The means of the monthly versus daily flows differ slightly due to the varying number of days in the 12 months of the year. The *TABLES* 6FRE CFS option and HEC-DSSVue compute exactly the same means.

The results of statistical frequency analyses of the storage contents of each of the 15 reservoirs in each of the 11 simulations is presented in Table 10.8. Each of the columns in Table 10.8 represents one of the alternative simulations defined in Tables 10.2 and 10.3. Storage plots are included in the discussions presented throughout the remainder of Chapter 10. The frequency tables and time series plots are for 1940-2017 series of 936 end-of-month (simulations M1, M2, M3) or 28,490 end-of-day (D1, D2, D3, D4, D5, D6, D7, D8) storage volumes in acre-feet.

The statistical frequency metrics presented in Table 10.6 include the mean, standard deviation, maximum, minimum, and end-of-period storage volumes that are exceeded specified percentages of the 936 months or 28,490 days of the 1940-2017 hydrologic period-of-analysis. The statistics are computed with HEC-DSSVue using the options: Tools/Math Functions/ Statistics/Basic and Duration Analysis. Exceedance frequency is defined as follows where m is the relative rank and N is the sample size of 28,490 days or 936 months.

$$\text{Exceedance Frequency} = \frac{\text{m}}{\text{N} + 1}(100\%)$$

Units for Stream Flow Rates and End-of-Period Reservoir Storage Volumes

SIMD performs a simulation using a daily computational time step. The 42 time series output variables selected with the *OF* record [2], along with other variables, are computed for each of the 28,490 days of the simulation for all control points, water rights, and/or reservoirs. Daily values of user-specified variables at user-selected control points, water rights, and/or reservoirs are included in the *SIMD* output DSS and/or SUB files. The corresponding monthly quantities may also be recorded in the *SIMD* output DSS and/or OUT files. Monthly flow rates in acre-feet/month are summations of the daily flow rates in acre-feet/day. End-of-month reservoir storage volumes in acre-feet are the simulated end-of-day storage volume in acre-feet for the last day of each month. Daily, monthly, or annual flow quantities are expressed in this report alternatively both as mean flow rates in cubic feet per second (cfs) or flow volumes (rates) in acre-feet per day, year, or month.

All days have the same length of 86,400 seconds. The 12 months of the year have lengths of either 28, 29, 30, or 31 days. February has 29 days in leap years and 28 days in all other years. The 1940-2017 period-of-analysis contains the leap years 1940 and every fourth year thereafter in both reality and the *SIMD* simulation. The conversion of daily volumes in acre-feet to daily mean flow rates in cfs consists simply of applying the multiplier factor 0.50416667. Monthly volume to mean flow rate conversions vary with number of days in each month. The mean of 936 monthly values is slightly different than the mean of 28,490 daily values due to the different number of days in each of the 12 months of the year. Relevant conversion factors are as follows.

1.0 acre-feet per day = 0.50416667 cubic feet per second (cfs)
1.0 day = 86,400 seconds
1.0 acre-foot = 43,560 cubic feet (ft^3)
1.0 second-foot-day (sfd) = (1.0 ft^3/s)×(1.0 day) = 86,400 ft^3
1940-2017 contains 78 years = 936 months = 28,490 days

The 1940-2017 time series of simulated reservoir storage content volumes consist of either 936 end-of-month volumes or 28,490 end-of-day volumes. The 936 end-of-month storage volumes are a subset of the 28,490 end-of-day storage volumes which includes only the end-of-day storage at the end of the last day of each month. Differences between plots of only 936 end-of-month volumes and the corresponding 28,490 end-of-day volumes are typically not visually noticeable.

Table 10.6
1940-2017 Mean Observed, Naturalized, and Simulated Regulated Stream Flow (cfs)

Control Point	Gaged Flow	Natural Monthly	1940-2017 Mean Regulated Flow (cfs) from Simulations M1	M2	D1	D2	D3	D4	D5	D6	D7	D8	D9	M3
SFAS06	85.35	89.27	83.15	83.15	83.29	88.04	80.83	87.27	83.29	160.3	83.45	83.49	83.49	83.15
DMAS09	128.5	135.4	112.6	112.6	116.2	132.4	123.9	121.6	116.2	124.0	111.5	111.6	111.6	112.6
BRSE11	297.2	303.8	285.0	285.0	288.1	301.0	291.9	292.9	288.1	292.0	285.3	285.4	285.4	285.0
CFNU16	70.34	111.7	50.62	50.62	48.87	70.26	70.39	71.65	48.86	70.38	60.94	60.97	60.97	50.62
CON026	-	130.2	69.25	69.25	82.56	89.55	89.37	89.96	82.55	89.34	91.51	91.58	91.58	69.25
BRSB23	719.0	805.5	682.7	682.7	691.0	760.9	756.7	733.3	691.0	758.3	704.5	704.7	704.7	682.7
BRPP27	847.5	990.9	469.3	469.3	637.4	580.3	581.1	576.1	637.5	584.7	641.4	642.2	642.2	469.3
BRGR30	1,201	1,398	745.3	745.3	861.7	879.6	875.0	872.5	861.8	880.7	885.1	886.0	886.0	745.4
NBCL36	230.1	224.8	212.9	212.9	212.7	214.6	213.7	213.6	212.7	213.9	212.3	212.3	212.3	212.9
BRWA41	1,216	2,570	1,759	1,759	1,702	1,763	1,756	1,734	1,694	1,767	1,757	1,757	1,757	1,759
LEGT47	322.5	347.4	302.5	302.5	309.4	314.1	314.9	314.6	309.3	310.9	309.4	309.4	309.4	302.5
LAKE50	161.8	165.8	160.6	160.6	160.7	160.8	160.7	160.7	160.7	160.8	161.4	161.5	161.5	160.6
LRLR53	1,062	1,167	801.4	801.4	838.3	838.5	840.2	840.9	837.8	827.5	857.6	857.7	857.7	801.4
LRCA58	1,772	1,844	1,401	1,401	1,420	1,438	1,441	1,442	1,420	1,424	1,442	1,442	1,442	1,401
BRBR59	4,805	5,479	4,162	4,162	4,097	4,207	4,208	4,207	4,090	4,203	4,159	4,160	4,160	4,161
NAEA66	427.9	465.8	331.4	331.4	341.9	335.1	339.3	337.9	341.9	339.7	343.9	343.9	343.9	331.4
BRHE68	6,850	7,390	5,839	5,839	5,763	6,874	5,885	5,883	5,755	5,878	5,821	5,821	5,821	5,838
BRRI70	7,633	8,073	6,353	6,353	6,302	6,387	6,403	6,400	6,294	6,397	6,381	6,380	6,380	6,353
BRRO72	8,208	8,457	6,251	6,251	6,151	6,303	6,340	6,335	6,145	6,339	6,304	6,305	6,305	6,251

Table 10.7
1940-2017 Mean Observed, Naturalized, and Unappropriated Stream Flow (cfs)

CP	Gaged Flow	Natural Daily	1940-2017 Mean Unappropriated Flow (cfs) from Simulations M1	M2	D1	D2	D3	D4	D5	D6	D7	D8	D9	M3
SFAS06	85.35	89.58	44.53	44.53	19.64	6.33	12.85	6.657	12.94	9.784	11.81	11.70	20.99	37.73
DMAS09	128.5	135.8	46.53	46.53	18.40	4.19	6.79	3.179	12.10	5.295	11.79	11.63	20.92	39.94
BRSE11	297.2	304.7	141.6	141.6	62.11	20.69	21.48	20.53	40.60	14.07	36.56	36.08	58.94	117.7
CFNU16	70.34	112.0	27.85	27.85	19.16	5.91	5.82	5.846	10.71	4.146	8.09	8.04	13.34	23.38
CON026	-	130.5	41.04	41.04	30.13	10.08	6.33	6.133	20.15	5.335	15.18	15.19	21.04	35.54
BRSB23	719.0	806.9	297.7	297.7	156.3	44.64	46.03	37.65	95.17	29.63	83.82	81.89	117.0	253.9
BRPP27	847.5	992.3	358.1	358.1	204.0	67.56	57.40	50.18	136.3	39.51	126.5	124.4	152.9	293.6
BRGR30	1,201	1,400	635.7	635.7	415.1	155.5	172.0	159.1	268.1	80.82	289.2	288.8	361.4	483.8
NBCL36	230.1	224.4	175.1	175.1	99.03	72.75	62.66	62.82	72.67	44.82	104.4	105.4	122.4	155.8
BRWA41	1,216	2,569	1,355	1,355	883.4	753.4	898.9	869.8	758.8	529.7	748.4	763.4	864.0	1,176
LEGT47	322.5	347.1	226.3	226.3	127.2	62.88	58.08	65.09	83.31	43.24	82.77	82.58	94.64	205.5
LAKE50	161.8	165.3	109.6	109.6	66.16	59.49	56.65	57.38	33.00	36.62	29.20	30.15	34.97	97.62
LRLR53	1,062	1,165	661.6	661.6	508.9	415.3	478.6	478.1	433.2	279.8	400.1	397.9	447.4	604.6
LRCA58	1,772	1,841	1,131	1,131	873.5	764.9	898.9	783.3	736.1	517.1	777.0	775.1	888.1	1,011
BRBR59	4,805	5,474	3,121	3,121	2,429	2,318	2,247	2,228	2,006	1,511	2,005	2,011	2,396	2,654
NAEA66	427.9	464.7	287.9	287.9	152.2	125.0	138.9	134.5	134.1	105.0	137.5	137.5	153.3	262.4
BRHE68	6,850	7,378	3,835	3,835	3,700	3,598	3,302	3,286	3,199	2,266	3,017	3,017	3,499	3,352
BRRI70	7,633	8,061	4,769	4,769	4,312	4,144	4,082	4,071	3,608	3,078	3,652	3,647	4,358	3,984
BRRO72	8,208	8,445	5,810	5,810	6,083	5,871	5,848	5,841	4,516	4,077	4,602	4,601	6,149	4,096

Table 10.8
Reservoir Storage Frequency Metrics for the Eleven Simulations

Whitney Reservoir End-of-Month (M1, M2, M3) or End-of-Day (D1-D8) Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	605,121	591,787	589,737	574,212	571,693	575,827	593,528	561,431	602,395	603,766	602,138
Std Dev	39,819	53,599	53,352	62,340	60,665	61,937	85,196	117,822	64,862	64,881	39,095
Maximum	636,100	636,100	636,100	636,100	636,100	636,100	1,999,500	1,985,488	1,749,563	1,700,512	636,100
Minimum	449,157	363,485	388,964	367,465	339,942	351,579	393,123	313,056	464,168	453,450	447,563
Frequency (%)											
0.2	636,100	636,100	636,100	636,100	636,100	636,100	1,341,321	1,779,395	1,244,574	1,206,839	636,100
0.5	636,100	636,100	636,100	636,100	636,100	636,100	987,155	1,400,262	917,311	937,597	636,100
1	636,100	636,100	636,100	636,100	636,100	636,100	806,618	939,041	770,266	774,712	636,100
2	636,100	636,100	636,100	636,100	636,100	636,100	660,417	700,622	666,569	667,553	636,100
5	636,100	636,100	636,100	636,100	634,702	635,318	636,100	632,895	636,100	636,100	636,100
10	636,100	636,100	636,100	634,253	629,635	632,506	636,092	623,696	636,092	636,100	636,100
15	636,100	635,840	635,619	631,132	624,806	629,859	635,266	616,649	635,236	635,561	635,621
20	635,962	635,156	634,365	628,009	620,087	626,296	633,254	608,496	633,285	634,496	634,565
30	634,771	630,089	627,983	619,048	610,560	617,995	625,345	594,764	627,520	630,463	630,299
40	628,759	621,023	618,002	605,362	599,180	607,154	616,272	580,313	619,244	622,797	624,076
50	622,298	609,588	606,702	592,085	588,169	594,534	603,882	565,146	609,320	612,207	617,326
60	612,309	598,318	597,238	576,782	576,018	580,901	594,063	549,575	599,891	602,100	606,630
70	598,825	580,718	581,424	557,002	558,341	562,578	576,212	535,500	586,700	588,567	593,375
80	576,085	557,919	552,406	529,702	533,729	535,867	551,618	508,466	565,903	567,214	572,786
85	561,758	540,665	532,780	514,099	519,026	519,370	529,614	493,953	552,084	554,176	561,258
90	544,944	514,592	514,486	494,730	495,822	496,243	511,652	478,093	537,081	537,440	543,426
95	519,734	485,750	463,768	427,109	435,356	432,220	465,760	379,316	512,269	510,841	515,979
98	487,492	427,945	440,603	389,730	365,190	375,746	442,512	337,819	491,092	485,358	490,442
99	464,998	378,688	403,377	376,105	355,247	367,924	407,733	329,124	482,163	469,506	474,675
99.5	462,944	374,579	395,715	370,515	347,369	358,660	400,020	326,832	472,584	462,091	461,462
99.8	450,836	365,724	391,813	368,921	345,328	352,565	396,268	320,644	466,113	455,892	449,232

Waco Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	178,183	177,898	168,050	155,916	146,996	147,996	167,613	145,328	164,790	164,528	178,646
Std Dev	33,366	33,200	43,025	55,126	56,210	55,661	43,323	61,780	47,165	47,705	33,361
Maximum	206,561	206,561	206,562	206,562	206,562	206,562	250,513	431,908	268,321	284,147	206,562
Minimum	63,219	63,228	16,018	531	372	533	15,177	2,385	8,484	7,578	63,786
Frequency (%)											
0.2	206,561	206,561	206,562	206,562	206,562	206,562	216,027	242,357	226,456	228,494	206,561
0.5	206,550	206,550	206,562	206,562	206,562	206,562	208,531	225,145	216,035	218,973	206,556
1	206,548	206,548	206,562	206,562	206,562	206,534	206,562	211,604	208,474	210,761	206,550
2	206,543	206,544	206,562	206,562	206,511	205,559	206,562	206,562	206,562	206,562	206,543
5	206,519	206,474	206,562	206,562	204,618	203,354	206,562	206,431	206,450	206,521	206,517
10	206,129	206,020	206,548	206,520	200,520	200,285	206,388	205,061	205,943	205,940	206,498
15	205,917	205,906	206,303	206,191	197,668	197,469	205,960	203,024	205,395	205,329	206,242
20	205,816	205,662	205,667	204,920	195,224	195,610	205,214	200,710	204,590	204,472	206,109
30	204,050	203,463	199,587	196,930	188,267	189,531	199,297	190,397	200,260	200,187	205,541
40	199,530	199,134	191,567	186,852	178,172	179,153	191,196	178,743	191,885	192,010	199,986
50	191,122	190,828	182,622	174,934	166,036	166,160	182,185	166,717	181,473	181,436	191,769
60	181,255	181,450	172,071	163,393	153,386	153,918	171,500	151,767	169,908	169,779	181,754
70	169,318	168,430	158,689	141,990	131,068	132,231	158,004	129,395	153,554	153,302	169,729
80	152,372	152,307	137,494	111,908	95,801	99,512	136,560	84,031	131,843	130,872	152,390
85	140,379	140,598	119,119	88,318	73,336	79,033	118,368	62,802	111,369	110,465	140,381
90	124,774	125,042	101,645	63,708	58,753	62,167	100,723	39,098	90,227	88,822	124,790
95	106,534	106,530	74,529	31,953	21,698	20,285	73,730	14,033	61,390	60,665	108,956
98	85,996	85,987	50,336	14,532	4,533	4,542	49,464	4,723	31,772	29,099	85,975
99	75,545	75,567	34,407	7,514	2,584	3,119	33,463	3,896	20,420	18,129	76,748
99.5	69,503	69,512	23,240	1,231	668	597	22,290	3,319	15,313	12,649	70,072
99.8	63,497	63,507	18,239	534	452	582	17,264	2,746	11,756	9,519	64,065

Aquilla Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	44,383	44,470	38,273	32,828	36,484	36,575	38,366	38,520	42,964	42,830	44,383
Std Dev	9,471	9,448	15,205	16,573	14,792	15,087	15,246	15,848	11,291	11,513	9,471
Maximum	52,400	52,400	52,400	52,400	52,400	52,400	65,826	136,513	106,126	106,929	52,400
Minimum	2,101	1,816	0	0	0	0	0	0	0	0	2,101
Frequency (%)											
0.2	52,400	52,400	52,400	52,400	52,400	52,400	56,292	98,502	84,083	83,459	52,400
0.5	52,400	52,400	52,400	52,400	52,400	52,400	53,300	82,903	73,136	73,877	52,400
1	52,400	52,400	52,400	52,400	52,400	52,400	52,400	69,562	62,144	62,064	52,400
2	52,400	52,400	52,400	52,400	52,345	52,400	52,400	55,542	53,681	53,800	52,400
5	52,400	52,400	52,400	52,400	51,832	52,068	52,400	52,400	52,400	52,400	52,400
10	52,400	52,400	52,400	51,838	51,148	51,532	52,400	52,391	52,400	52,400	52,400
15	52,400	52,400	52,248	50,201	50,364	50,962	52,332	52,089	52,397	52,393	52,400
20	52,400	52,400	51,500	47,967	49,509	50,038	51,583	51,321	52,241	52,221	52,400
30	51,990	52,077	48,705	44,158	46,566	46,876	48,810	48,507	50,877	50,818	51,990
40	49,528	49,542	45,872	41,144	43,378	43,550	46,004	45,359	48,487	48,428	49,528
50	47,173	47,227	43,137	37,576	40,916	40,887	43,231	42,505	45,949	45,903	47,173
60	44,849	45,006	40,312	32,769	37,857	37,720	40,412	39,488	43,193	43,136	44,849
70	41,622	41,919	36,232	26,771	33,572	33,797	36,345	35,575	39,679	39,633	41,622
80	38,060	38,155	27,132	18,093	25,583	26,012	27,187	28,061	35,378	35,321	38,060
85	35,847	36,093	20,360	8,876	18,164	18,294	20,383	19,887	32,020	31,707	35,847
90	32,042	31,632	11,820	1,761	11,157	10,320	11,901	12,430	26,460	26,308	32,042
95	24,059	24,040	288	0	983	0	284	1,872	19,708	19,079	24,059
98	17,316	17,574	0	0	0	0	0	0	12,650	11,125	17,316
99	9,706	9,918	0	0	0	0	0	0	8,067	5,308	9,706
99.5	4,640	4,822	0	0	0	0	0	0	2,665	693	4,640
99.8	2,616	2,334	0	0	0	0	0	0	779	0	2,616

Proctor Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	43,562	44,010	36,969	36,777	23,022	22,981	37,196	37,081	36,981	36,934	43,562
Std Dev	16,271	15,932	19,193	22,145	21,068	21,393	19,577	39,083	19,837	19,985	16,271
Maximum	59,400	59,400	59,400	59,400	59,400	59,400	112,143	374,200	108,404	109,352	59,400
Minimum	0	0	0	0	0	0	0	0	0	0	0
Frequency (%)											
0.2	59,400	59,400	59,400	59,400	59,400	87,849	344,797	97,889	100,518	59,400	59,400
0.5	59,400	59,400	59,400	59,400	59,400	74,119	290,232	89,124	91,287	59,400	59,400
1	59,400	59,400	59,400	59,351	59,400	63,974	220,646	81,567	82,595	59,400	59,400
2	59,400	59,400	59,400	58,664	59,188	59,628	154,854	65,746	67,171	59,400	59,400
5	59,400	59,400	59,400	56,597	57,285	59,400	75,520	59,400	59,400	59,400	59,400
10	59,400	59,400	59,400	53,879	54,636	59,400	59,400	59,329	59,343	59,400	59,400
15	59,400	59,400	59,226	50,239	51,306	59,247	58,461	58,740	58,716	59,400	59,400
20	59,400	59,400	57,745	46,054	47,375	57,745	56,110	57,143	57,156	59,400	59,400
30	57,766	57,745	51,546	39,032	38,840	51,546	48,869	51,174	51,088	57,766	57,766
40	52,608	52,871	45,631	30,968	31,078	45,623	41,446	44,925	44,853	52,608	52,608
50	47,325	48,039	40,512	20,192	18,824	40,516	35,591	39,669	39,696	47,325	47,325
60	42,662	43,473	34,022	9,321	8,576	34,092	24,294	33,461	33,382	42,662	42,662
70	37,560	37,819	27,949	1,600	1,049	27,986	14,915	25,306	25,162	37,560	37,560
80	31,097	31,166	18,532	0	0	18,576	7,741	16,790	16,633	31,097	31,097
85	23,176	24,063	11,715	0	0	11,721	3,299	13,112	12,893	23,176	23,176
90	18,039	18,704	5,470	0	0	5,486	4	6,955	6,972	18,039	18,039
95	9,830	11,742	0	0	0	0	0	582	573	9,830	9,830
98	1,276	2,927	0	0	0	0	0	0	0	1,276	1,276
99	0	284	0	0	0	0	0	0	0	0	0
99.5	0	0	0	0	0	0	0	0	0	0	0
99.8	0	0	0	0	0	0	0	0	0	0	0

Belton Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	386,907	398,390	364,368	300,495	279,862	284,069	369,138	352,340	370,551	370,715	386,907
Std Dev	99,996	85,199	127,818	148,269	144,355	145,245	133,715	168,607	132,270	132,819	99,996
Maximum	457,600	457,600	457,600	457,600	457,600	457,600	864,151	1,097,600	729,014	754,385	457,600
Minimum	0	66,963	0	0	0	0	0	0	0	0	0
Frequency (%)											
0.2	457,600	457,600	457,600	457,600	457,600	457,600	720,423	1,097,600	662,331	678,355	457,600
0.5	457,600	457,600	457,600	457,600	457,600	457,600	642,347	1,043,839	630,917	641,253	457,600
1	457,600	457,600	457,600	457,600	457,600	457,600	605,053	949,307	604,084	614,994	457,600
2	457,600	457,600	457,600	457,600	454,683	457,396	530,507	746,337	544,588	551,781	457,600
5	457,600	457,600	457,600	457,600	448,542	453,225	478,440	548,445	478,523	481,401	457,600
10	457,600	457,600	457,600	456,585	439,181	445,914	457,600	462,769	457,600	457,600	457,600
15	457,600	457,600	457,600	448,306	429,752	433,947	457,600	457,379	457,600	457,600	457,600
20	457,600	457,600	457,600	433,899	411,943	416,200	457,600	450,584	457,351	457,335	457,600
30	457,600	457,600	449,499	404,692	379,785	384,889	449,577	428,244	448,164	447,919	457,600
40	441,519	448,772	431,899	381,335	351,458	356,397	431,984	406,515	433,122	432,914	441,519
50	425,047	434,129	414,634	352,495	326,437	331,298	414,711	385,563	415,829	415,444	425,047
60	403,393	413,634	395,884	309,323	280,120	283,957	395,903	361,977	395,372	395,128	403,393
70	381,284	393,044	359,237	250,206	226,545	232,036	359,229	315,445	365,187	365,126	381,284
80	342,270	359,844	306,159	173,033	144,401	151,967	306,196	245,091	314,975	314,710	342,270
85	309,137	328,027	263,453	91,210	75,414	76,192	263,528	188,445	263,558	264,421	309,137
90	259,716	276,682	164,619	11,780	5,177	5,829	164,725	93,404	162,255	161,781	259,716
95	145,089	193,107	0	0	0	0	0	0	280	263	145,089
98	42,402	113,173	0	0	0	0	0	0	0	0	42,402
99	19,062	92,318	0	0	0	0	0	0	0	0	19,062
99.5	6,207	80,432	0	0	0	0	0	0	0	0	6,207
99.8	0	72,980	0	0	0	0	0	0	0	0	0

Stillhouse Hollow Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	191,917	191,616	171,460	168,910	166,494	166,075	174,522	186,278	171,791	171,299	191,917
Std Dev	62,051	62,649	72,036	72,899	68,924	71,767	76,508	91,638	76,212	76,211	62,071
Maximum	235,700	235,700	235,700	235,700	235,700	235,700	520,611	630,400	508,943	502,585	235,700
Minimum	0	0	0	0	0	0	0	0	0	0	0
Frequency (%)											
0.2	235,700	235,700	235,700	235,700	235,700	235,700	419,599	630,400	436,808	435,582	235,700
0.5	235,700	235,700	235,700	235,700	235,700	235,700	349,888	600,410	382,971	369,548	235,700
1	235,700	235,700	235,700	235,700	235,700	235,700	326,003	538,609	307,584	318,915	235,700
2	235,700	235,700	235,700	235,700	235,700	235,700	281,430	431,048	281,237	280,872	235,700
5	235,700	235,700	235,700	235,700	235,330	235,700	248,558	283,223	245,102	245,818	235,700
10	235,700	235,700	235,700	235,700	231,486	232,488	235,700	238,924	235,700	235,700	235,700
15	235,700	235,700	235,697	235,289	226,435	228,896	235,700	235,700	235,275	235,326	235,700
20	235,700	235,700	231,655	230,080	220,868	224,757	231,721	233,953	231,055	231,096	235,700
30	234,656	234,607	220,932	219,444	213,899	217,516	221,017	225,978	219,510	219,398	234,656
40	226,735	227,010	211,473	209,524	204,110	206,290	211,942	216,366	207,744	207,538	226,735
50	218,857	218,664	200,658	197,380	192,093	192,361	200,761	203,333	194,012	193,520	218,857
60	208,057	207,771	182,944	178,720	176,369	175,746	183,047	187,492	178,196	177,808	208,057
70	186,924	187,515	156,203	152,455	151,376	149,885	156,317	167,458	153,464	153,465	186,924
80	160,311	159,543	123,716	120,333	119,850	114,144	123,909	130,880	113,871	113,957	160,311
85	139,159	137,762	97,954	91,610	95,398	89,531	98,184	104,951	85,073	85,199	139,159
90	85,973	82,995	30,188	17,585	33,369	22,541	30,491	43,269	36,685	36,490	85,973
95	28,115	25,919	0	0	2	0	0	4	0	0	28,115
98	5,390	3,939	0	0	0	0	0	0	0	0	5,390
99	0	0	0	0	0	0	0	0	0	0	0
99.5	0	0	0	0	0	0	0	0	0	0	0
99.8	0	0	0	0	0	0	0	0	0	0	0

Georgetown Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	29,375	29,369	26,027	25,734	22,600	22,095	26,039	31,012	26,788	26,778	29,375
Std Dev	9,951	9,949	12,514	12,630	11,324	11,585	12,515	8,208	12,043	12,037	9,951
Maximum	37,100	37,100	37,100	37,100	37,100	37,100	37,100	85,603	64,066	63,733	37,100
Minimum	0	0	0	0	0	0	0	670	0	0	0
Frequency (%)											
0.2	37,100	37,100	37,100	37,100	37,100	37,100	37,100	43,110	37,846	38,692	37,100
0.5	37,100	37,100	37,100	37,100	37,100	37,100	37,100	38,574	37,100	37,100	37,100
1	37,100	37,100	37,100	37,100	37,058	37,100	37,100	37,100	37,100	37,100	37,100
2	37,100	37,100	37,100	37,100	36,793	36,831	37,100	37,100	37,100	37,100	37,100
5	37,100	37,100	37,100	37,100	36,296	36,177	37,100	37,100	37,100	37,100	37,100
10	37,100	37,100	37,100	37,100	35,345	35,352	37,100	37,100	37,100	37,100	37,100
15	37,100	37,100	37,100	37,100	33,666	33,450	37,100	37,100	37,100	37,100	37,100
20	37,100	37,100	37,099	37,093	32,148	32,092	37,100	37,100	37,100	37,100	37,100
30	37,100	37,100	35,841	35,512	30,645	30,201	35,854	37,100	36,348	36,337	37,100
40	35,538	35,357	33,814	33,472	28,992	28,728	33,824	36,272	34,171	34,166	35,538
50	33,504	33,389	31,736	31,377	26,094	25,672	31,762	34,444	32,161	32,138	33,504
60	31,239	31,073	27,754	27,516	22,683	22,120	27,773	32,202	28,397	28,309	31,239
70	27,123	27,123	21,916	21,577	17,651	17,003	21,932	29,369	23,367	23,257	27,123
80	21,919	22,129	14,994	13,950	11,700	10,799	15,008	25,507	17,119	17,157	21,919
85	19,131	19,812	8,943	8,170	7,596	6,278	8,987	23,134	11,860	12,276	19,131
90	14,864	15,038	602	423	2,149	465	605	19,455	3,084	3,222	14,864
95	5,724	5,752	0	0	0	0	0	13,025	0	0	5,724
98	0	0	0	0	0	0	0	5,212	0	0	0
99	0	0	0	0	0	0	0	3,219	0	0	0
99.5	0	0	0	0	0	0	0	2,341	0	0	0
99.8	0	0	0	0	0	0	0	1,007	0	0	0

Granger Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	56,296	56,126	51,893	65,215	50,776	50,803	52,291	59,960	53,501	53,466	56,296
Std Dev	13,639	13,666	17,916	19,046	18,070	18,423	18,182	11,023	16,967	17,033	13,639
Maximum	65,500	65,500	65,500	65,500	65,500	65,500	122,426	148,789	123,294	123,031	65,500
Minimum	0	0	0	0	0	0	0	0	0	0	0
Frequency (%)											
0.2	65,500	65,500	65,500	65,500	65,500	65,500	82,582	110,997	86,534	87,606	65,500
0.5	65,500	65,500	65,500	65,500	65,500	65,500	74,517	94,695	74,236	75,985	65,500
1	65,500	65,500	65,500	65,500	65,500	65,500	72,849	80,141	72,895	73,203	65,500
2	65,500	65,500	65,500	65,500	65,500	65,500	71,055	73,169	70,848	71,553	65,500
5	65,500	65,500	65,500	65,500	65,500	65,500	67,282	69,659	67,301	67,851	65,500
10	65,500	65,500	65,500	65,500	65,307	65,412	65,500	66,338	65,500	65,500	65,500
15	65,500	65,500	65,500	65,500	64,826	64,947	65,500	65,500	65,500	65,500	65,500
20	65,500	65,500	65,500	65,500	64,306	64,514	65,500	65,500	65,500	65,500	65,500
30	65,500	65,500	65,444	65,432	63,316	63,748	65,460	65,500	65,478	65,490	65,500
40	65,500	65,500	63,709	63,428	61,816	62,271	63,744	65,500	63,964	63,902	65,500
50	63,468	62,629	60,212	59,668	59,102	59,130	60,248	64,951	60,990	60,975	63,468
60	59,116	58,622	54,567	54,136	54,215	54,006	54,600	62,614	55,743	55,632	59,116
70	54,390	54,023	47,985	47,046	47,453	47,911	48,136	58,399	50,139	49,858	54,390
80	47,458	47,430	39,572	35,278	38,043	38,507	39,639	53,064	41,957	41,535	47,458
85	43,796	43,293	32,638	29,704	30,565	31,748	32,854	49,496	35,728	35,649	43,796
90	37,126	36,795	26,460	21,489	23,752	21,201	26,604	44,914	29,132	28,938	37,126
95	26,276	26,102	4,448	1,187	4,365	1,620	4,972	37,697	12,984	13,236	26,276
98	12,267	11,019	0	0	0	0	0	27,434	1,472	1,653	12,267
99	3,982	4,509	0	0	0	0	0	20,983	0	0	3,982
99.5	76	0	0	0	0	0	0	19,343	0	0	76
99.8	0	0	0	0	0	0	0	17,975	0	0	0

Somerville Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	132,631	133,333	129,376	128,055	125,642	124,634	133,291	139,216	128,915	128,994	132,631
Std Dev	33,974	33,374	36,281	38,044	41,376	41,879	41,103	39,290	42,049	42,063	33,974
Maximum	160,110	160,110	160,110	160,110	160,110	160,110	380,422	438,640	330,546	330,533	160,110
Minimum	0	0	0	0	0	0	0	8,825	0	0	0
Frequency (%)											
0.2	160,110	160,110	160,110	160,110	160,110	160,110	287,219	337,956	250,630	243,989	160,110
0.5	160,110	160,110	160,110	160,110	160,110	160,110	256,527	274,135	223,254	219,240	160,110
1	160,110	160,110	160,110	160,110	160,110	160,110	224,805	246,944	208,745	208,372	160,110
2	160,110	160,110	160,110	160,110	160,110	160,110	208,044	219,222	192,974	196,262	160,110
5	160,110	160,110	160,110	160,110	160,110	160,110	181,402	193,295	174,547	176,160	160,110
10	160,110	160,110	160,110	160,110	160,110	160,110	163,739	172,004	160,981	162,154	160,110
15	160,110	160,110	160,110	160,110	160,110	160,110	160,110	160,485	160,110	160,110	160,110
20	160,110	160,110	160,110	160,110	160,041	160,027	160,110	160,110	160,110	160,110	160,110
30	160,110	160,110	158,182	158,213	157,477	156,499	158,999	159,591	157,662	157,653	160,110
40	153,693	154,432	150,524	149,931	149,015	148,055	152,600	154,328	149,917	149,383	153,693
50	145,010	146,263	141,900	141,296	139,718	139,025	143,392	145,998	140,117	139,958	145,010
60	136,223	136,605	133,128	132,062	130,870	129,564	133,842	138,160	130,056	130,009	136,223
70	125,104	126,012	121,128	119,565	117,941	116,677	121,586	127,995	118,069	118,153	125,104
80	108,426	110,362	102,726	101,074	98,418	96,466	103,042	111,557	99,285	99,350	108,426
85	96,513	97,613	90,779	87,485	83,763	78,602	92,189	100,006	81,720	81,822	96,513
90	80,536	81,450	72,696	70,995	63,056	62,828	72,937	84,920	66,527	66,828	80,536
95	60,649	61,276	51,570	46,760	28,590	25,089	52,839	64,447	44,576	44,850	60,649
98	36,472	41,216	24,219	11,085	0	0	25,115	52,445	6,644	6,651	36,472
99	14,284	24,269	14,617	2	0	0	14,967	40,946	0	0	14,284
99.5	0	3,766	0	0	0	0	0	17,556	0	0	0
99.8	0	0	0	0	0	0	0	13,197	0	0	0

Possum Kingdom Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	632,584	633,373	606,488	447,829	400,802	430,039	606,483	379,793	483,705	476,537	632,584
Std Dev	132,472	130,591	146,364	225,004	202,026	227,434	146,372	193,282	204,406	202,898	132,472
Maximum	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,739
Minimum	0	0	0	0	0	0	0	0	0	0	0
Frequency (%)											
0.2	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,739
0.5	724,739	724,739	724,739	724,739	724,739	724,739	724,739	724,502	724,739	724,739	724,739
1	724,739	724,739	724,739	724,739	724,400	724,030	724,739	721,270	724,600	722,978	724,739
2	724,739	724,739	724,739	724,739	720,296	717,778	724,739	713,529	721,665	718,074	724,739
5	724,739	724,739	724,739	724,707	680,924	690,682	724,739	677,517	712,760	703,322	724,739
10	724,739	724,739	724,739	711,300	627,453	646,898	724,739	600,440	701,325	690,592	724,739
15	724,739	724,739	724,147	682,173	610,650	616,865	724,147	567,904	687,463	676,557	724,739
20	724,739	724,739	721,462	660,040	590,798	588,753	721,473	546,902	670,610	660,983	724,739
30	720,536	721,402	707,476	608,795	541,884	528,994	707,476	510,422	626,350	616,356	720,536
40	704,774	705,455	686,046	562,586	497,818	467,043	686,059	462,962	581,880	574,288	704,774
50	685,169	685,155	660,290	506,972	443,548	404,384	660,298	415,034	537,906	531,480	685,169
60	658,818	658,609	624,682	438,784	375,802	327,839	624,682	350,926	484,367	478,326	658,818
70	620,417	620,879	579,926	363,785	296,871	237,686	579,873	278,989	419,398	414,667	620,417
80	562,451	563,304	517,017	198,975	203,462	102,068	517,017	197,766	320,355	317,688	562,451
85	517,031	523,553	476,469	141,952	149,753	27,310	476,499	142,097	223,387	216,055	517,031
90	481,581	481,072	414,594	82,018	84,493	473	414,578	78,752	145,656	132,808	481,581
95	367,974	368,580	305,771	226	818	0	305,729	116	10,235	6,263	367,974
98	149,141	174,741	107,613	0	0	0	107,597	0	0	0	149,141
99	2,499	14,450	0	0	0	0	0	0	0	0	2,499
99.5	0	0	0	0	0	0	0	0	0	0	0
99.8	0	0	0	0	0	0	0	0	0	0	0

Granbury Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	131,872	130,115	131,239	78,415	80,767	82,001	131,241	78,719	137,591	137,135	131,872
Std Dev	30,855	32,110	31,338	53,817	45,849	47,750	31,341	49,218	26,024	25,951	30,855
Maximum	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000
Minimum			0	0	0	0	0	0	0	0	
Frequency (%)											
0.2	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000
0.5	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000	155,000
1	155,000	155,000	155,000	155,000	155,000	154,999	155,000	154,887	155,000	155,000	155,000
2	155,000	155,000	155,000	155,000	154,419	154,179	155,000	153,681	155,000	155,000	155,000
5	155,000	155,000	155,000	155,000	148,865	149,808	155,000	148,570	155,000	155,000	155,000
10	155,000	155,000	155,000	153,718	138,619	141,078	155,000	141,878	155,000	155,000	155,000
15	155,000	155,000	155,000	146,645	129,704	134,500	155,000	135,434	154,877	154,823	155,000
20	155,000	155,000	155,000	135,633	124,015	129,145	155,000	128,474	154,584	154,455	155,000
30	155,000	155,000	153,815	117,577	111,704	115,489	153,819	112,803	153,420	153,262	155,000
40	152,690	151,371	149,721	101,450	97,503	100,455	149,727	98,470	151,383	151,257	152,690
50	145,053	142,912	143,619	82,652	87,515	90,091	143,617	86,750	147,978	147,788	145,053
60	137,606	133,988	136,229	59,618	75,107	76,843	136,238	68,203	142,526	142,477	137,606
70	125,679	123,042	125,955	37,606	57,016	57,234	125,953	47,696	135,399	135,439	125,679
80	108,513	106,530	112,777	18,605	33,320	33,803	112,767	25,645	122,893	122,989	108,513
85	101,102	98,500	102,990	5,640	21,986	14,700	102,989	8,585	115,726	115,800	101,102
90	87,038	83,631	89,508	0	1,799	32	89,501	8	106,155	106,167	87,038
95	64,019	61,555	62,351	0	0	0	62,334	0	93,214	93,207	64,019
98	43,967	34,826	33,047	0	0	0	33,047	0	45,591	45,410	43,967
99	23,684	20,791	6,567	0	0	0	6,567	0	17,580	17,277	23,684
99.5	8,402	3,683	0	0	0	0	0	0	1,275	1,092	8,402
99.8	4,904	39	0	0	0	0	0	0	0	0	4,904

Limestone Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	187,868	189,004	179,047	169,272	154,745	160,423	179,224	154,958	182,856	182,830	187,868
Std Dev	44,417	43,240	48,238	55,496	58,835	59,956	48,260	59,657	44,553	44,568	44,417
Maximum	225,400	225,400	225,400	225,400	225,400	225,400	225,400	225,400	225,400	225,400	225,400
Minimum	15,881	19,815	0	0	0	0	0	0	11,031	10,741	15,881
Frequency (%)											
0.2	225,400	225,400	225,400	225,400	224,414	225,400	225,400	224,490	225,400	225,400	225,400
0.5	225,400	225,400	225,400	225,400	224,187	225,310	225,400	224,317	225,400	225,400	225,400
1	225,400	225,400	225,400	225,400	222,534	225,091	225,400	222,530	225,400	225,400	225,400
2	225,400	225,400	225,400	225,400	221,111	223,800	225,400	220,593	225,400	225,400	225,400
5	225,400	225,400	225,400	225,400	216,874	220,805	225,400	218,219	224,897	224,678	225,400
10	225,400	225,400	225,089	225,307	211,839	217,541	225,361	214,049	224,336	224,186	225,400
15	225,400	225,400	224,704	224,297	208,789	215,365	224,880	209,691	223,067	223,010	225,400
20	225,400	225,400	223,046	221,287	204,818	212,541	223,190	204,973	221,882	221,896	225,400
30	221,405	221,993	215,077	208,028	194,474	202,683	215,265	194,613	215,435	215,420	221,405
40	211,733	211,733	202,968	195,107	183,686	190,273	203,138	183,705	205,769	205,751	211,733
50	200,907	201,388	190,677	182,360	171,408	177,807	190,861	171,851	194,498	194,435	200,907
60	188,801	189,841	179,678	169,911	159,967	166,062	179,910	161,213	183,722	183,705	188,801
70	178,118	179,831	166,178	153,984	140,562	147,251	166,487	141,636	172,984	173,039	178,118
80	161,250	164,130	145,812	128,841	111,145	114,438	146,022	110,423	153,031	153,013	161,250
85	148,377	149,750	132,343	116,161	95,233	97,362	132,572	94,327	140,629	140,585	148,377
90	128,199	132,546	112,142	95,455	63,338	71,775	112,280	61,569	121,681	121,648	128,199
95	86,846	88,277	74,289	39,869	7,971	14,694	74,279	4,611	82,814	82,603	86,846
98	48,122	51,721	40,187	4,874	0	0	40,187	0	51,909	51,887	48,122
99	29,771	35,833	18,622	0	0	0	18,623	0	29,547	29,317	29,771
99.5	23,346	29,133	4,775	0	0	0	4,775	0	22,714	22,490	23,346
99.8	17,648	23,621	0	0	0	0	0	0	17,026	16,749	17,648

Allen’s Creek Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	134,399	133,670	137,820	138,159	136,140	144,692	137,842	134,269	136,564	136,110	134,399
Std Dev	23,121	23,139	15,039	14,898	15,553	15,709	15,025	16,023	15,567	15,693	23,122
Maximum	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533
Minimum	5,001	4,081	44,087	43,413	40,798	38,648	44,250	36,874	37,433	36,600	4,994
Frequency (%)											
0.2	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533
0.5	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533
1	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533
2	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533
5	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533
10	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533	145,533
15	145,533	145,533	145,533	145,533	145,533	145,260	145,533	145,338	145,533	145,533	145,533
20	145,533	145,533	145,533	145,533	145,533	144,562	145,533	144,598	145,533	145,533	145,533
30	145,533	145,533	145,533	145,533	144,770	143,233	145,533	143,136	145,320	144,874	145,533
40	145,533	145,533	145,533	145,533	143,922	141,923	145,533	141,700	144,454	143,879	145,533
50	145,533	145,533	145,433	145,515	142,984	140,742	145,513	140,094	143,439	142,795	145,533
60	145,533	145,533	144,163	144,624	141,383	139,051	144,189	138,480	141,884	141,244	145,533
70	138,234	135,250	140,693	141,295	137,847	136,059	140,722	135,916	138,711	138,169	138,234
80	129,076	123,991	133,205	133,890	130,434	128,679	133,264	128,193	131,262	130,573	129,076
85	118,703	116,995	126,674	128,325	124,451	122,807	126,720	121,991	125,432	124,792	118,703
90	104,543	104,677	118,136	119,550	115,291	113,755	118,190	112,821	116,142	115,409	104,543
95	83,046	83,550	102,305	103,213	101,553	98,876	102,360	97,917	100,116	99,570	83,046
98	48,936	55,297	87,678	87,261	84,302	81,772	87,703	81,273	84,273	83,313	48,936
99	28,982	27,878	79,332	78,962	73,237	74,312	79,340	72,577	77,572	76,688	28,980
99.5	20,165	14,754	70,766	67,465	64,408	67,300	70,818	63,142	70,256	69,491	20,163
99.8	11,775	7,402	52,796	52,005	50,395	47,467	52,960	46,737	48,248	47,405	11,768

Alan Henry Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	10,979	13,902	6,340	3,164	4,186	3,846	6,340	3,936	7,654	7,637	10,979
Std Dev	23,074	25,482	19,988	14,410	16,358	14,671	19,987	15,666	20,289	20,285	23,074
Maximum	115,937	115,937	115,937	115,850	115,850	115,850	115,940	115,850	115,937	115,937	115,937
Minimum	0	0	0	0	0	0	0	0	0	0	0
Frequency (%)											
0.2	115,937	115,937	115,918	110,963	111,047	110,963	115,918	111,047	115,937	115,937	115,937
0.5	115,937	115,937	114,025	99,899	100,042	100,294	114,025	100,042	114,354	114,409	115,937
1	111,449	111,449	110,903	82,981	89,520	79,410	110,903	85,196	110,539	110,609	111,449
2	99,173	97,877	96,117	68,302	79,792	68,317	96,117	74,265	95,449	95,446	99,173
5	63,315	73,603	44,478	16,299	26,704	22,791	44,478	23,488	45,422	45,521	63,315
10	39,199	54,753	13,357	0	4,158	5,486	13,357	3,747	19,302	19,168	39,199
15	26,777	39,730	6,223	0	13	1,554	6,226	9	12,065	11,858	26,777
20	16,199	24,502	2,701	0	6	59	2,703	6	7,762	7,757	16,199
30	5,579	9,112	1	0	2	0	1	2	2,144	2,079	5,579
40	0	2,151	0	0	0	0	0	0	14	12	0
50	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0
99	0	0	0	0	0	0	0	0	0	0	0
99.5	0	0	0	0	0	0	0	0	0	0	0
99.8	0	0	0	0	0	0	0	0	0	0	0

Hubbard Reservoir Storage Volumes (acre-feet)

	M1	M2	D1	D2	D3	D4	D5	D6	D7	D9	M3
Mean	87,400	101,047	64,895	24,885	19,438	24,381	64,890	16,944	42,900	42,831	87,400
Std Dev	97,655	98,111	89,527	66,133	57,862	62,814	89,522	54,735	75,061	74,985	97,655
Maximum	317,750	317,750	317,750	317,750	317,559	317,559	317,750	317,559	317,750	317,750	317,750
Minimum	0	0	0	0	0	0	0	0	0	0	0
Frequency (%)											
0.2	317,750	317,750	317,750	317,395	309,168	308,876	317,750	309,326	317,750	317,750	317,750
0.5	317,750	317,750	317,750	312,349	295,361	300,523	317,750	295,806	315,670	315,606	317,750
1	317,750	317,750	316,880	304,654	283,290	291,892	316,880	282,005	310,973	310,751	317,750
2	317,750	317,750	312,228	284,893	260,508	276,384	312,213	258,075	297,968	297,717	317,750
5	300,260	302,060	290,710	198,842	171,170	194,925	290,674	140,200	226,918	226,487	300,260
10	260,990	270,807	208,851	100,649	67,854	95,279	208,824	43,329	159,739	159,983	260,990
15	205,209	222,741	139,544	31,912	11,198	32,152	139,549	4,431	106,551	105,766	205,209
20	177,720	194,749	120,856	7,514	0	14,975	120,830	0	69,088	68,950	177,720
30	116,193	140,521	87,176	0	0	1,956	87,155	0	34,522	34,425	116,193
40	83,493	103,144	48,305	0	0	0	48,279	0	15,068	14,933	83,493
50	52,758	77,821	18,155	0	0	0	18,150	0	3,519	3,461	52,758
60	24,579	47,003	2,136	0	0	0	2,136	0	0	0	24,579
70	2,894	23,182	0	0	0	0	0	0	0	0	2,894
80	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0
99	0	0	0	0	0	0	0	0	0	0	0
99.5	0	0	0	0	0	0	0	0	0	0	0
99.8	0	0	0	0	0	0	0	0	0	0	0

Monthly and Daily Naturalized Stream Flows

The hydrology input DSS file for the Brazos WAM includes *IN* record 1940-2017 monthly naturalized flow volumes in acre-feet/month at 77 control points and *DF* record 1940-2017 daily naturalized flow volumes in acre-feet/day at 58 control points. In either a *SIM* monthly or *SIMD* daily simulation, the monthly naturalized flows input for the 77 primary control points are distributed to the over 3,700 other control points in the WAM. In a daily simulation, the monthly flow volumes at the over 3,700 control points are disaggregated to daily flow volumes based on the daily flow pattern hydrographs input for 58 control points.

The naturalized flow disaggregation algorithm requires only daily patterns for each month, in any units, which do not have to be daily naturalized flows in acre-feet/day. However, an initial set of *DF* record daily pattern flows in cfs were converted to actual naturalized flows in ac-ft/day as explained in Chapter 6. *SIMD* was executed with the original *DF* record flows in cfs, and the daily naturalized flow volumes in acre-feet were recorded in the *SIMD* simulation results output DSS file. Employing *HEC-DSSVue*, the daily flow volumes in acre-feet were easily transferred to *DF* records in the hydrology input DSS file. Thus, the monthly and daily flows in the input as well as output file are consistently all volumes in acre-feet per month or day. The daily flows are identical in the input and output files for the 58 control points with *DF* records in the input file.

HEC-DSSVue plots of daily and monthly naturalized flow volumes at the Cameron gage on the Little River (control point LRCA58), Seymour gage on the Brazos River (control point BRSE11), Waco gage on the Brazos River (control point BRWA41), and Richmond gage on the Brazos River (control point BRRI70) are presented as Figures 10.1 through 10.8. Observed flows at three of these USGS gage sites are plotted in Figures 2.4 through 2.12 of Chapter 2. The plots illustrate the extreme flow variability characteristic of rivers throughout the Brazos River Basin and throughout Texas. Monthly flows are highly variable. Daily flows are much more variable. Variability patterns differ between daily and monthly flows. Within-month variations in daily flows are removed in the averaging to mean monthly flows or summing to monthly flow volumes. Likewise, within-day variations in instantaneous flows are missing in daily flows.

HEC-DSSVue provides convenient capabilities for plotting and tabulating naturalized daily and monthly naturalized stream flows as well as regulated and unappropriated flows and the many other variables generated in each simulation at each of the 3,845 control points and the many other variables computed for each of the over 1,800 *WR* and *IF* record water rights. A comprehensive array of optional features for statistical analyses, arithmetic manipulations, comparisons, and other operations are available within HEC-DSSVue to explore flow characteristics. The DSS files accompanying this report and inventoried in the preceding Chapter 9 supplement the statistical frequency analysis tables and time series plots included in this report, facilitating further more comprehensive and detailed analyses.

Results from the alternative monthly *SIM* and daily *SIMD* simulations defined in Tables 10.2 and 10.3 are presented in the remaining sections of this chapter. The same naturalized flows are incorporated in all of these simulations. All of the simulations use the same hydrology input file BrazosHYD.DSS. Means of naturalized flows, observed gaged flows, and simulated regulated and unappropriated flows at the 19 SB3 EFS control point are compared in Tables 10.6 and 10.7.

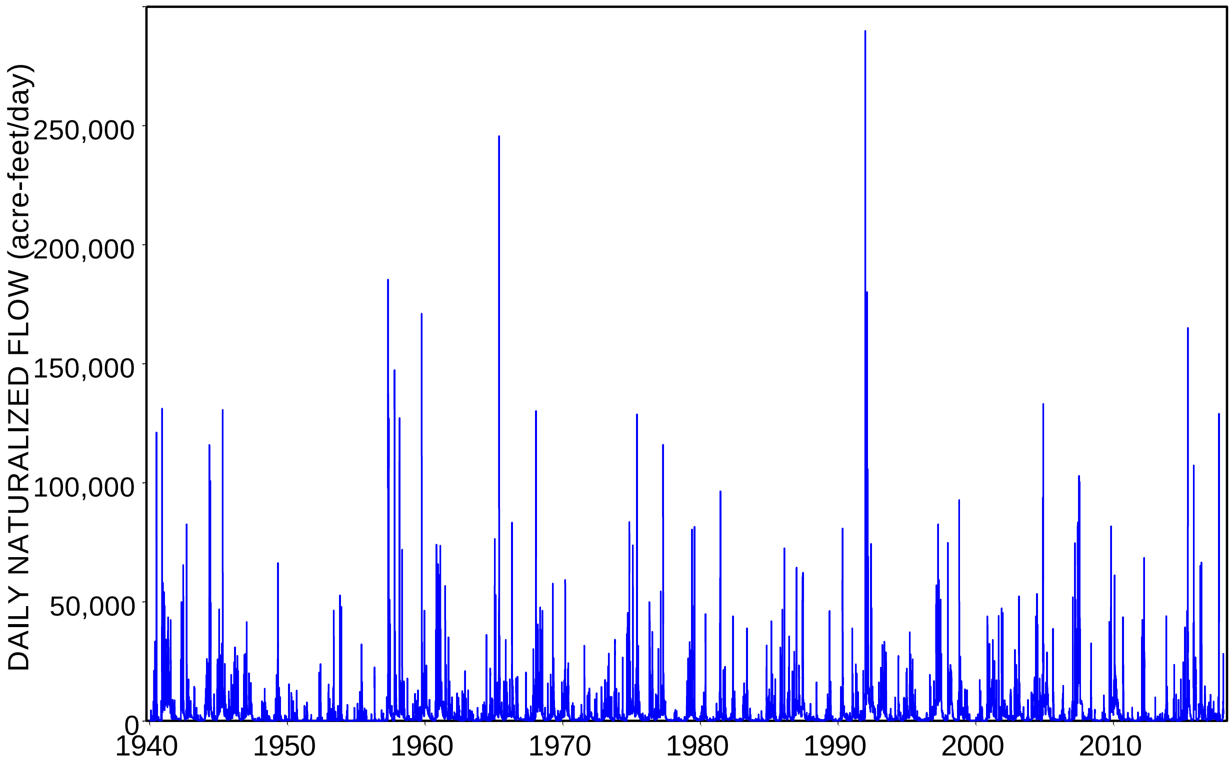

Figure 10.1 Daily Naturalized Flow of the Little River at Cameron (Control Point LRCA58)

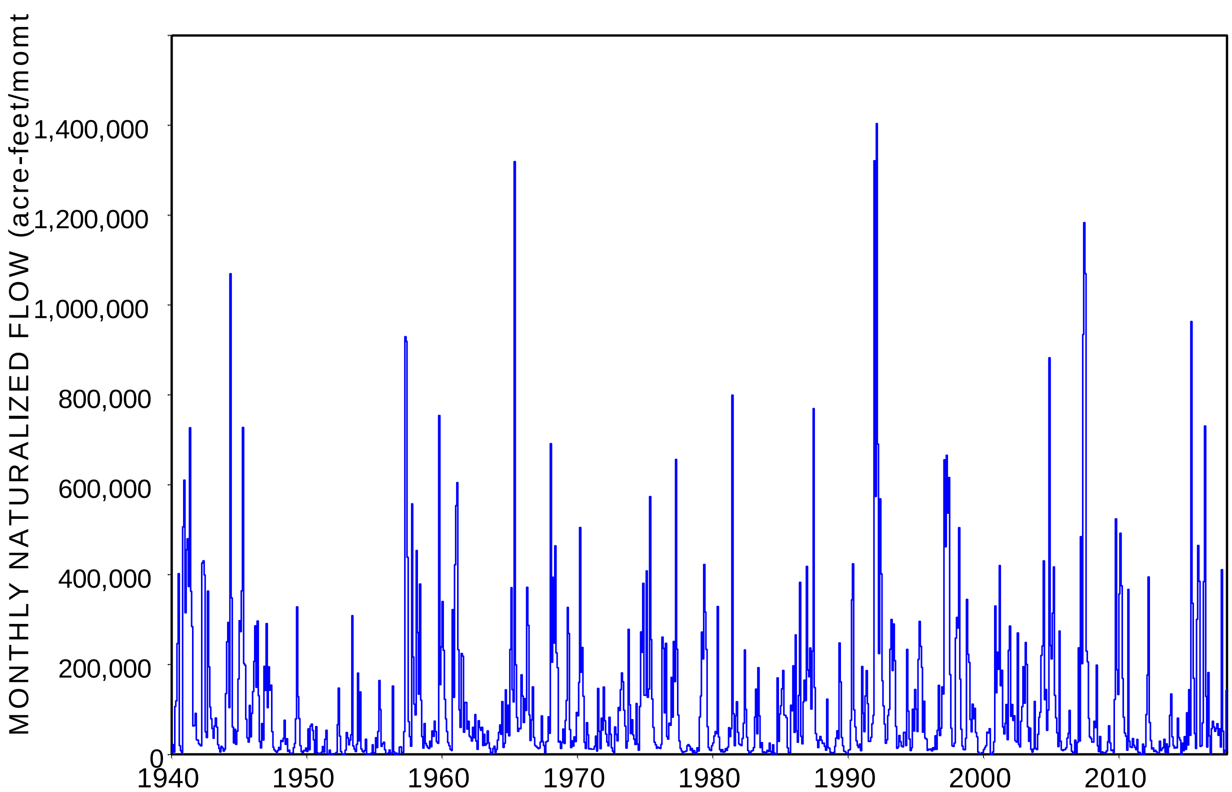

Figure 10.2 Monthly Naturalized Flow of the Little River at Cameron (Control Point LRCA58)

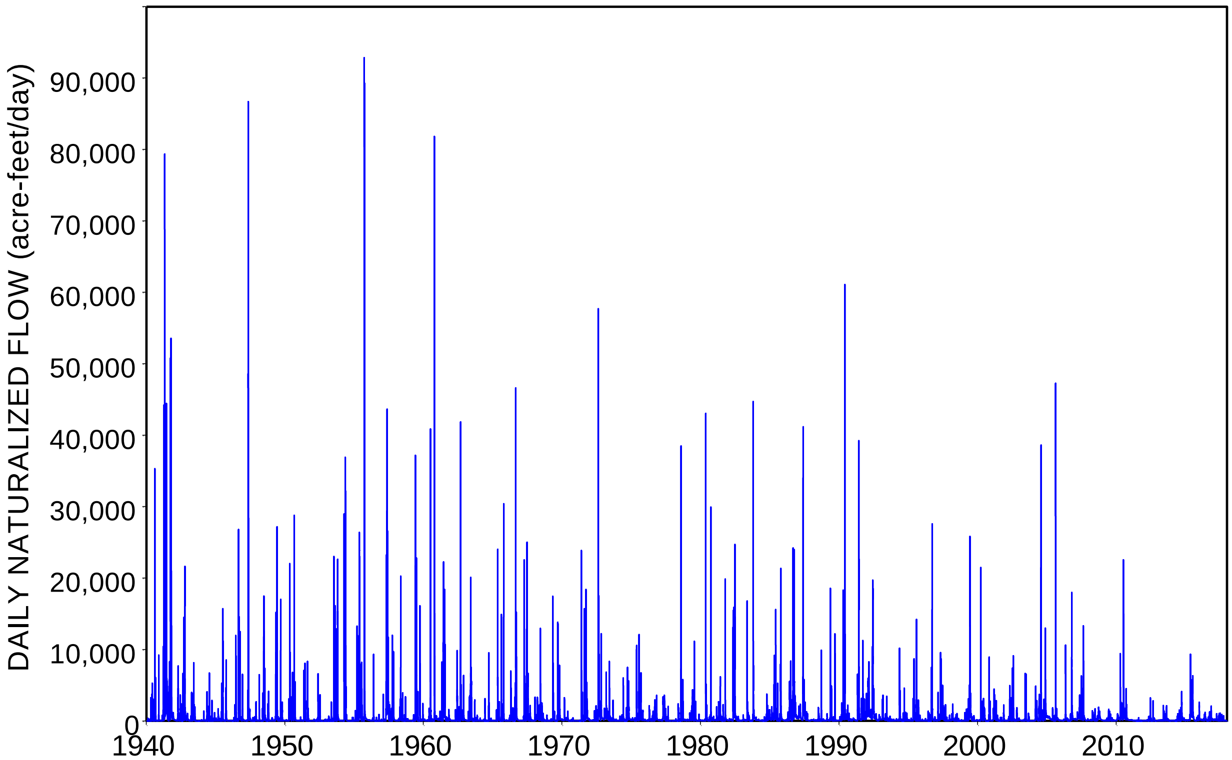

Figure 10.3 Daily Naturalized Flow of the Brazos River at Seymour (Control Point BRSE11)

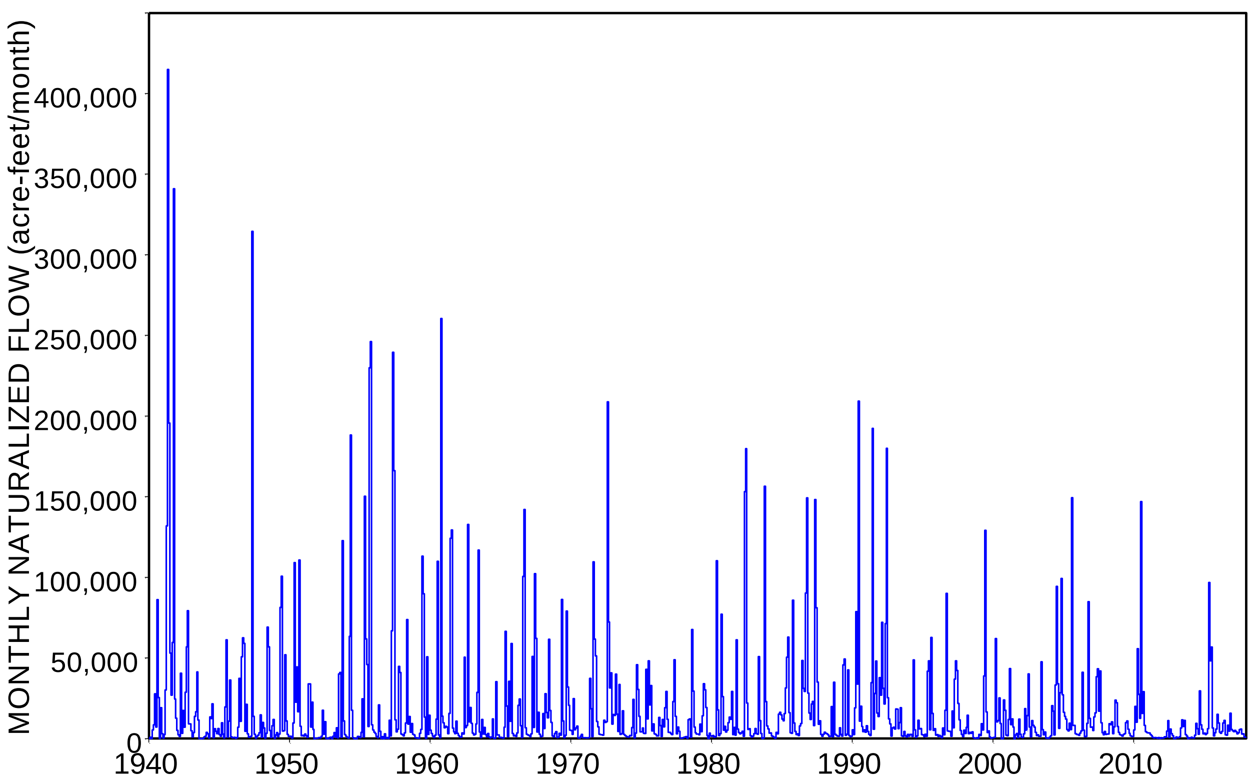

Figure 10.4 Monthly Naturalized Flow of the Brazos River at Seymour (Control Point BRSE11)

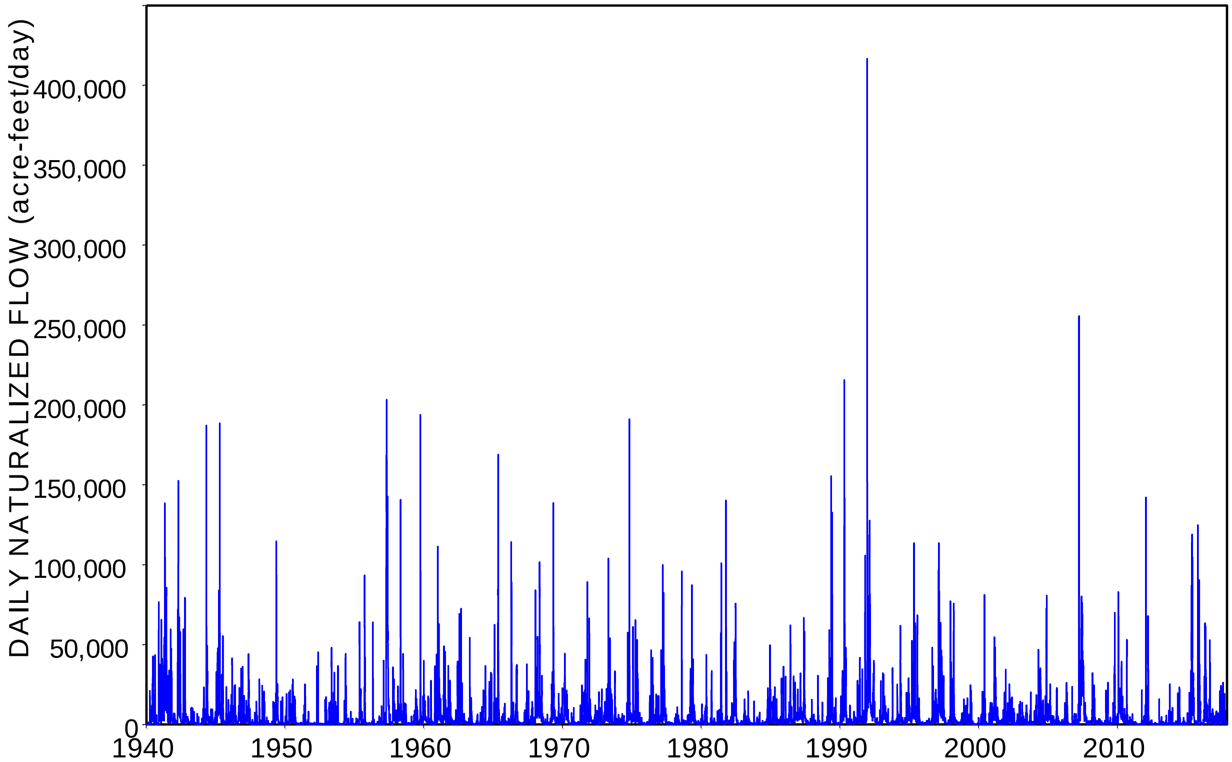

Figure 10.5 Daily Naturalized Flow of the Brazos River at Waco (Control Point BRWA41)

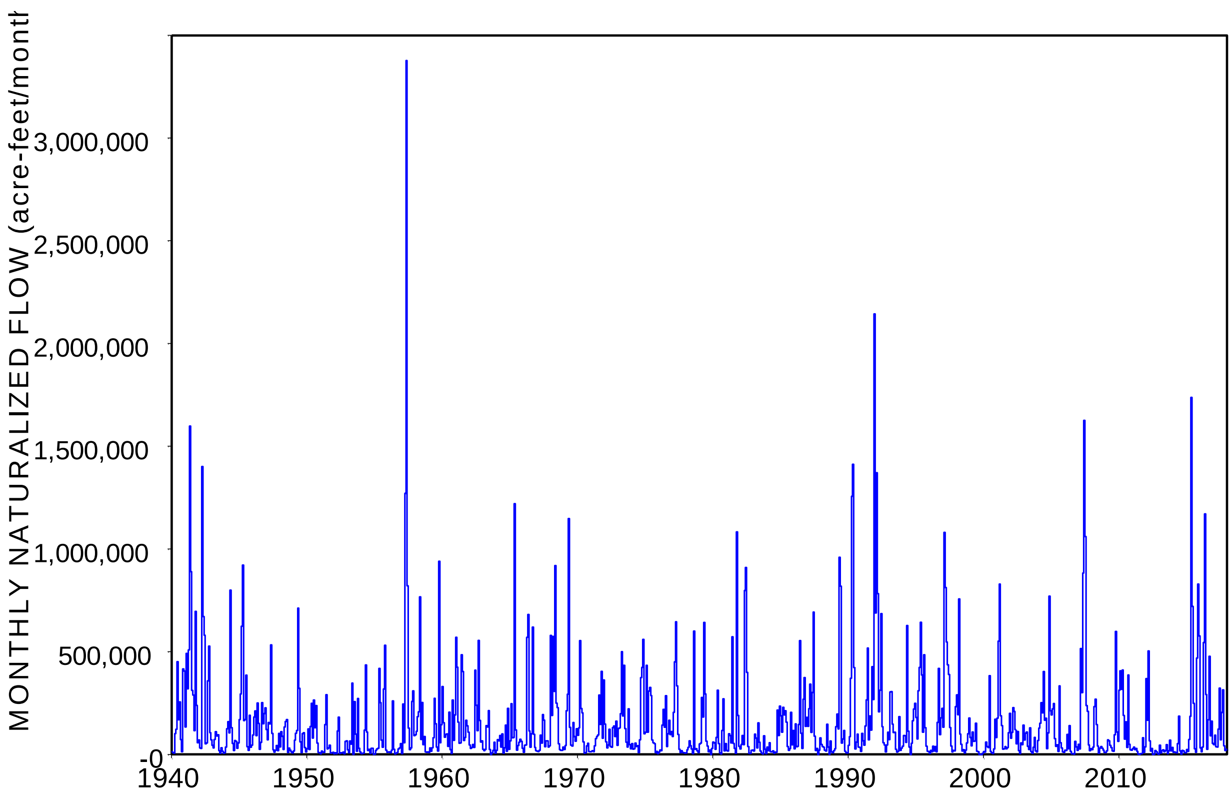

Figure 10.6 Monthly Naturalized Flow of the Brazos River at Waco (Control Point BRWA41)

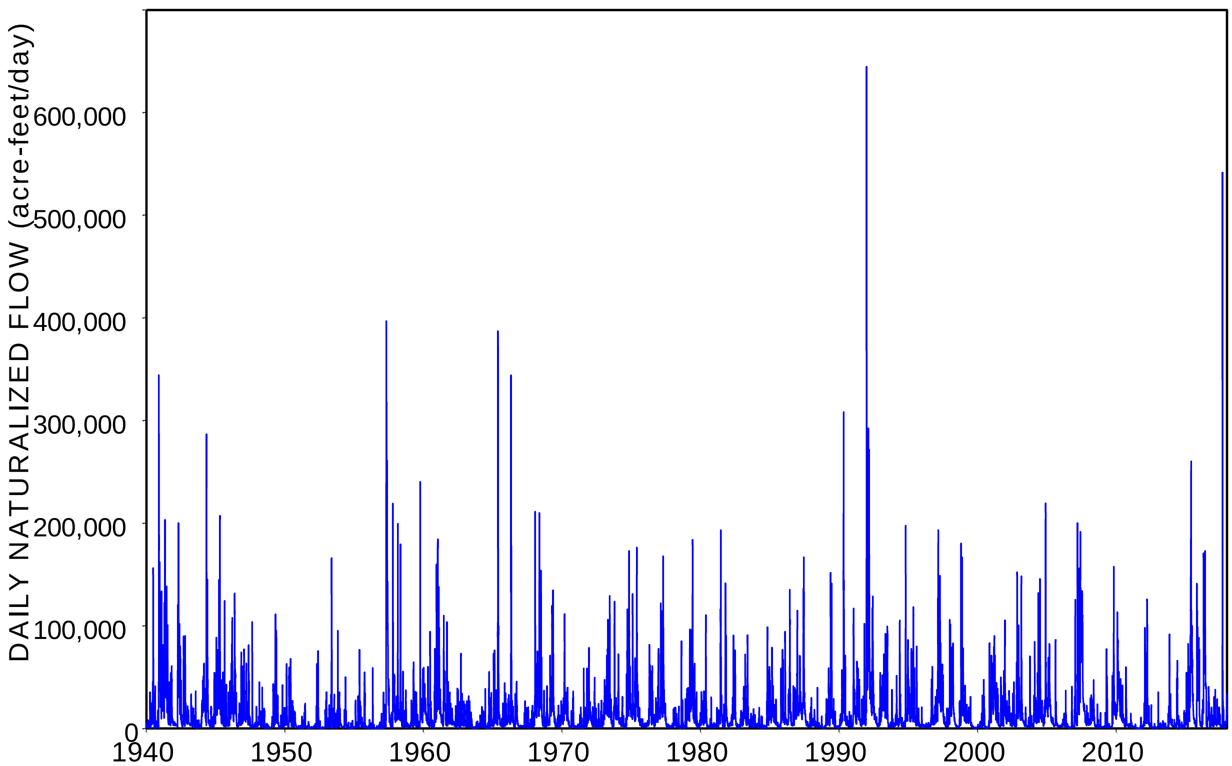

Figure 10.7 Daily Naturalized Flow of the Brazos River at Richmond (Control Point BRRI70)

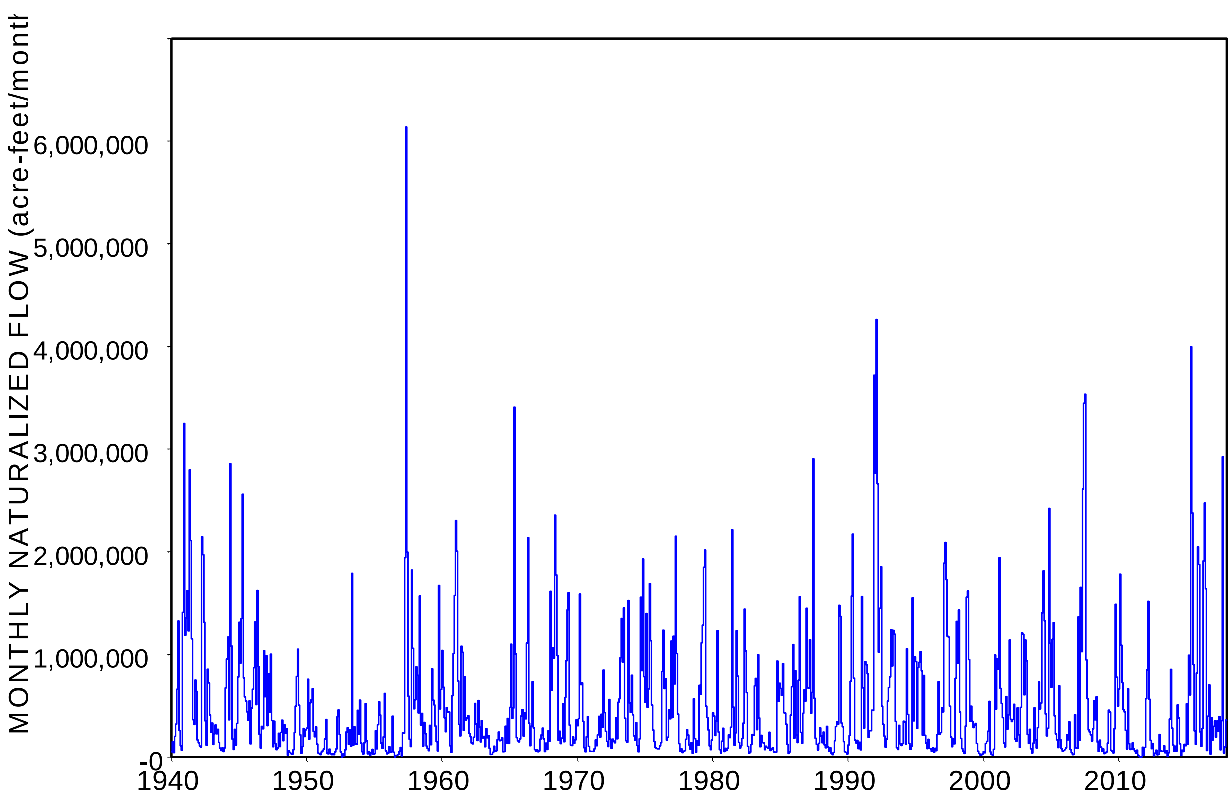

Figure 10.8 Monthly Naturalized Flow of the Brazos River at Richmond (Control Point BRRI70)

Simulations with Alternative Negative Incremental Flow Adjustment Options

Many simulations were performed in this study. The several selected simulations from which results are presented in this chapter are listed in Tables 10.2 and 10.3. This section deals with simulations M1, M2, D1, and D2. These simulations employ input datasets that do not include routing and forecasting, flood control operations, and SB3 EFS. The following discussion focuses on the effects of performing the computations on a daily rather than monthly time step, disaggregating monthly naturalized flows to daily, and negative incremental flow adjustment options. The basic methods employed to convert the monthly WAM to daily are described in Chapter 3.

The term *negative incremental flow* refers to situations in which the naturalized flow at a site in a particular time period is smaller than the corresponding upstream naturalized flow during the same time period. Negative incremental flows and options for dealing with negative incremental flows have been recognized as a significant issue for the monthly WAMs for many years. This is an even more important consideration in daily modeling. The *SIM* and *SIMD* simulation algorithms for computing the amount of stream flow available to each water right in the priority sequence in each time step is based on the minimum of the flow at the control point of the water right and all downstream control points. Forecasting considers flows at downstream control points during each day of the forecast. Negative incremental flows and *SIM/SIMD* options for dealing with them can significantly affect water availability for refilling reservoir storage and supplying diversion targets.

Negative incremental flows and associated adjustments are explained on pages 67-71 of Chapter 3 of the *Reference Manual* [1] and pages 42-44 in Chapter 3 of the *Daily Manual* [4]. Negative incremental flow adjustment options are specified by input parameter ADJINC in *JD* record field 8 [2]. ADJINC option 5 is employed in the official monthly Brazos WAM and WAMs for several other river basins. Option 4 or the equivalent option 6 is the standard recommended option for monthly simulations and option 7 is the recommended standard option for a daily simulation with routing. Option 4 is probably the best option for a daily simulation without routing. Options 4, 5, and 6 adjust monthly or daily naturalized flows in the current time step without consideration of the future forecast period. Option 7 adjusts each flows in each future time period of the forecast simulation as well as in the current simulation time interval. The ADJINC option 7 adjustments for future negative incremental flows during the forecast simulation are relevant only if forecasting is activated.

The analyses documented here confirm that either ADJINC options 4, 5, or 6 work fine for the monthly Brazos WAM. Option 4 or 6 is concluded to be optimal for the daily Brazos WAM if routing and forecasting are not activated. Option 7 should be employed in the daily Brazos WAM and other daily WAMs if forecasting is employed.

Storage frequency metrics for simulations M1 and D1 with ADJINC options 5 and 7, respectively, are presented in Table 10.8 along with storage frequency metrics for other simulations listed in Tables 10.2 and 10.3. End-of-month and end-of-day storage volumes are plotted in Figures 10.9 through 10.23 for simulations M1 and M2 with ADJINC options 5 and 4 and simulations D1 and D2 with ADJINC options 4 and 7. The legend for Figures 10.9 through 10.23 is as follows.

black solid line	Simulation M1 with ADJINC option 5
green dotted line	Simulation M2 with ADJINC option 4
red dotted line	Simulation D1 with ADJINC option 4
blue solid line	Simulation D2 with ADJINC option 7

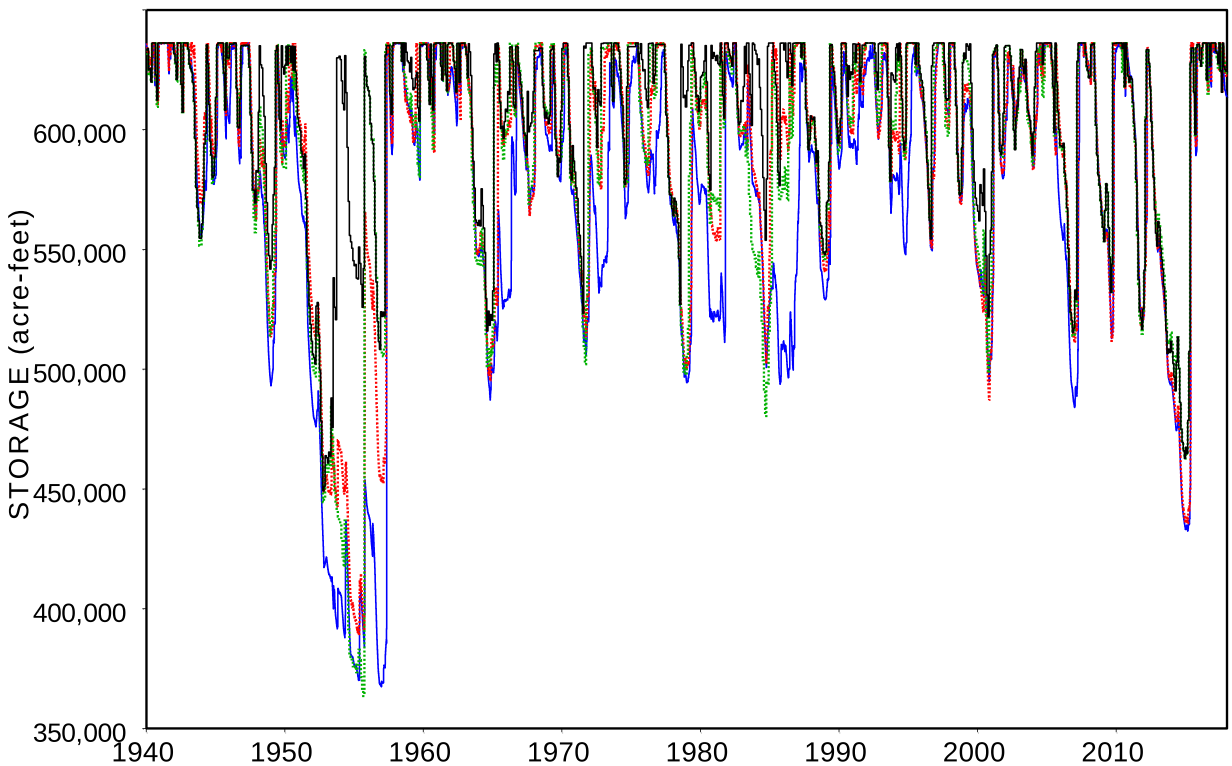

Figure 10.9 Storage Volume of Whitney Reservoir for Simulations M1, M2, D1, and D2
with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

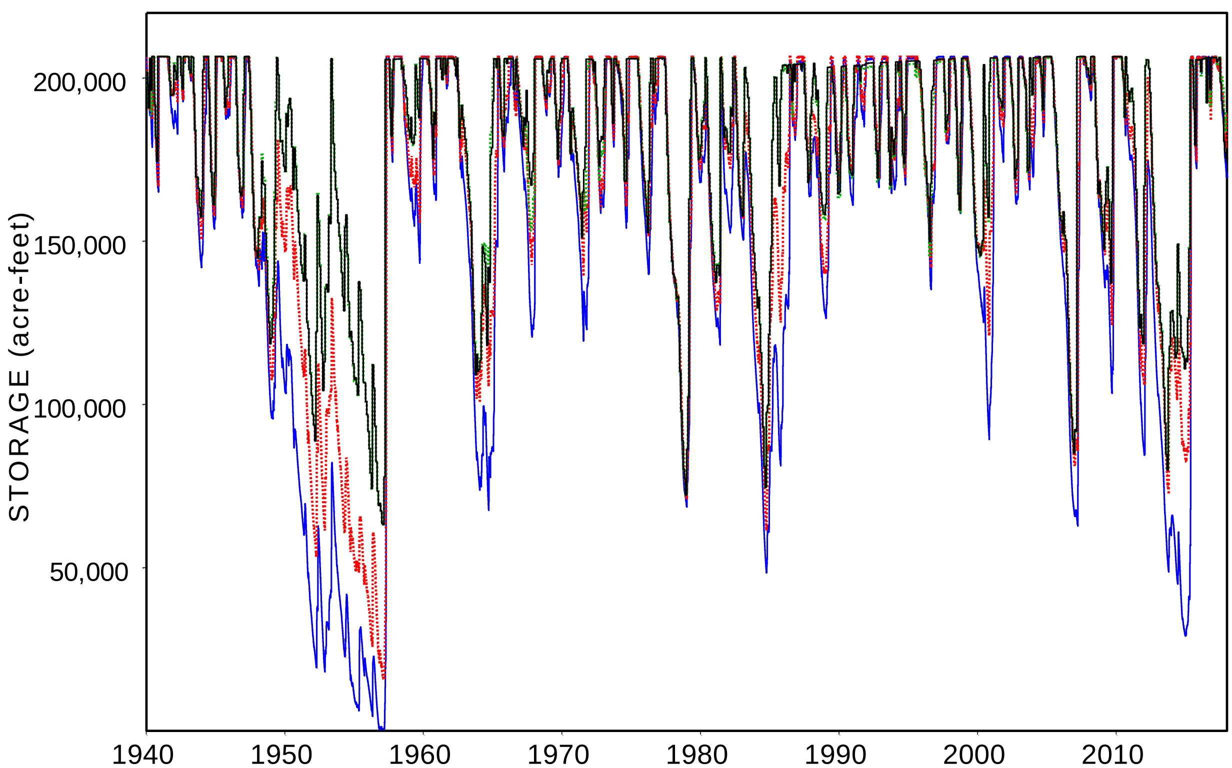

Figure 10.10 Storage Volume of Waco Reservoir for Simulations M1, M2, D1, and D2
with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

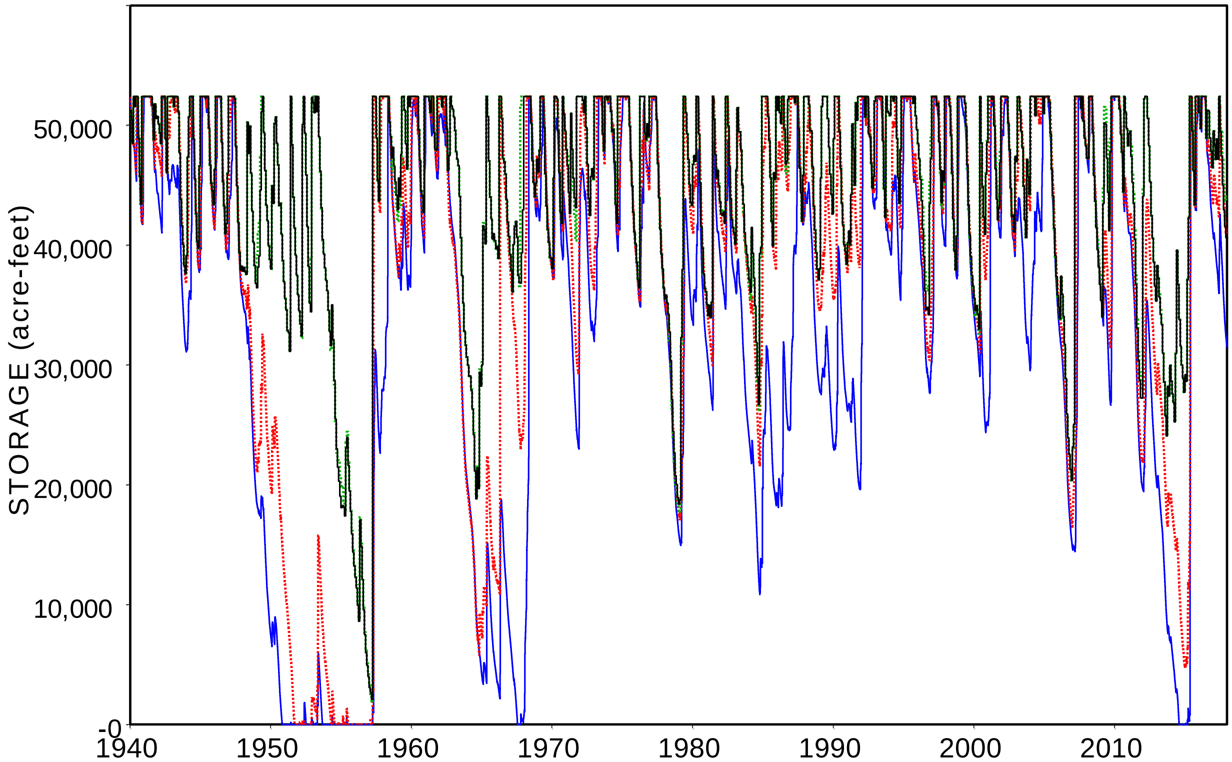

Figure 10.11 Storage Volume of Aquilla Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

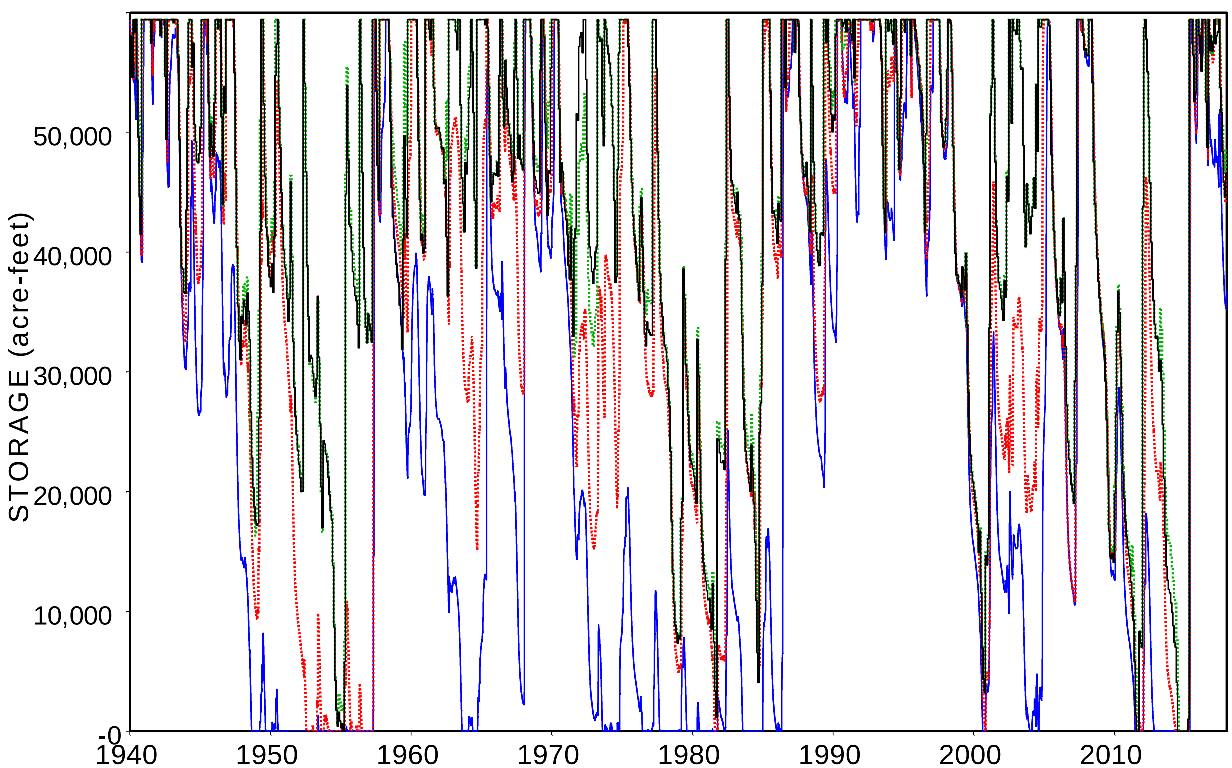

Figure 10.12 Storage Volume of Proctor Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

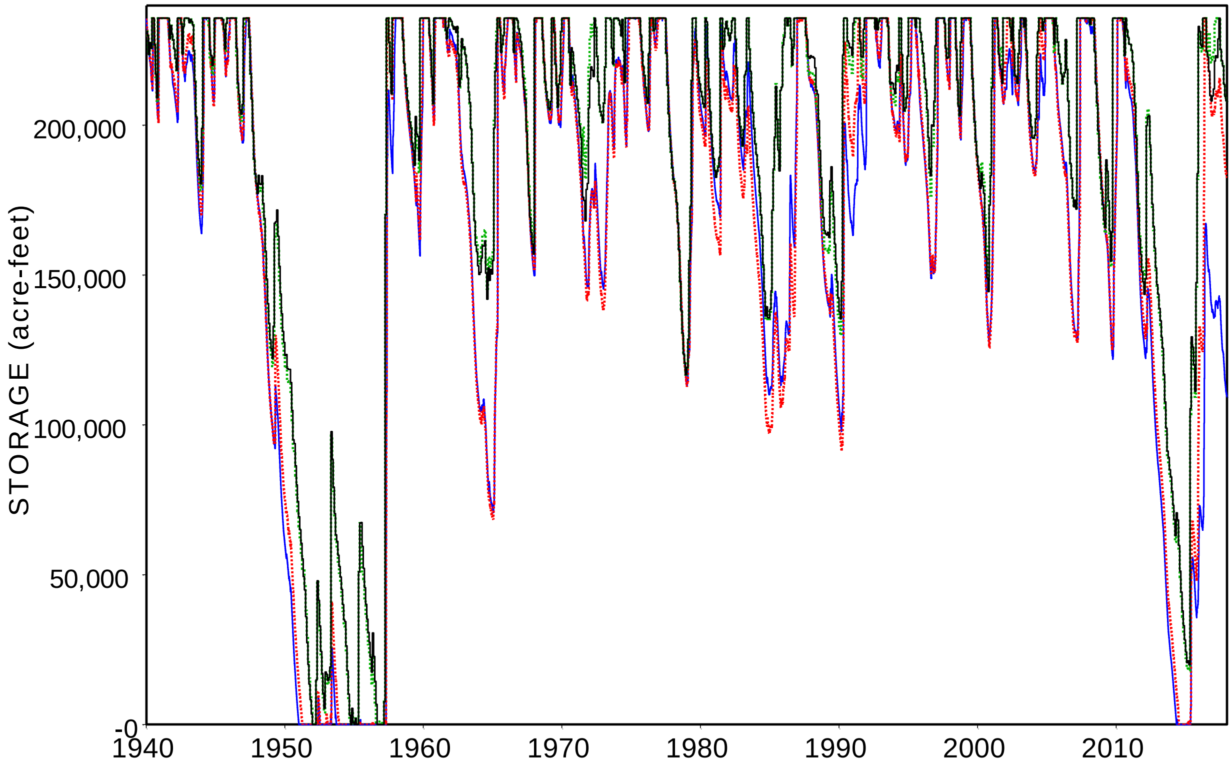

Figure 10.13 Storage Volume of Stillhouse Hollow Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

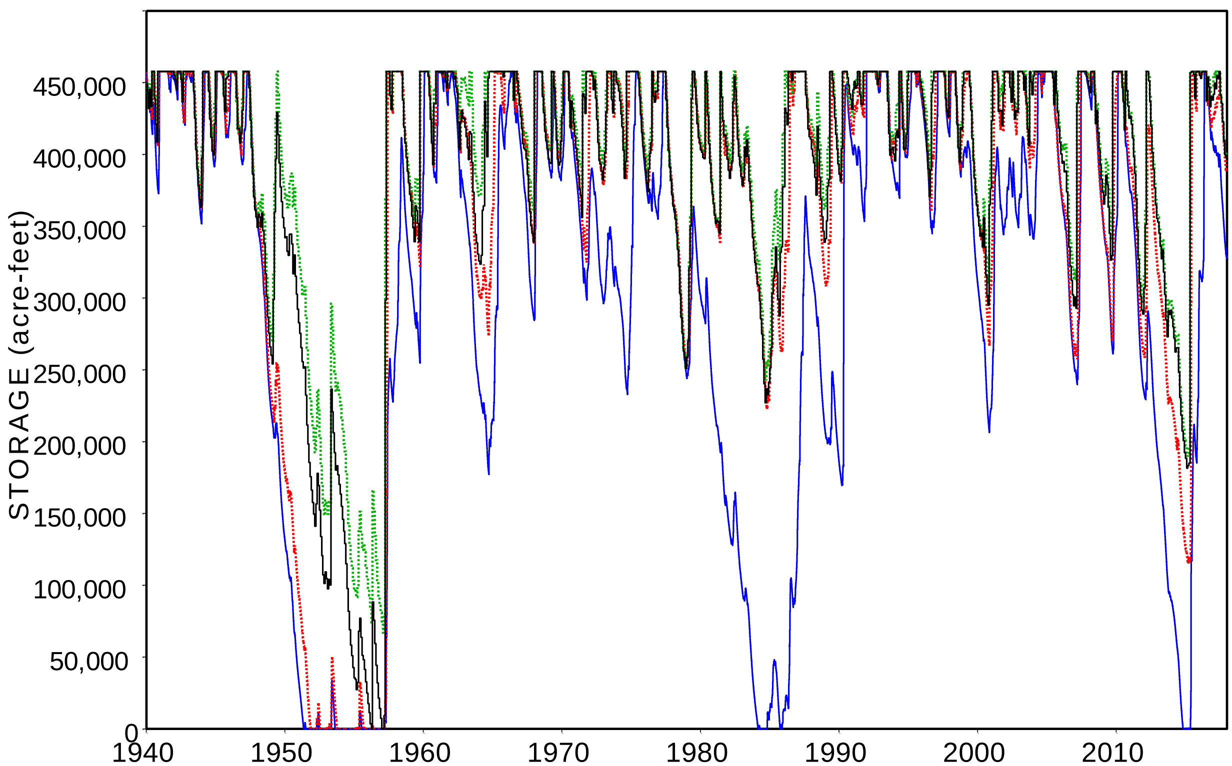

Figure 10.14 Storage Volume of Belton Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

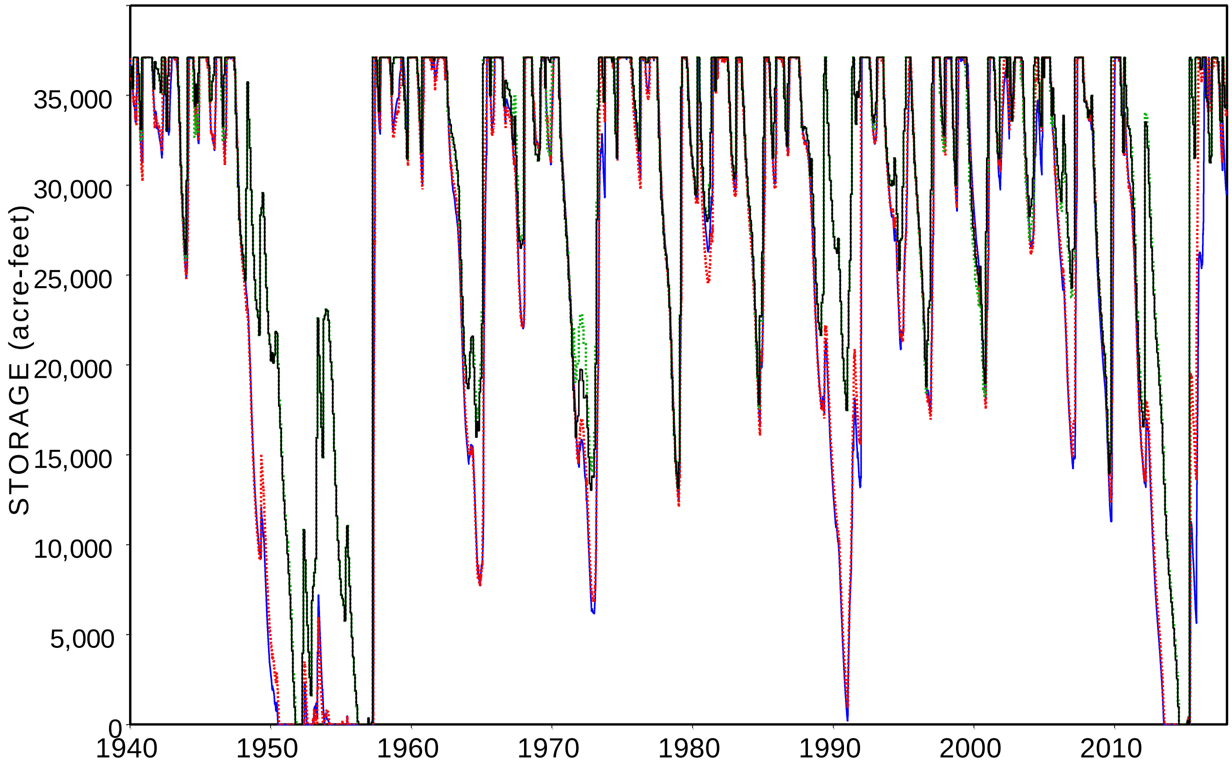

Figure 10.15 Storage Volume of Georgetown Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

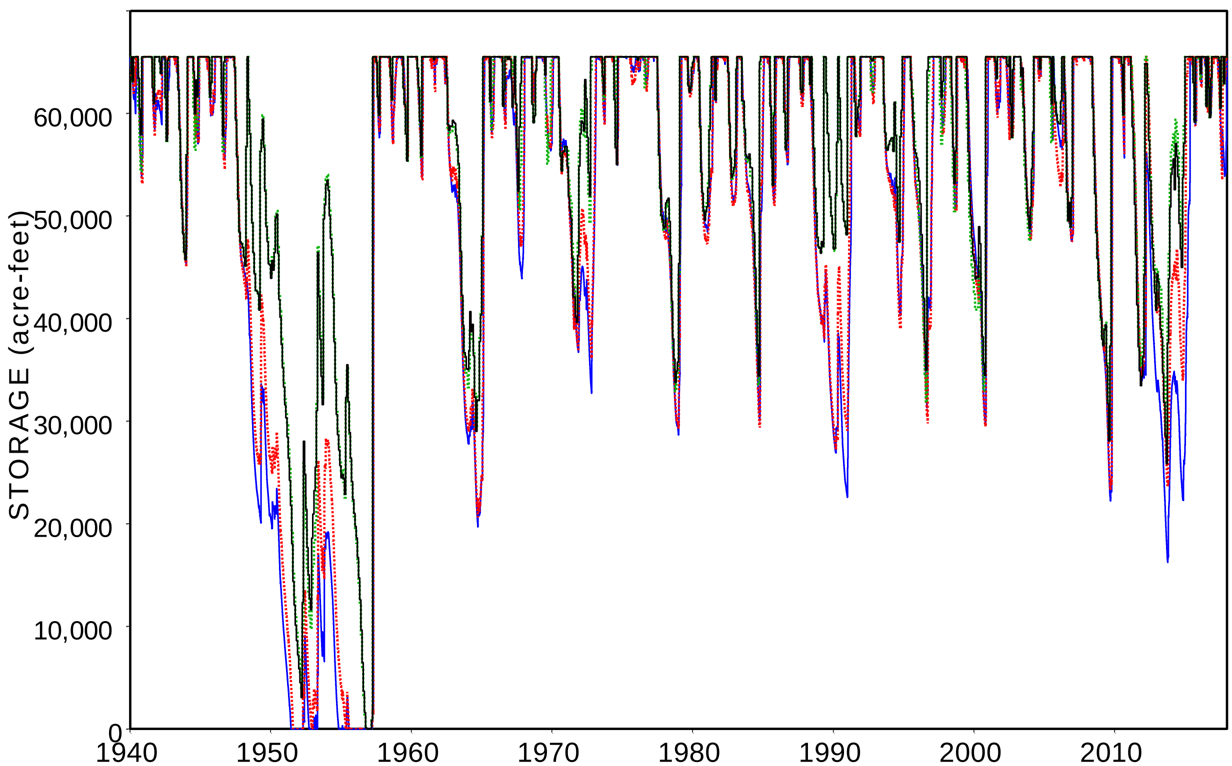

Figure 10.16 Storage Volume of Granger Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

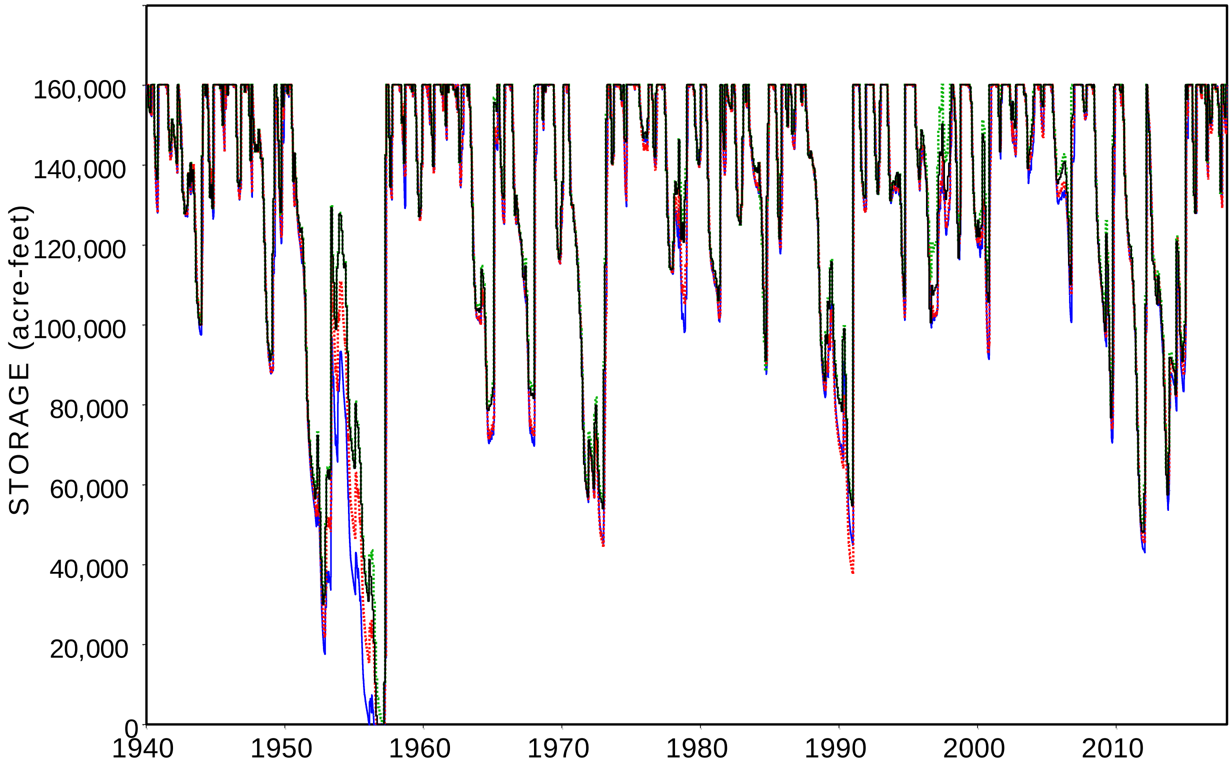

Figure 10.17 Storage Volume of Somerville Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

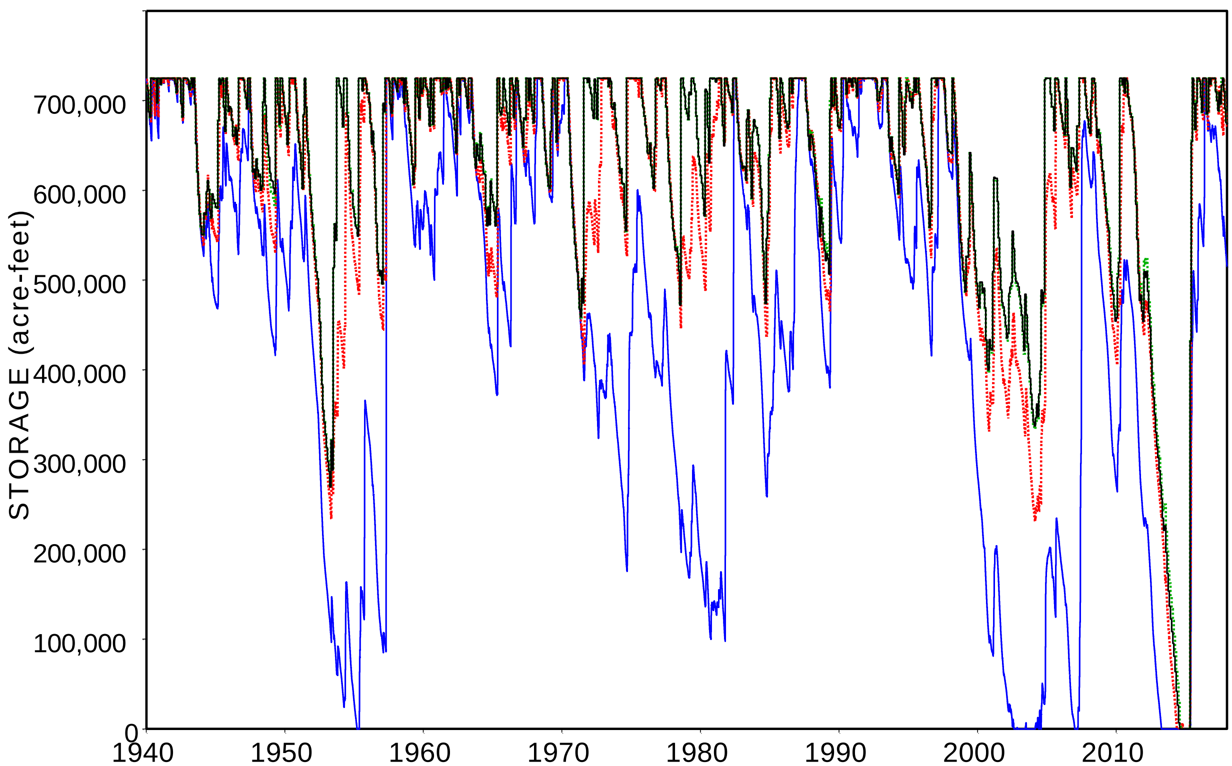

Figure 10.18 Storage Volume of Possum Kingdom Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

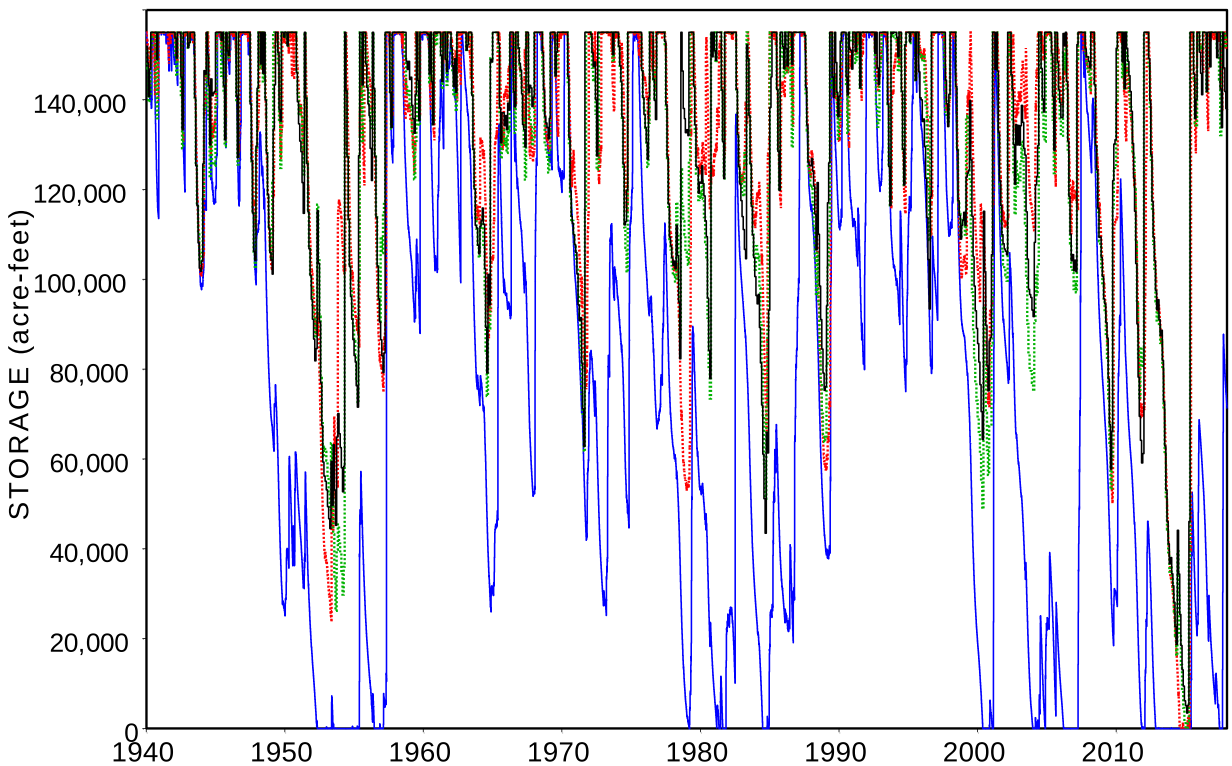

Figure 10.19 Storage Volume of Granbury Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

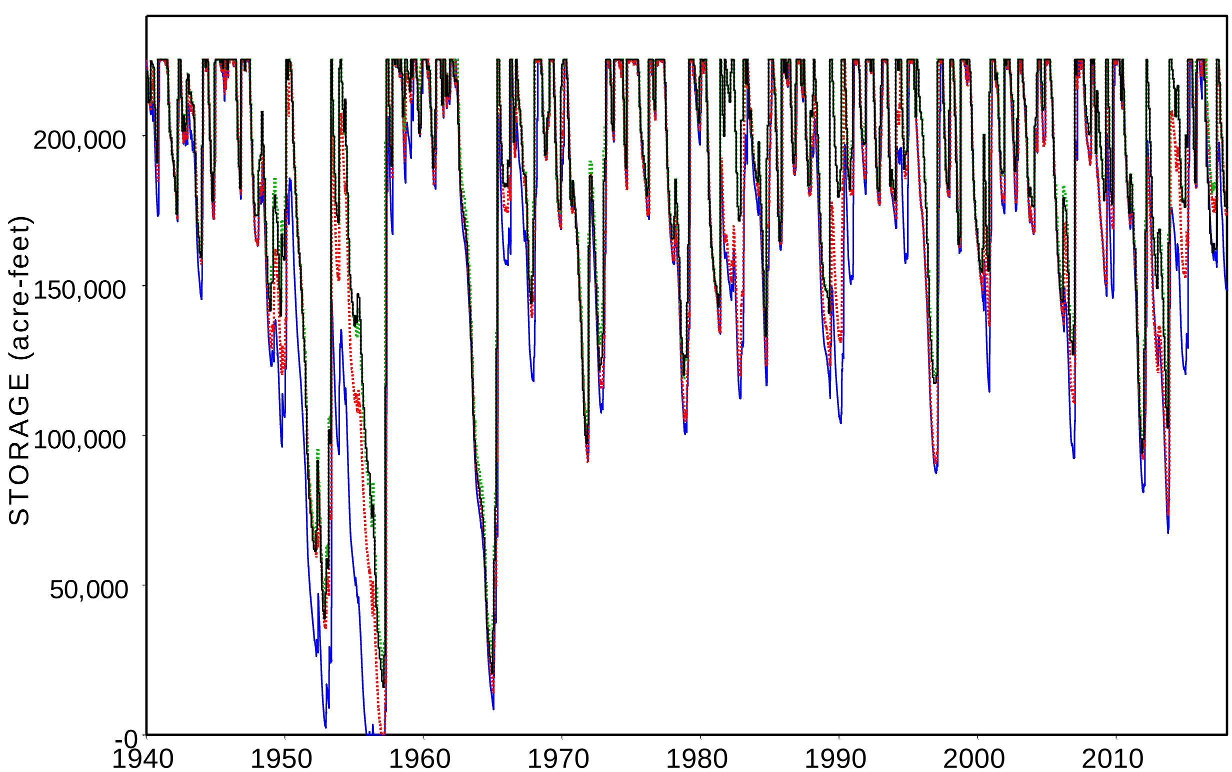

Figure 10.20 Storage Volume of Limestone Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

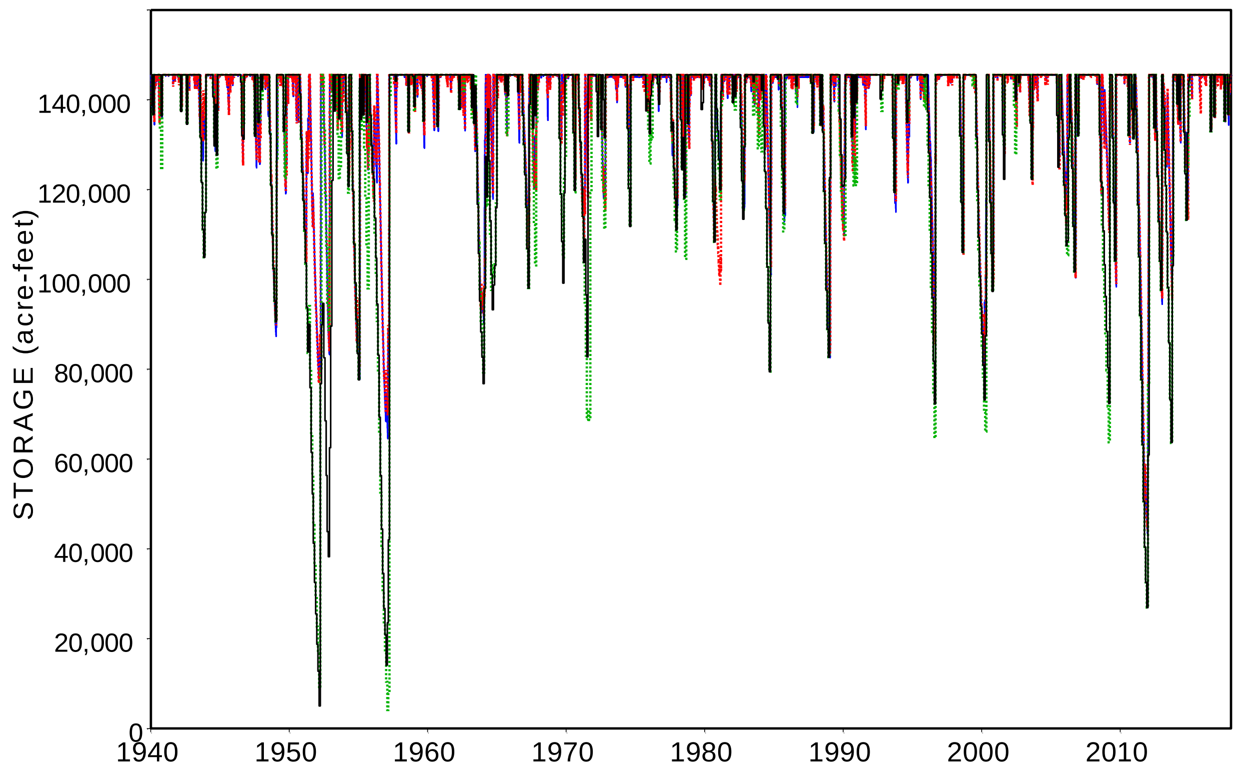

Figure 10.21 Storage Volume of Allen's Creek Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

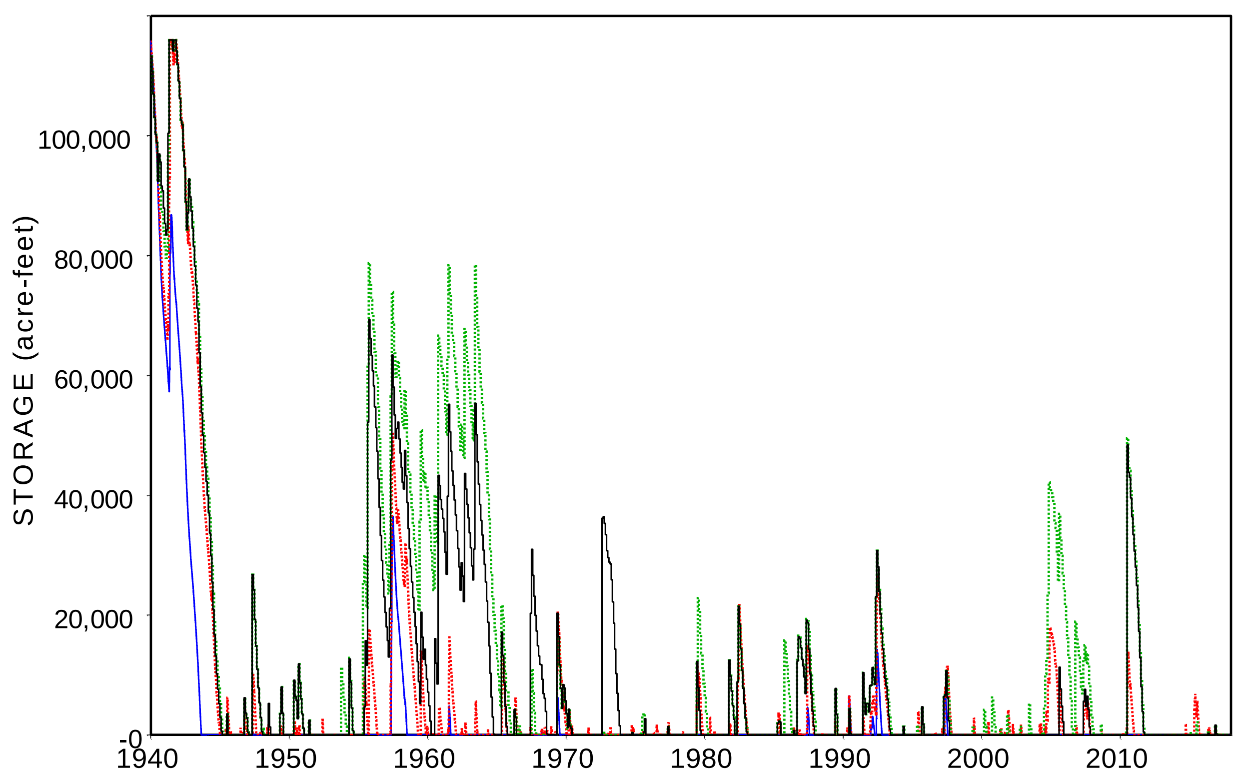

Figure 10.22 Storage Volume of Alan Henry Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

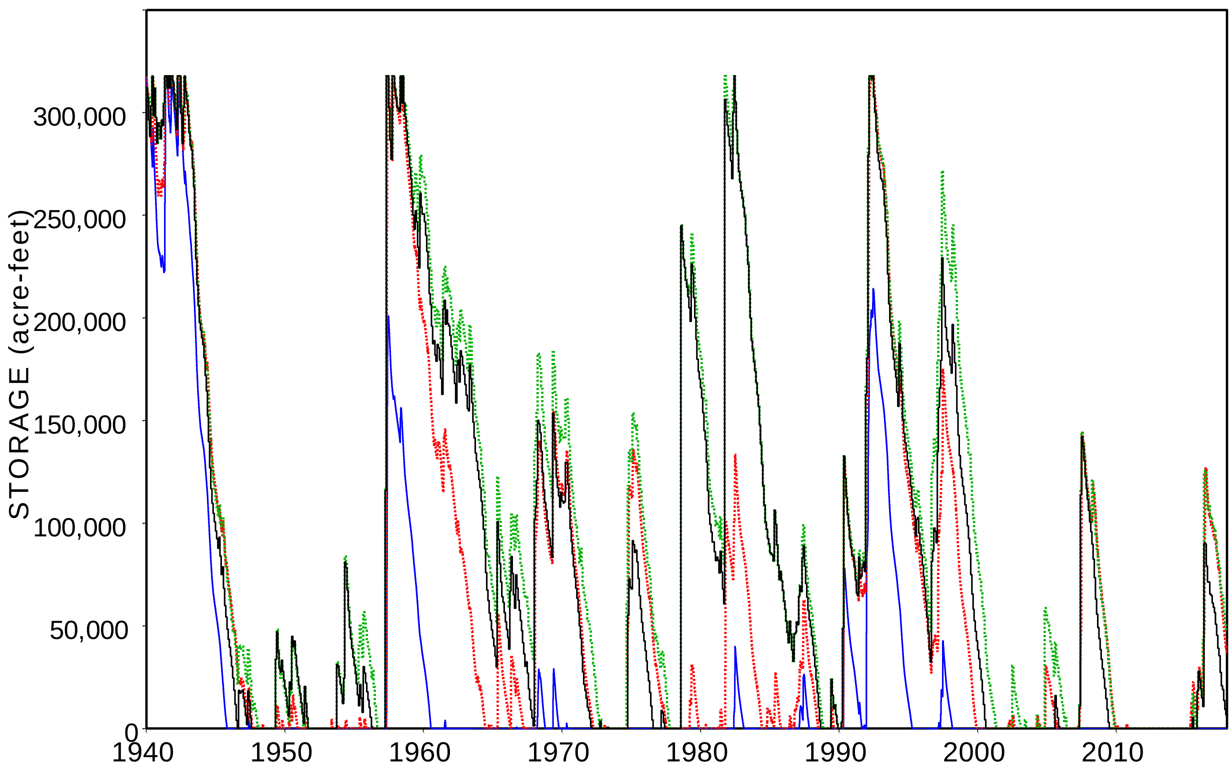

Figure 10.23 Storage Volume of Hubbard Creek Reservoir for Simulations M1, M2, D1, and D2 with Negative Incremental Flow Adjustment Options 5, 4, 4, and 7

Legend for Figures 10.9 through 10.23

———	black solid line:	end-of-month storage from simulation M1 with ADJINC option 5
········	green dotted line:	end-of-month storage from simulation M2 with ADJINC option 4
········	red dotted line:	end-of-day storage from simulation D1 with ADJINC option 4
———	blue solid line:	end-of-day storage from simulation D2 with ADJINC option 7

Alan Henry Reservoir on the Double Mountain Fork of the Brazos River in the extreme upper Brazos Basin is owned and operated by the City of Lubbock. Alan Henry Reservoir is empty or almost empty throughout most of the 1940-2017 hydrologic period-of-analysis in all of the simulations. Hubbard Creek Reservoir owned by the West Central Texas Municipal Water District is characterized by dramatic draw-downs in all simulations. The 13 other reservoirs behave reasonably in all simulations. The 1950-1957, 2008-2012, and multiple less severe droughts are evident in the plots.

Daily simulation reservoir drawdowns vary greatly between ADJINC options 4 and 7 at some of the reservoirs in some time periods. With option 4, storage levels are reasonably close in the daily versus monthly WAMs. Option 4 should be adopted for the daily WAM if forecasting is not employed. ADJINC option 7 should be activated in the daily WAM if forecasting is employed.

The daily WAM employed for simulation D1 with ADJINC option 4 provides a useful valid daily model for determining SB3 EFS targets and other applications even without adding routing and forecasting and flood control. Further improvements in model accuracy to be achieved by adding routing and forecasting and flood control are pursued in the next sections of this chapter.

Simulations with Routing and Forecasting Added

Routing simulates time lags that occur as flow changes due to reservoir refilling and releases and diversions and return flows propagate downstream. Forecasting serves only the two purposes of (1) protecting downstream senior rights and (2) preventing excessive flood releases. Forecasting is relevant in *SIMD* only if routing is employed. Forecasting should not and is not employed without routing. Routing is activated by *RT* records in the DIF file. Forecasting is controlled by parameters on the *JU* record in the DAT file. Simulations D3 and D4 employ the dataset of simulation D2 with ADJINC option 7 but with the addition of routing and forecasting. The routing parameters of Table 3.3 are activated in the DIF file. Input parameters FCST, FPRD, and APRD in *JU* record fields 6, 7, and 8 control forecasting. The two versions of the *JU* record replicated below for simulations D3 and D4 have forecast periods of 15 days and 30 days, respectively, with all other input being the same.

```
JU      1    0    0    0    2   15   15
JU      1    0    0    0    2   30   30
```

Input parameters WRMETH and WRFCST are entered in *JU* record fields 4 and 5. The defaults for WRMETH and WRFCST are adopted for all of the simulations presented in this chapter. Flow changes are placed at the beginning of the priority sequence in the next day of the simulation.

Forecasting is activated with input parameter FCST in *JU* record field 6. The forecast period FPRD is entered in *JU* record field 7, with a blank *JU* field 7 activating a *SIMD* routine that automatically computes the forecast period. The automatic default forecast period for the Brazos WAM is 93 days computed within *SIMD* as twice the longest flow path plus one day. As indicated in Table 10.1, the longest flow path is formed by 464 control points. The longest routing chain has normal flow lag times totaling 46 days. The default forecast period is 2×46 days + 1 day = 93 days. Forecasting future stream flows over the next 93 days is not feasible in actual water management and is not appropriate for adoption in the daily Brazos WAM.

Alternative forecast periods of 15 days and 30 days are explored in simulations D3 and D4. Simulation D1 with ADJINC option 4 and no routing/forecasting provides the advantage of circumventing additional negative incremental flow issues resulting from including future forecast period time steps in the determination of stream flow availability in the water rights priority sequence simulation computations.

Forecasting greatly increases computer execution (run) time. *SIMD* execution times for simulations D1, D3, and D4 are 11.0 minutes, 158 minutes, and 355 minutes, respectively. Even if routing and forecasting is adopted for a WAM, forecasting can be switched off with a blank *JU* field 6 to reduce execution time in preliminary simulations.

Storage and flow statistics for the simulations are provided in Tables 10.6, 10.7 and 10.8. End-of-month and end-of-day storage volumes are plotted in Figures 10.24 through 10.38 for simulations M1, D1, D3, and D4. The legend for Figures 10.24 through 10.38 is as follows.

———	black solid line	Simulation M1 with ADJINC option 5
··········	red dotted line	Simulation D1 with ADJINC option 4 and no routing/forecasting
- - - - -	purple dashed	Simulation D3 with ADJINC option 7 and 15 day forecast
—··—··—	green dash&dots	Simulation D4 with ADJINC option 7 and 30 day forecast

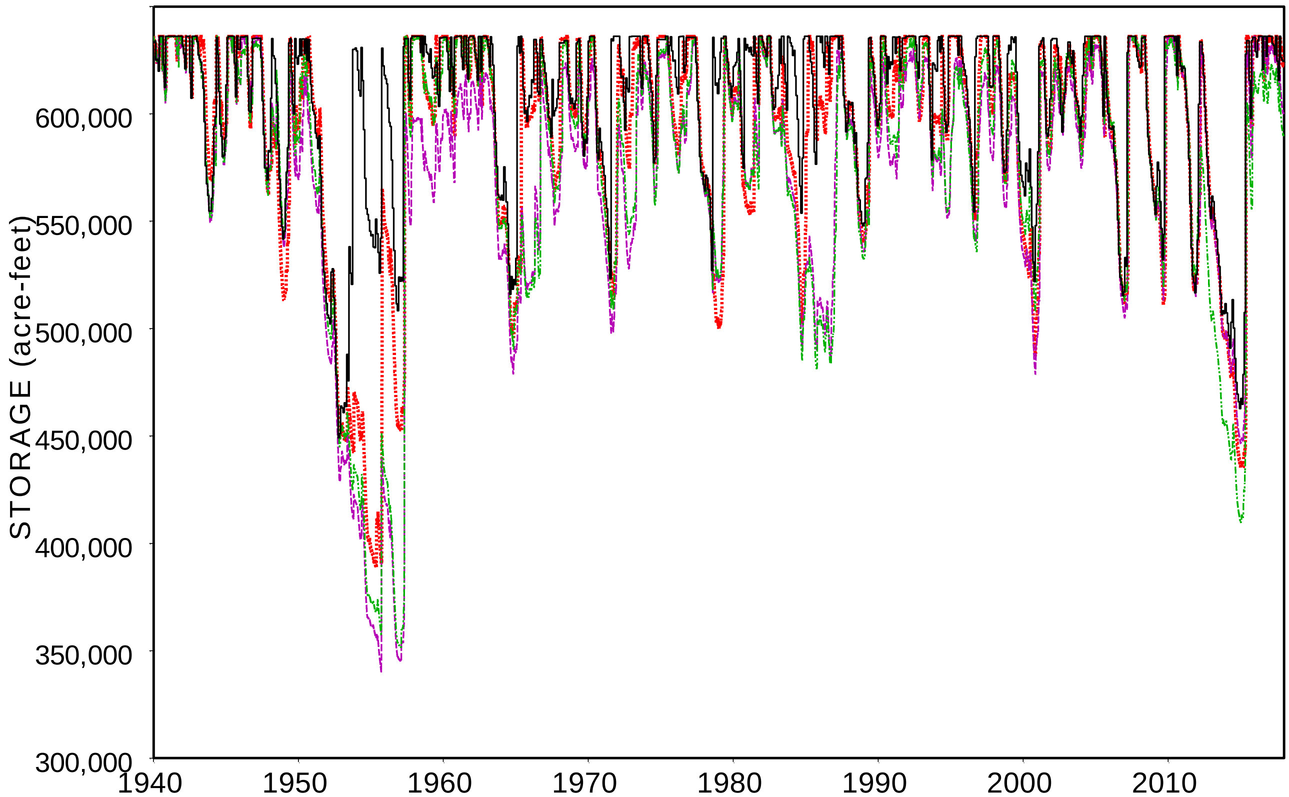

Figure 10.24 Whitney Reservoir Storage Contents with Alternative Routing Strategies

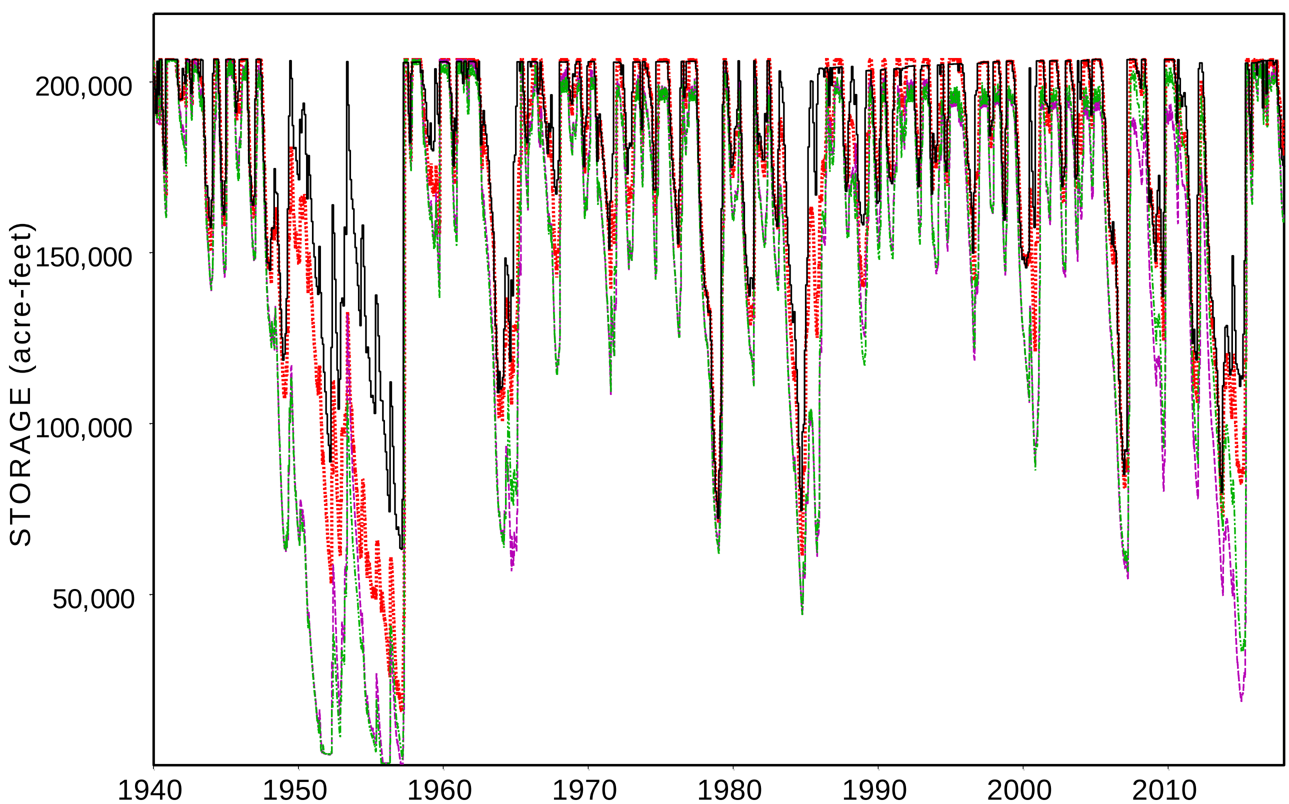

Figure 10.25 Waco Reservoir Storage Contents with Alternative Routing Strategies

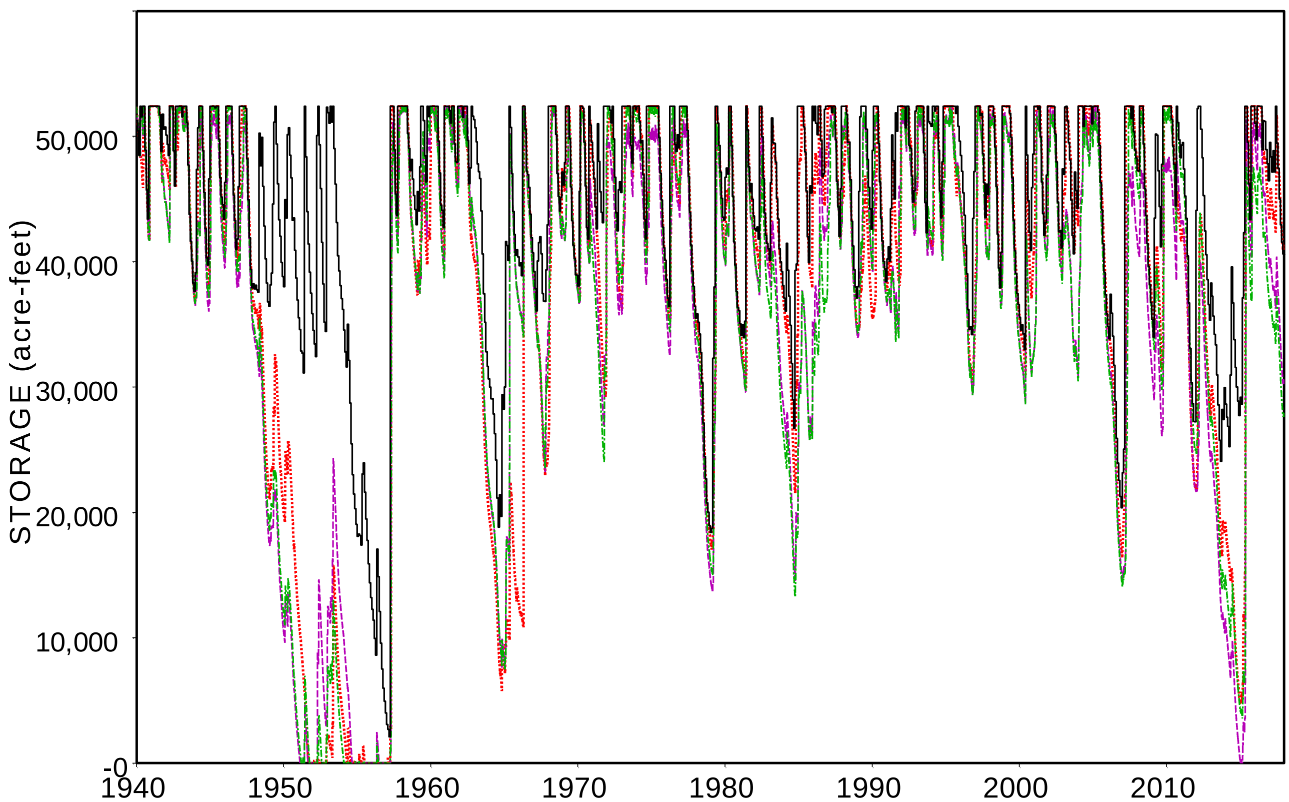

Figure 10.26 Aquilla Reservoir Storage Contents with Alternative Routing Strategies

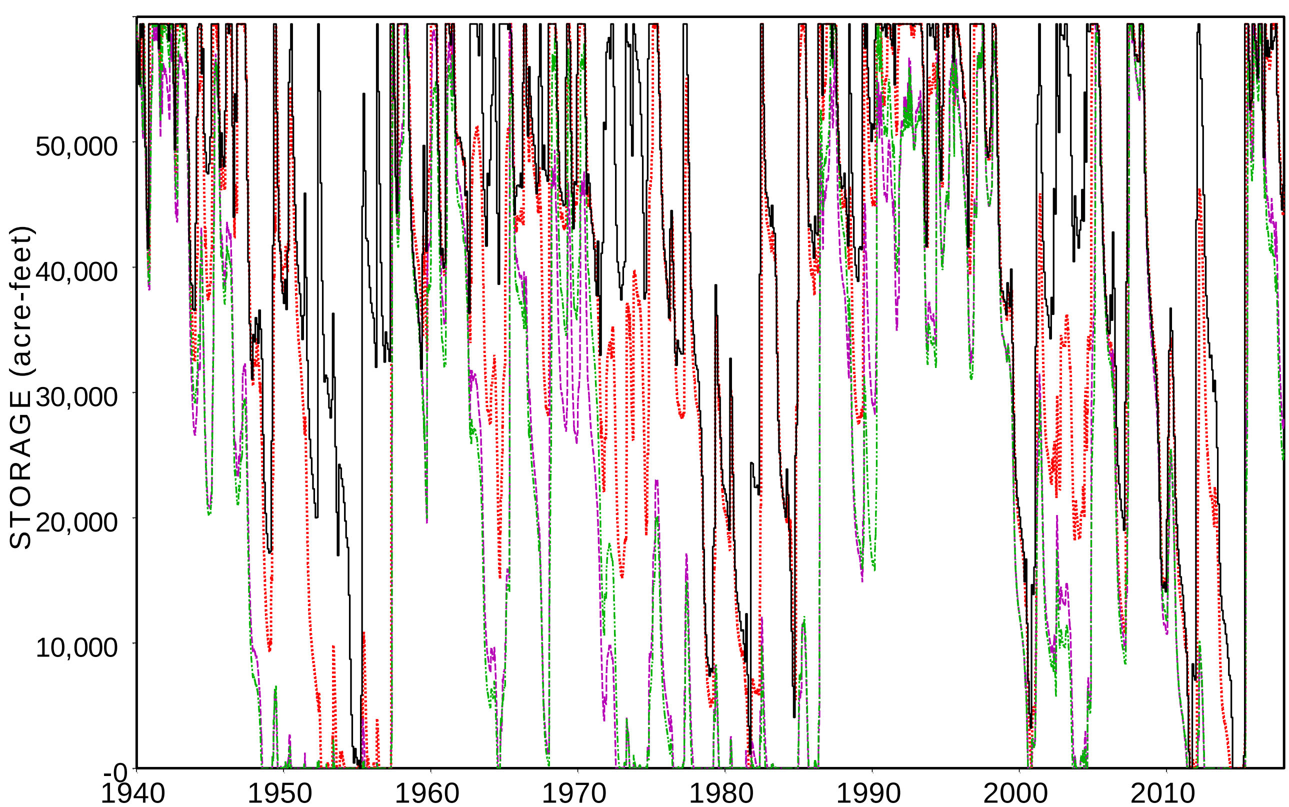

Figure 10.27 Proctor Reservoir Storage Contents with Alternative Routing Strategies

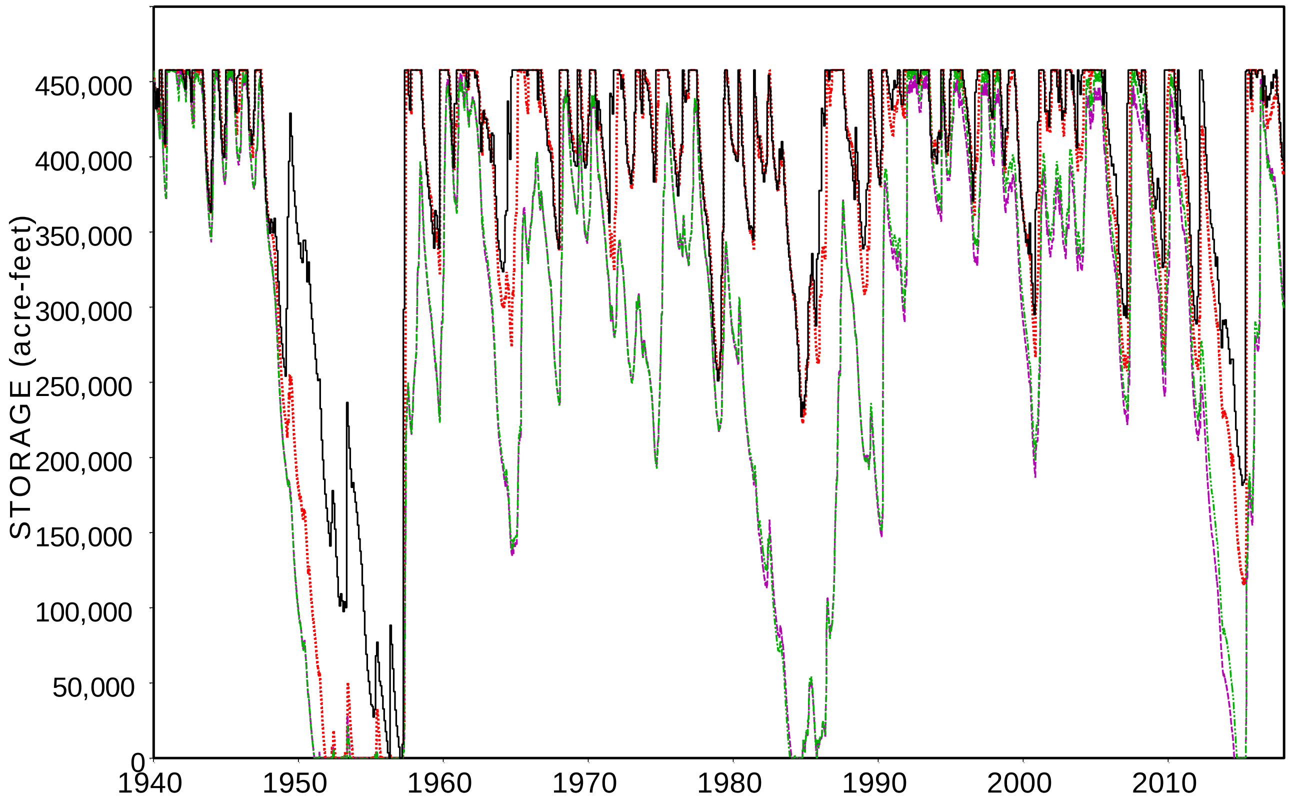

Figure 10.28 Belton Reservoir Storage Contents with Alternative Routing Strategies

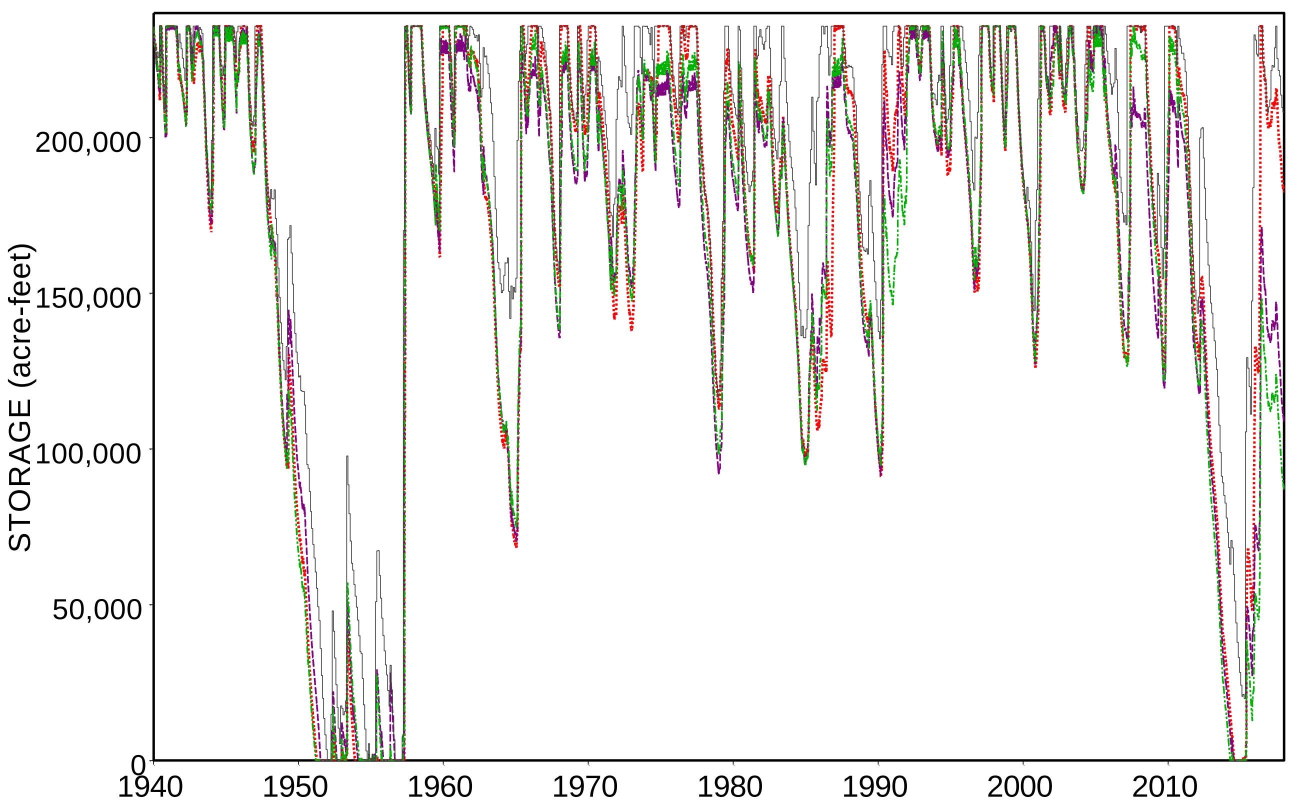

Figure 10.29 Stillhouse Hollow Reservoir Storage Contents with Alternative Routing Strategies

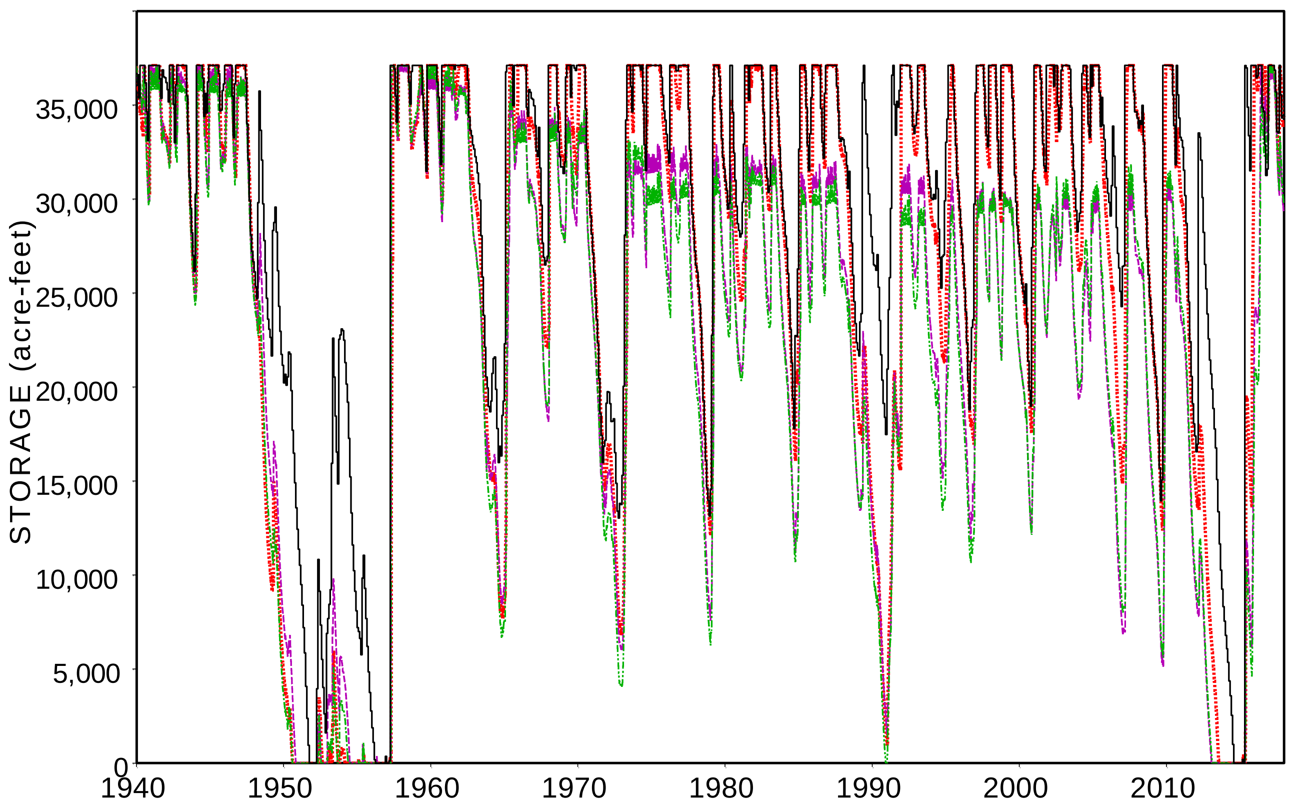

Figure 10.30 Georgetown Reservoir Storage Contents with Alternative Routing Strategies

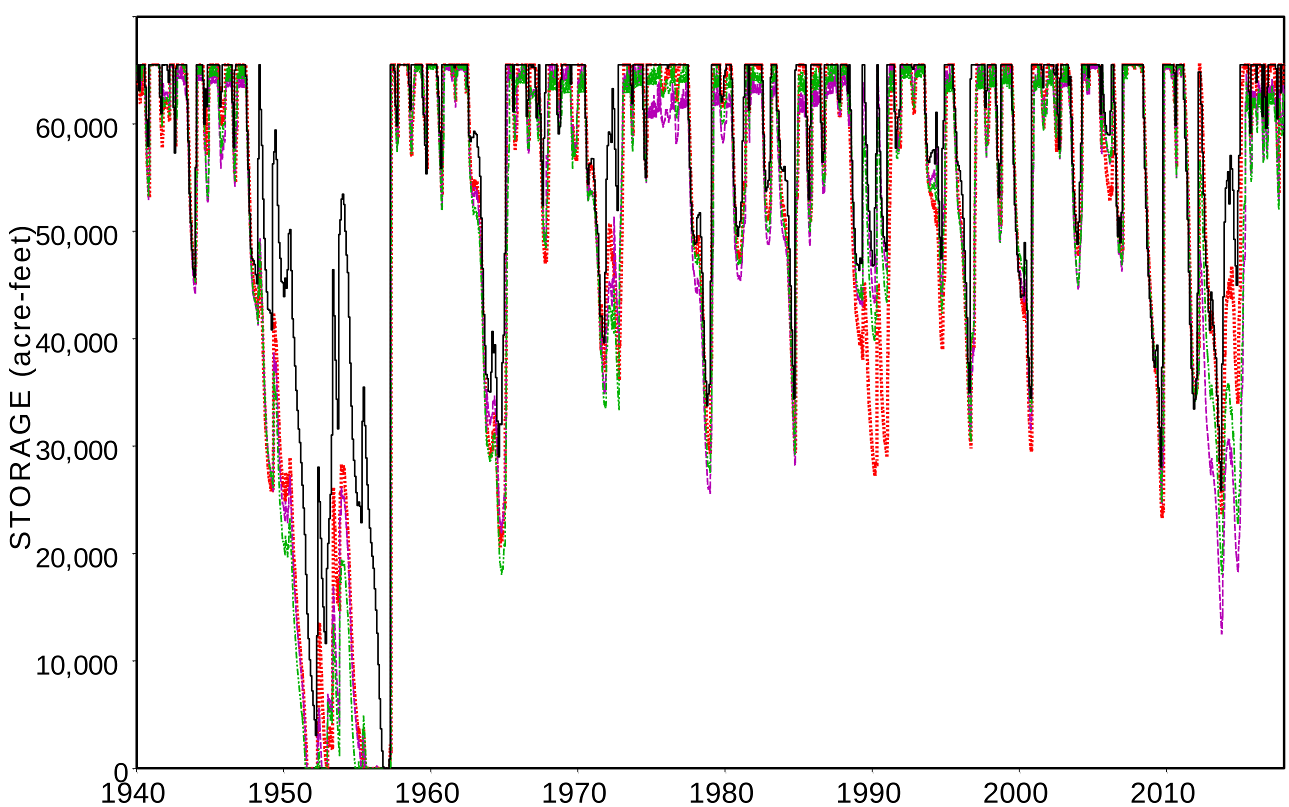

Figure 10.31 Granger Reservoir Storage Contents with Alternative Routing Strategies

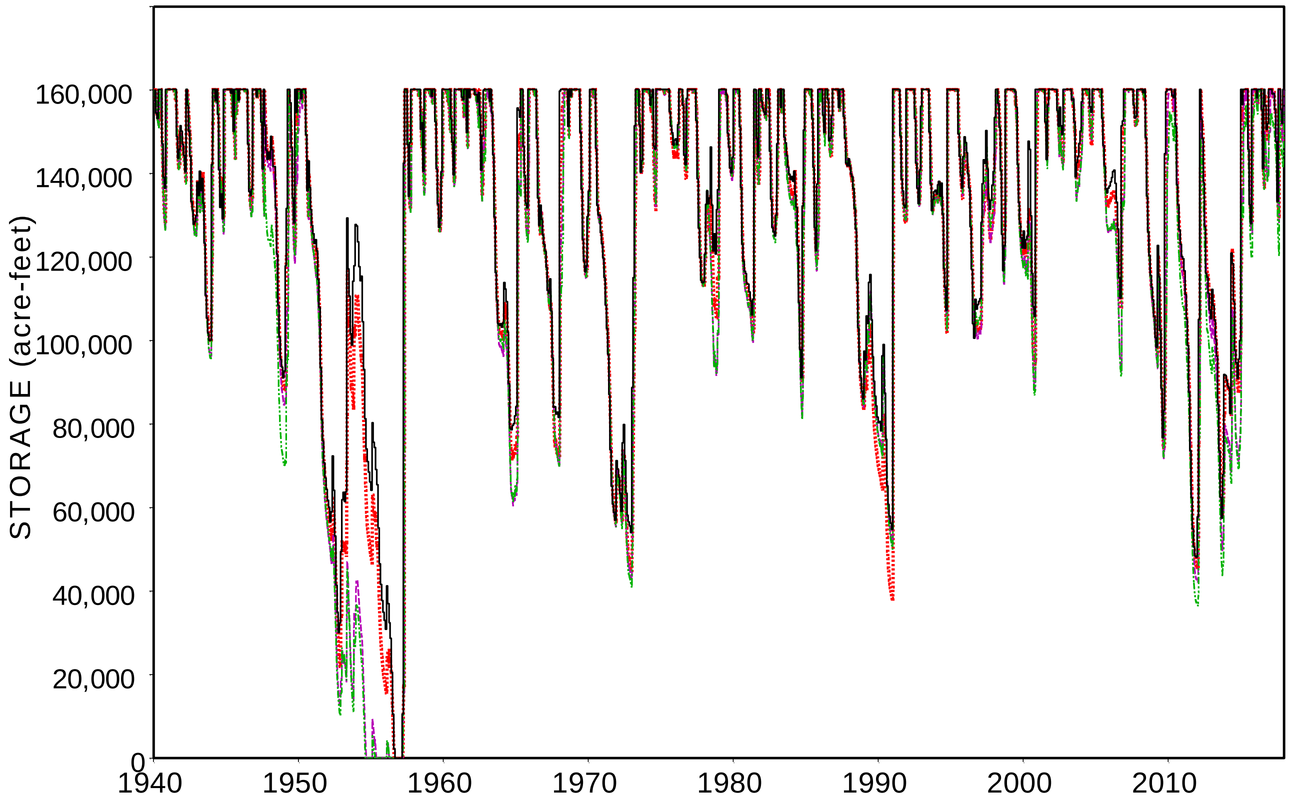

Figure 10.32 Somerville Reservoir Storage Contents with Alternative Routing Strategies

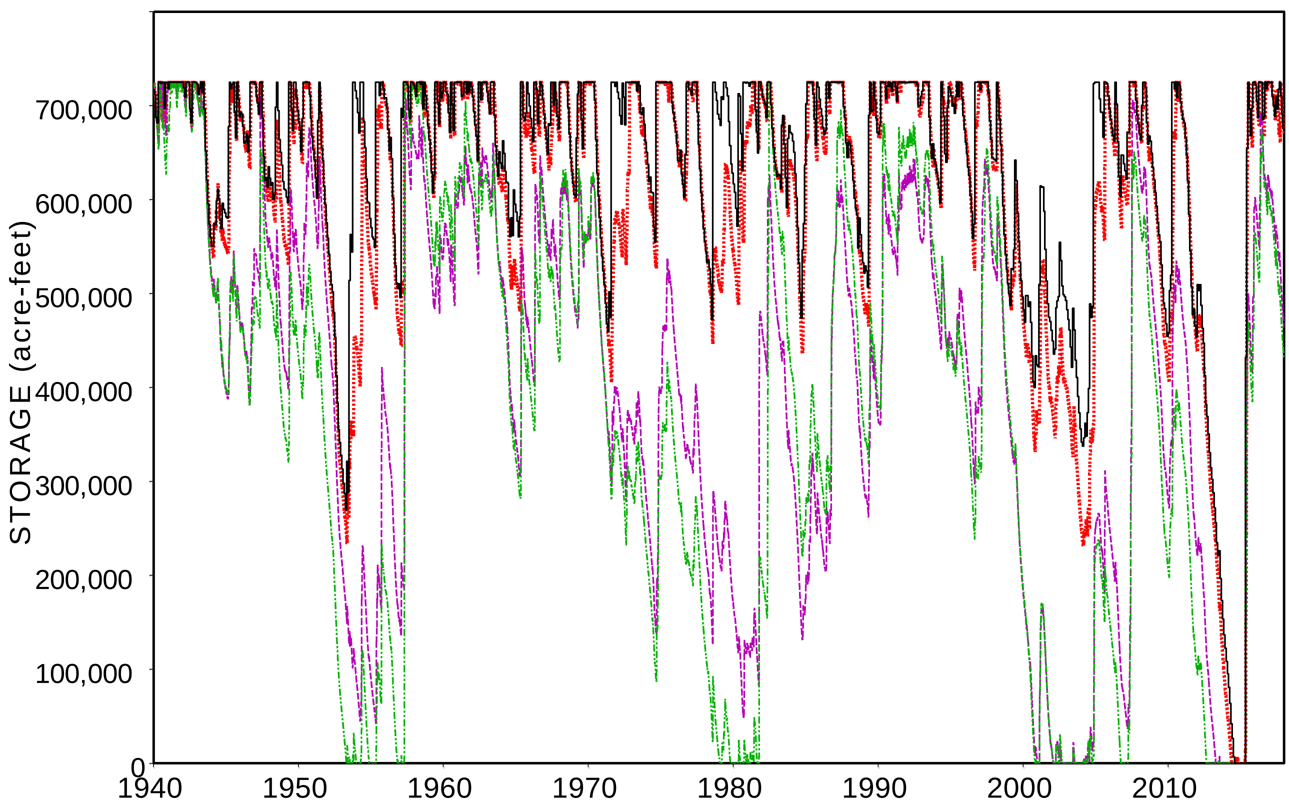

Figure 10.33 Possum Kingdom Reservoir Storage Contents with Alternative Routing Strategies

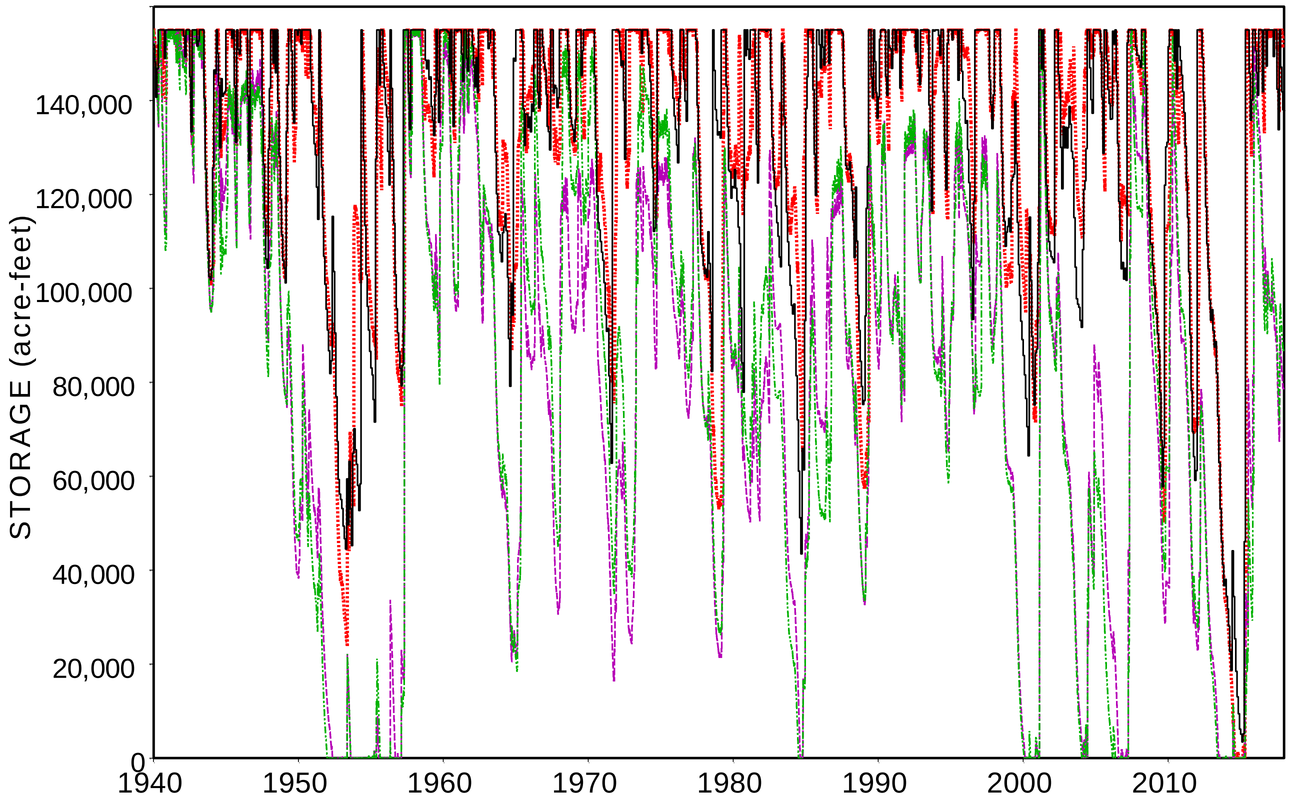

Figure 10.34 Granbury Reservoir Storage Contents with Alternative Routing Strategies

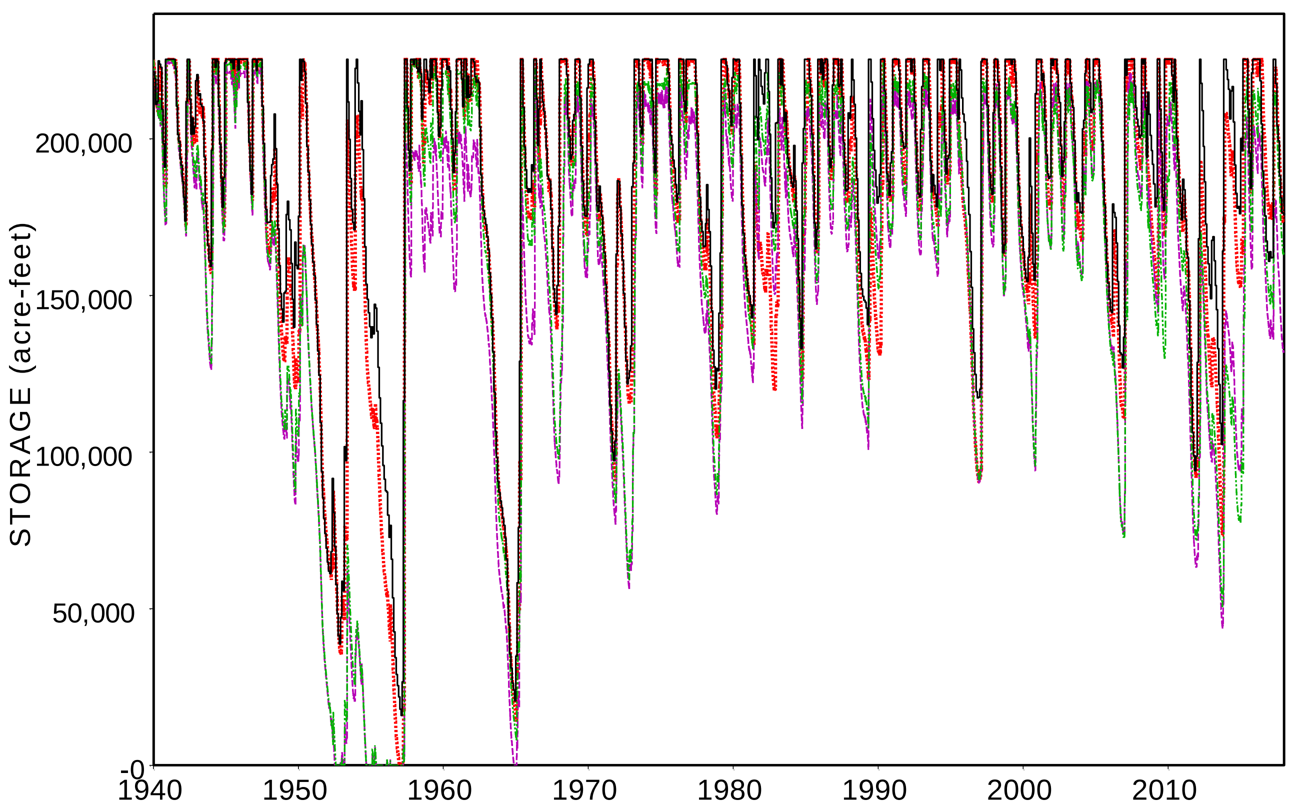

Figure 10.35 Limestone Reservoir Storage Contents with Alternative Routing Strategies

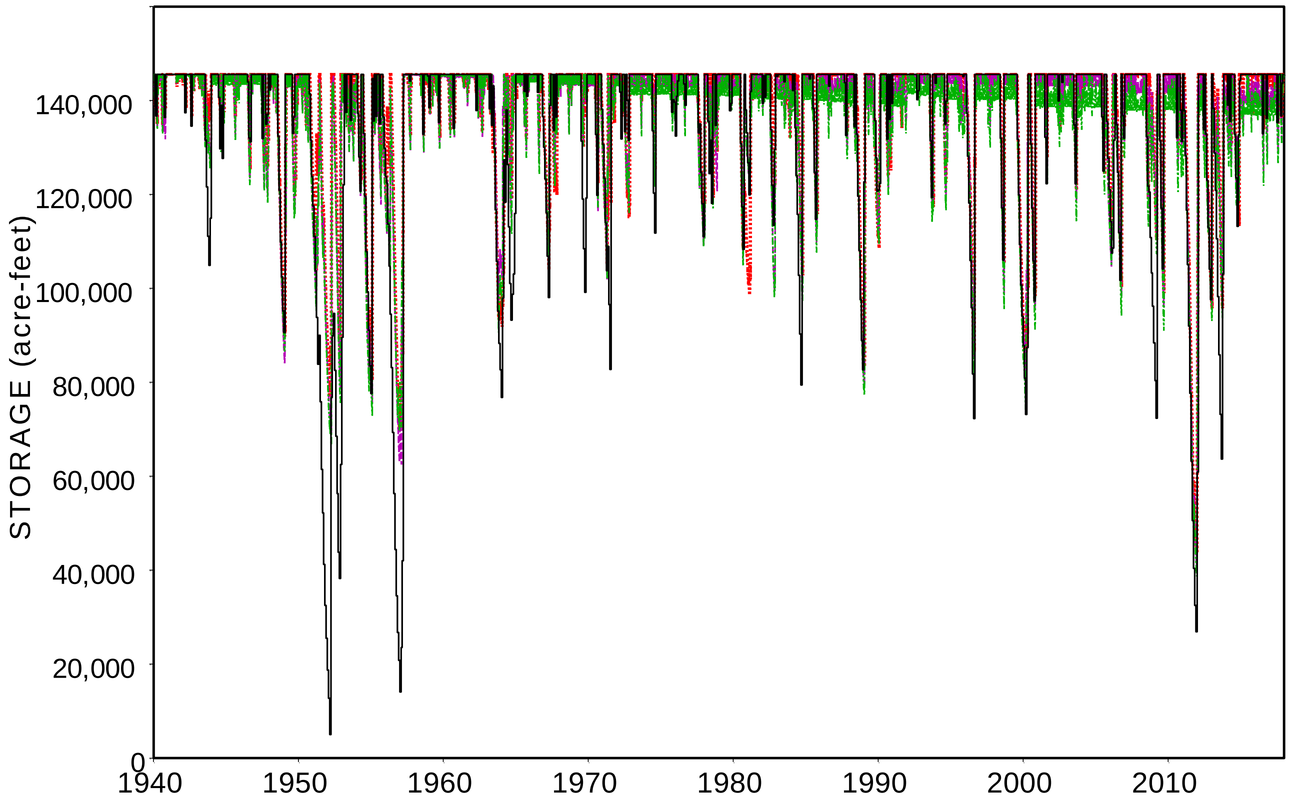

Figure 10.36 Allen’s Creek Reservoir Storage Contents with Alternative Routing Strategies

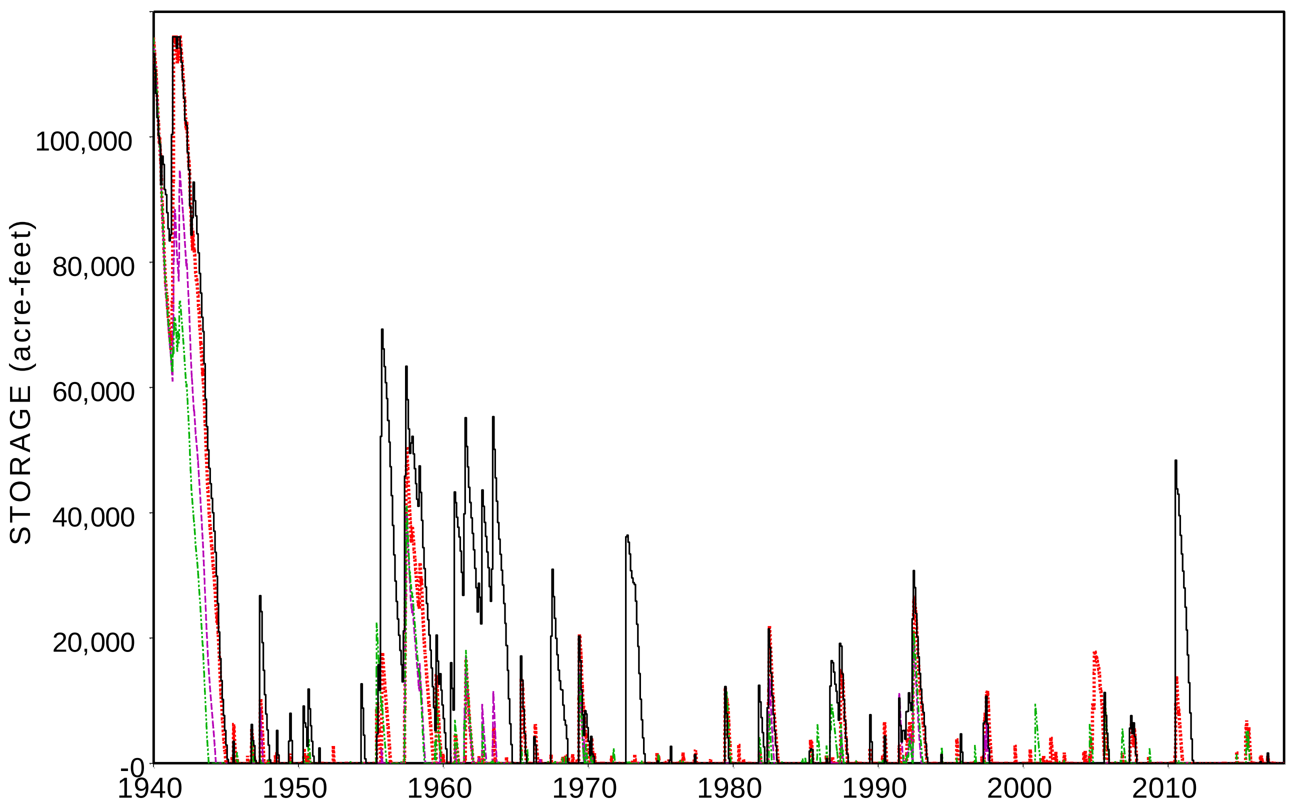

Figure 10.37 Alan Henry Reservoir Storage Contents with Alternative Routing Strategies

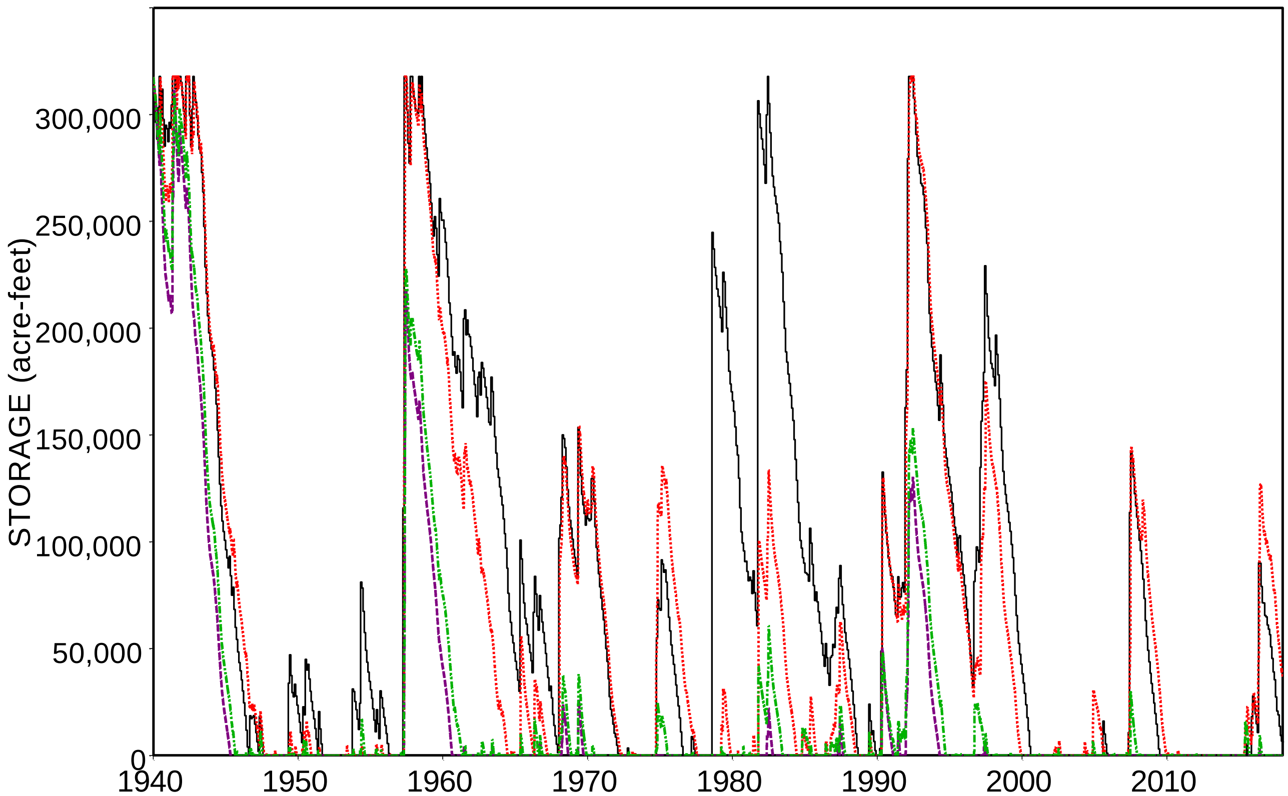

Figure 10.38 Hubbard Creek Reservoir Storage Contents with Alternative Routing Strategies

Legend for Figures 10.24 through 10.38

———	black solid line	Simulation M1 with ADJINC option 5
·········	red dotted line	Simulation D1 with ADJINC option 4 and no routing/forecasting
- - - - -	purple dashed	Simulation D3 with ADJINC option 7 and 15 day forecast
—·-·—·-·—	green dash&dots	Simulation D4 with ADJINC option 7 and 30 day forecast

The eleven alternative simulations referenced in this chapter are defined in Tables 10.2 and 10.3. Frequency metrics for end-of-month or end-of-day storage contents of each of the 15 reservoirs computed in each of the eleven simulations are tabulated in Table 10.8. The statistics in Table 10.8 include the mean, standard deviation, maximum and minimum, and storage volumes that are exceeded in specified percentages of the 936 months or 28,490 days of the simulation.

Simulation D1 with ADJINC option 4 provides a valid daily WAM even though routing and forecasting are not employed. Simulation D1 results replicate simulation M1 results significantly more closely than simulations D3 and D4 replicate simulation results M1. Results for simulation D1 seem to be generally more realistic than the results for simulations D3 and D4.

Due to considerations discussed further in the next section, the daily WAM is concluded be more accurate without forecasting. Routing is very approximate, does not dramatically affect simulation results, but probably contributes positively to model validity. Flood control operations and SB3 EFS are added to the WAM in the next section. Simulations D5, D6, and D7 are performed with flood control and SB3 EFS and either with or without forecasting and/or routing.

Simulation of Flood Control Operations and SB3 Environmental Flow Standards

Modeling of flood control operations of the nine U.S. Army Corps of Engineers (USACE) reservoirs is explained in Chapter 4. Input records added to the DAT file to model flood control operations in simulations D5, D6, D7, D8, and D9 are replicated in Tables 4.9, 4.12, 4.13, and 4.14. Various other simulations were performed as noted in Chapter 4 to investigate other alternative strategies for modeling flood control operations. The rules controlling flood control pool operations include both criteria specified on *FV* and *FQ* records that are relevant to individual reservoirs and maximum allowable downstream flow limits on *FF* records that are applicable to multiple upstream reservoirs. Both sets of criteria were found to significantly contribute to simulation results. Actual real-world reservoir operations include significant flexibility for operator judgement in balancing flood control storage in the multiple reservoirs operated based on common shared downstream allowable flow limits. Likewise, reasonable variations in the balancing priorities specified in *SIMD* can shift daily allocations of flood storage and releases between the different reservoirs in the system.

Modeling of the Senate Bill 3 (SB3) environmental flow standards (EFS) at the 19 sites listed in Tables 5.1 and 10.4 is described in Chapter 5. Records added to the DAT file to model SB3 EFS in simulations D5, D6, and D7 are replicated in Tables 5.8. Records added to the DAT file and hydrology input DSS file to model SB3 EFS in simulation M3 are shown in Tables 5.8 and 5.9.

Simulations D5, D6, D7, D8, and D9 are explored in this section of this chapter. Relevant summary metrics from the simulation results are tabulated in Tables 10.6, 10.7, and 10.8 presented earlier in the chapter. The reservoir storage plots for simulations D5, D6, and D7 in Figures 10.39 through 10.53 demonstrate the effects of routing and forecasting on simulation results. The reservoir storage plots for simulations D7 and D8, with-and-without SB3 EFS, in Figures 10.54 through 10.68 demonstrate the effects of SB3 EFS on simulation results.

Routing and Forecasting

Effects of routing and forecasting are investigated in the preceding section without flood control and SB EFS and further explored in this section after incorporation of flood control and SB EFS. Forecasting was found to overly constrain stream flow availability for reservoir storage and water supply diversions and channel flow capacity for releasing flood waters from flood control pools.

The monthly *SIM* and daily *SIMD* simulation algorithms for determining the amount of stream flow available to each water right is based on the minimum of the available flow at the control point of the water right and at all downstream control points. Inaccuracies at any one of multiple downstream control points may limit water availability. With forecasting, water availability in *SIMD* depends on available flows at multiple downstream control points in future days as well as during the current day. Without forecasting, the amount of water available to each water right in the current day depends on stream flow in the current day without consideration of future days. Forecast simulation inaccuracies result in over-constraining flow availability.

Likewise, inaccuracies in computing future flows at downstream control points during the forecast simulation may result in under estimation of channel flow capacities and over constraining releases from flood control pools. Flow forecasting results in storing flood waters sooner and longer and modeling inaccuracies may result in excessive filling of flood control pools.

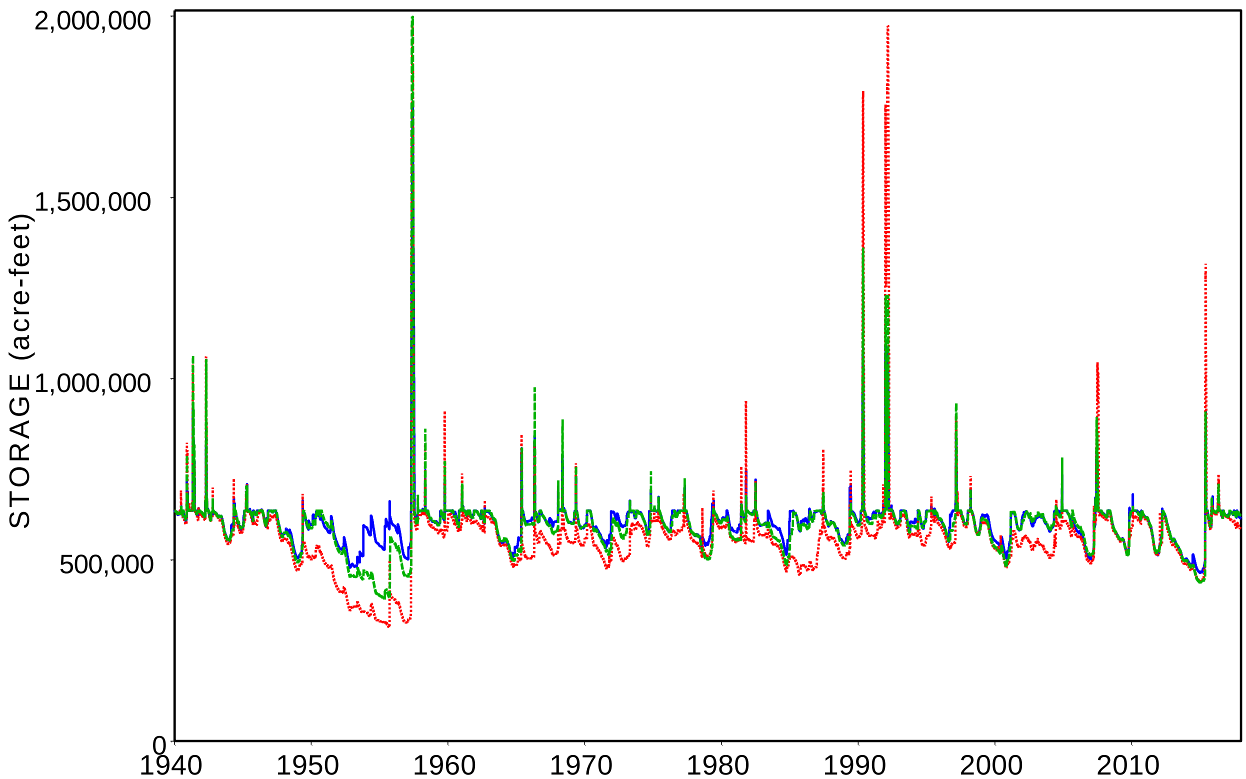

Figure 10.39 Whitney Reservoir Storage for Simulations D5 (green dashed line), D6 (red dotted line), and D7 (blue solid line)

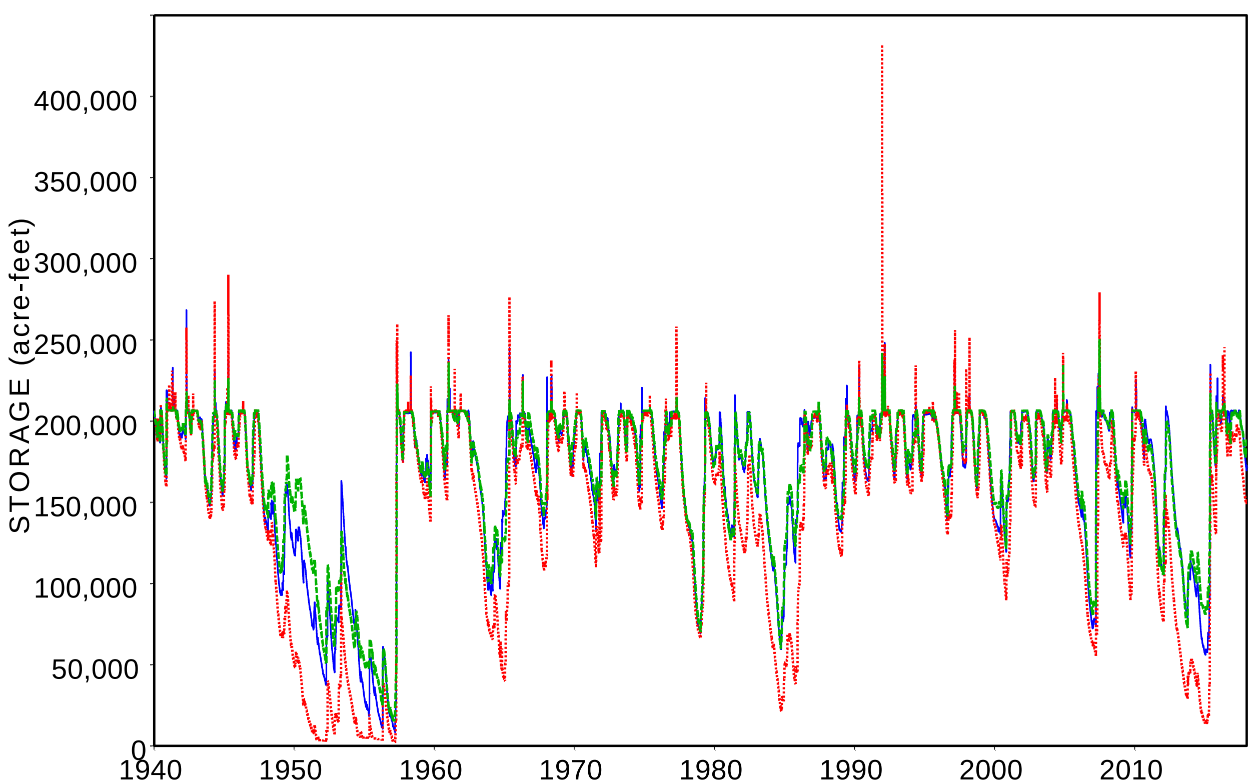

Figure 10.40 Waco Reservoir Storage for Simulations D5, D6, and D7

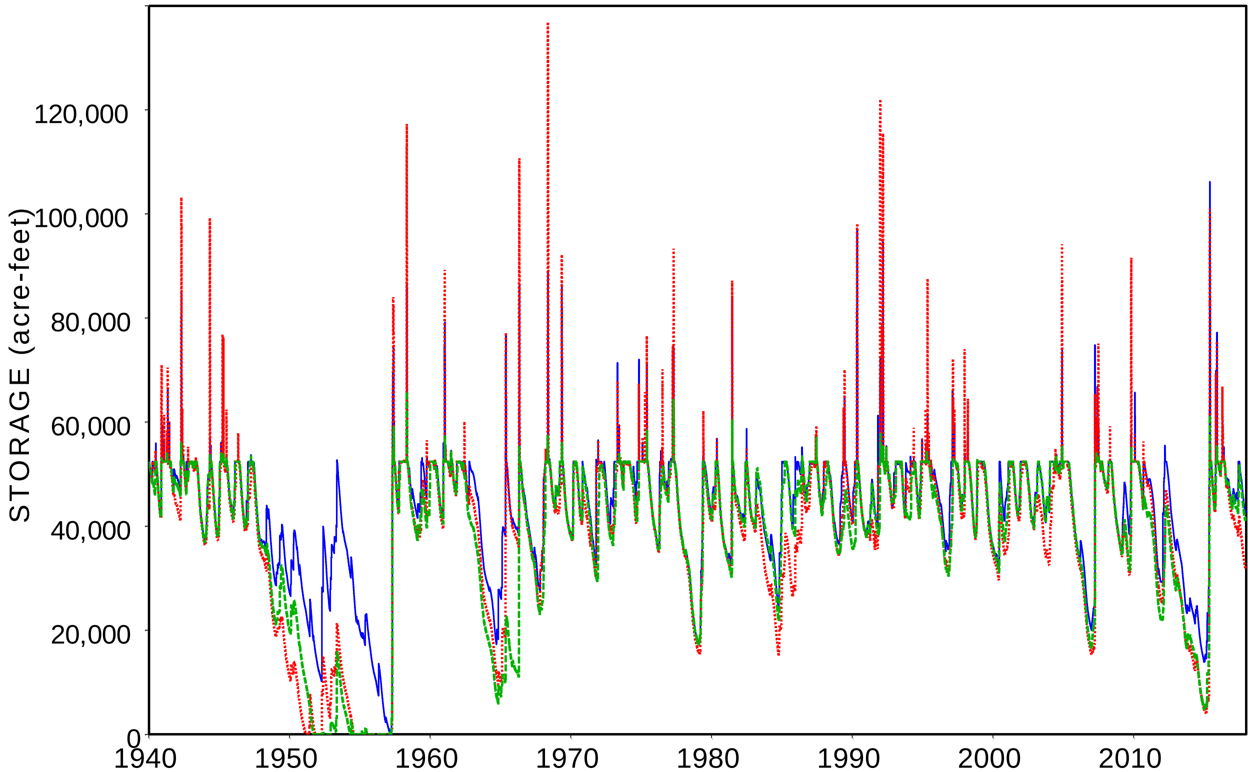

Figure 10.41 Aquilla Reservoir Storage for Simulations D5 (green dashed line), D6 (red dotted line), and D7 (blue solid line)

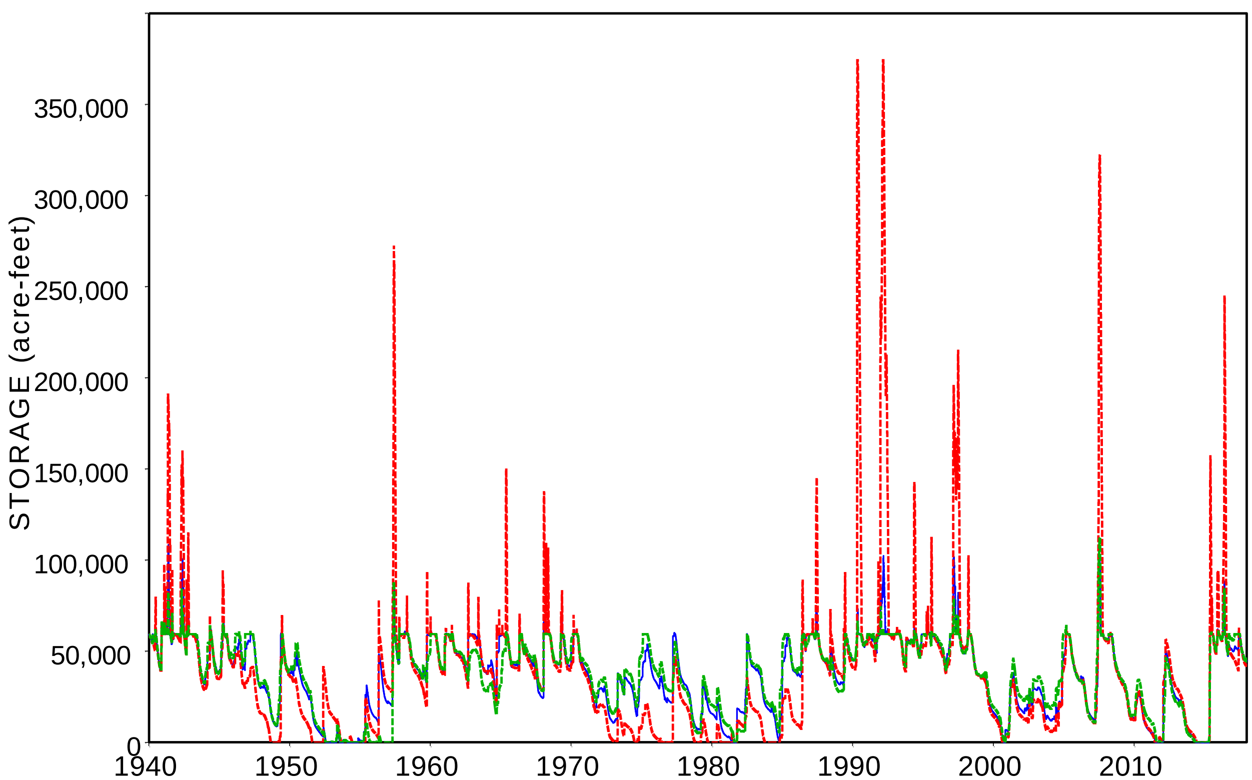

Figure 10.42 Proctor Reservoir Storage for Simulations D5, D6, and D7

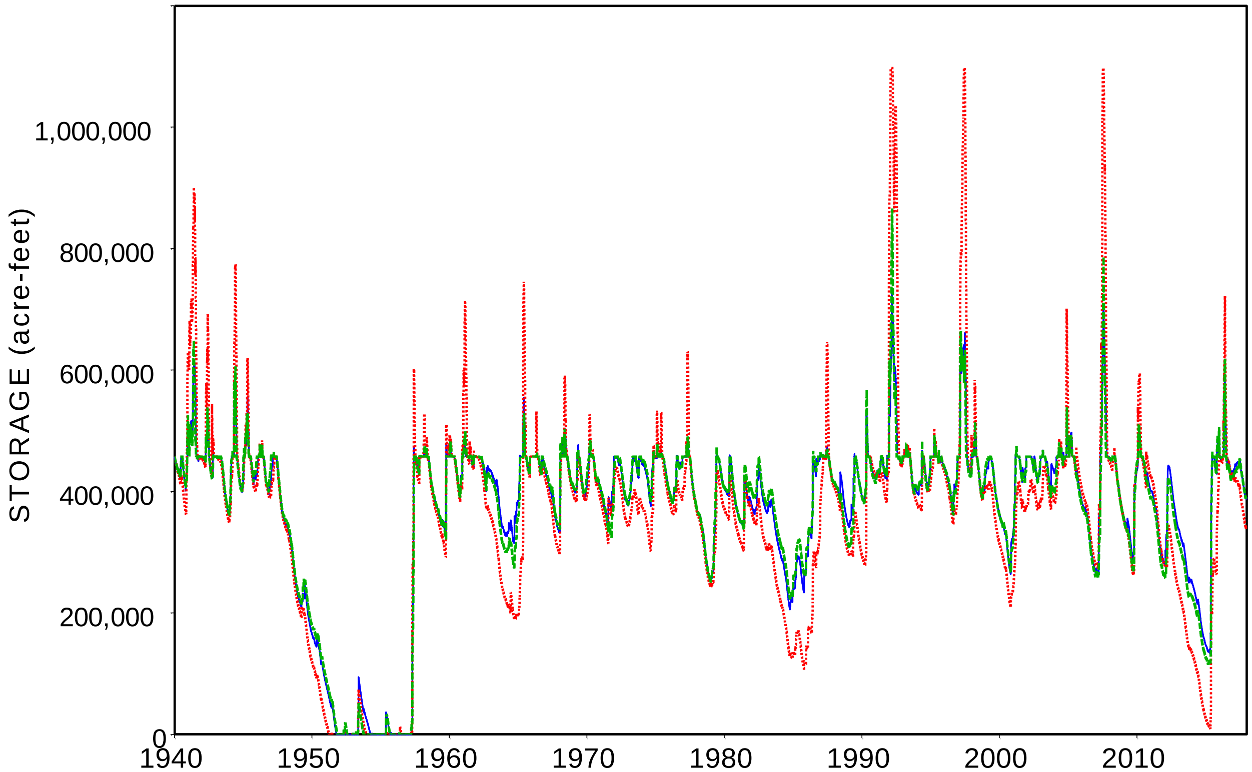

Figure 10.43 Belton Reservoir Storage for Simulations D5 (green dashed line), D6 (red dotted line), and D7 (blue solid line)

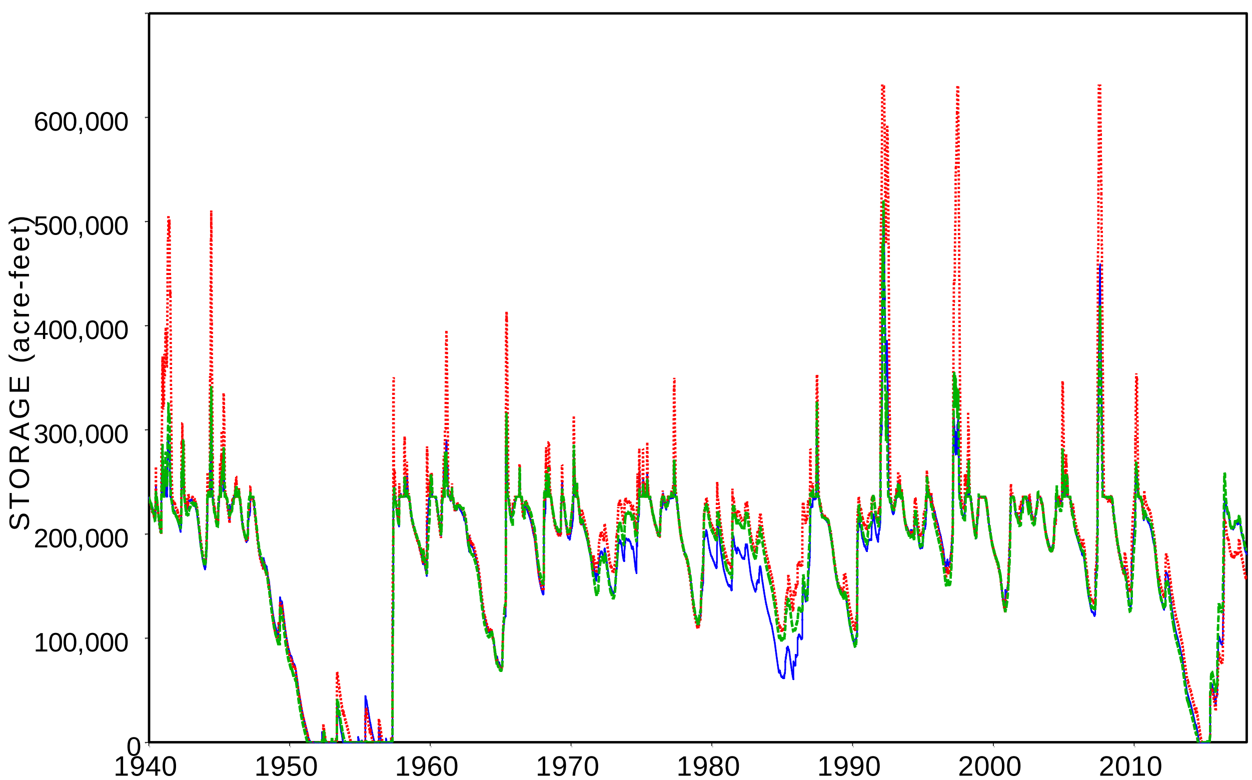

Figure 10.44 Stillhouse Hollow Reservoir Storage for Simulations D5, D6, and D7

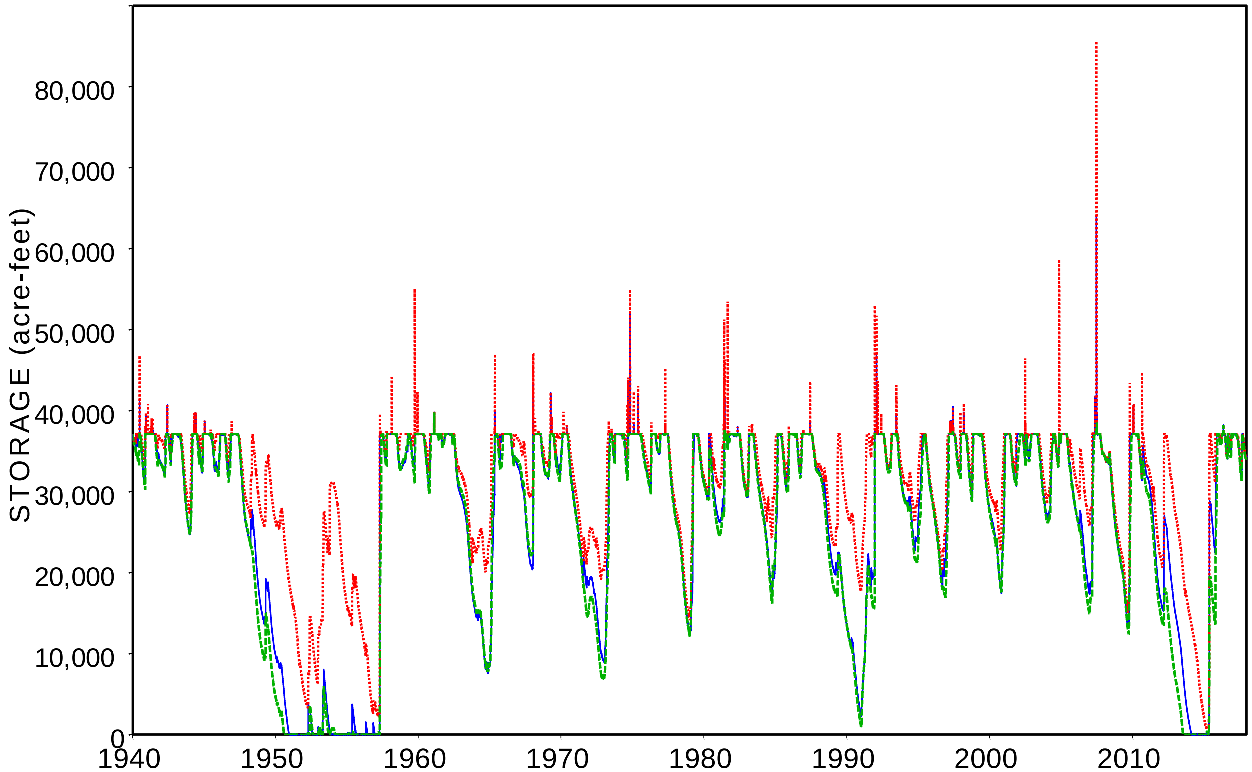

Figure 10.45 Georgetown Reservoir Storage for Simulations D5 (green dashed line), D6 (red dotted line), and D7 (blue solid line)

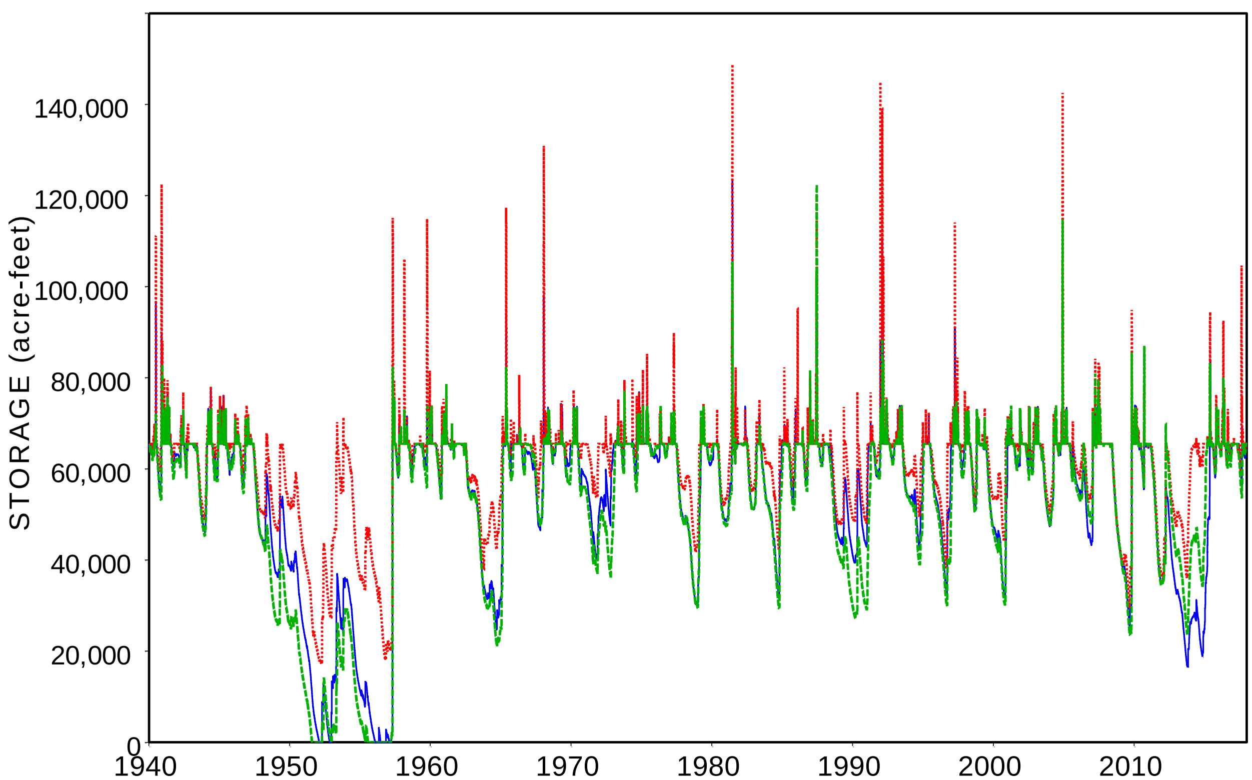

Figure 10.46 Granger Reservoir Storage for Simulations D5, D6, and D7

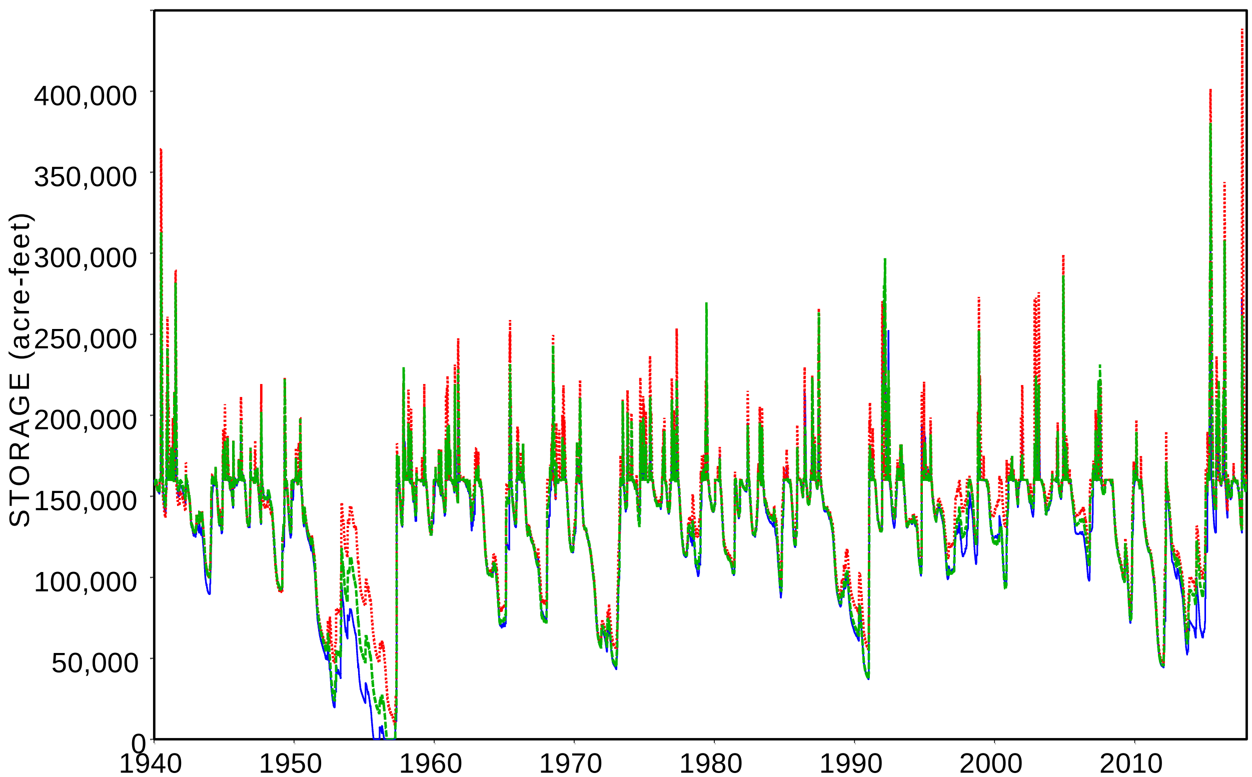

Figure 10.47 Somerville Reservoir Storage for Simulations D5 (green dashed line), D6 (red dotted line), and D7 (blue solid line)

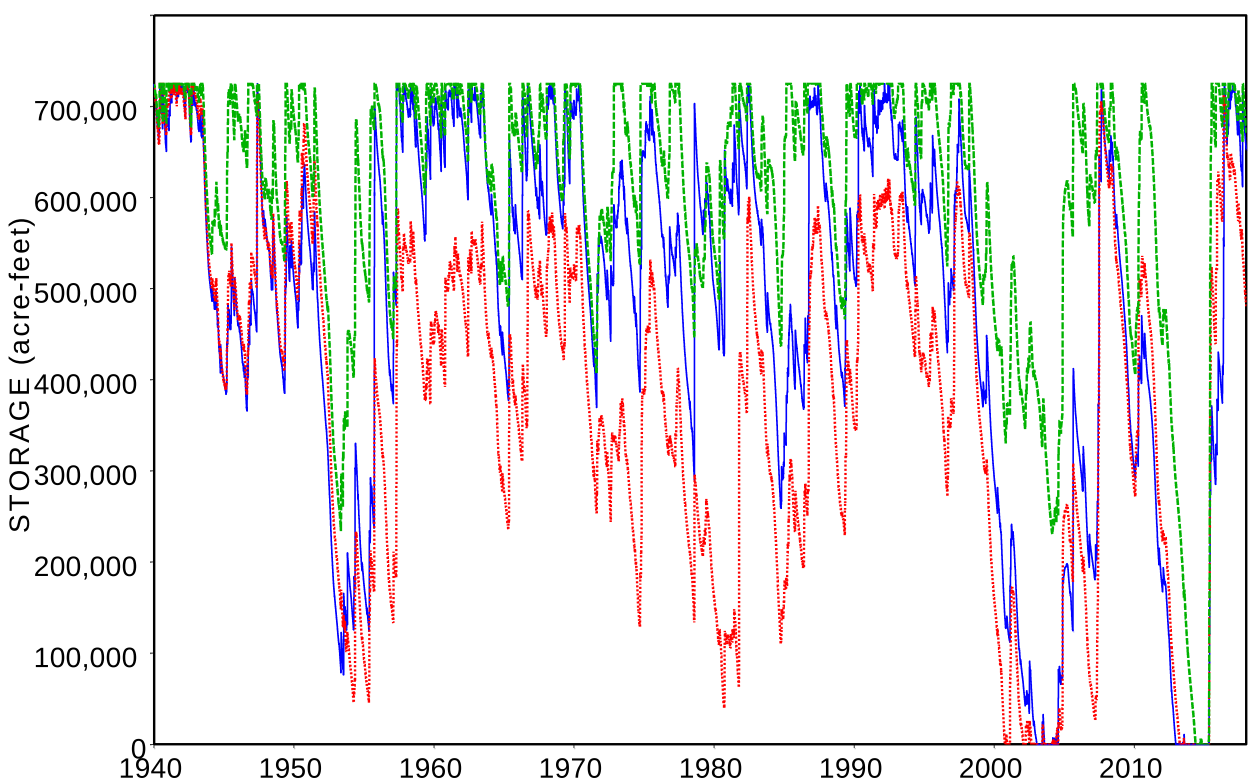

Figure 10.48 Possum Kingdom Reservoir Storage for Simulations D5, D6, and D7

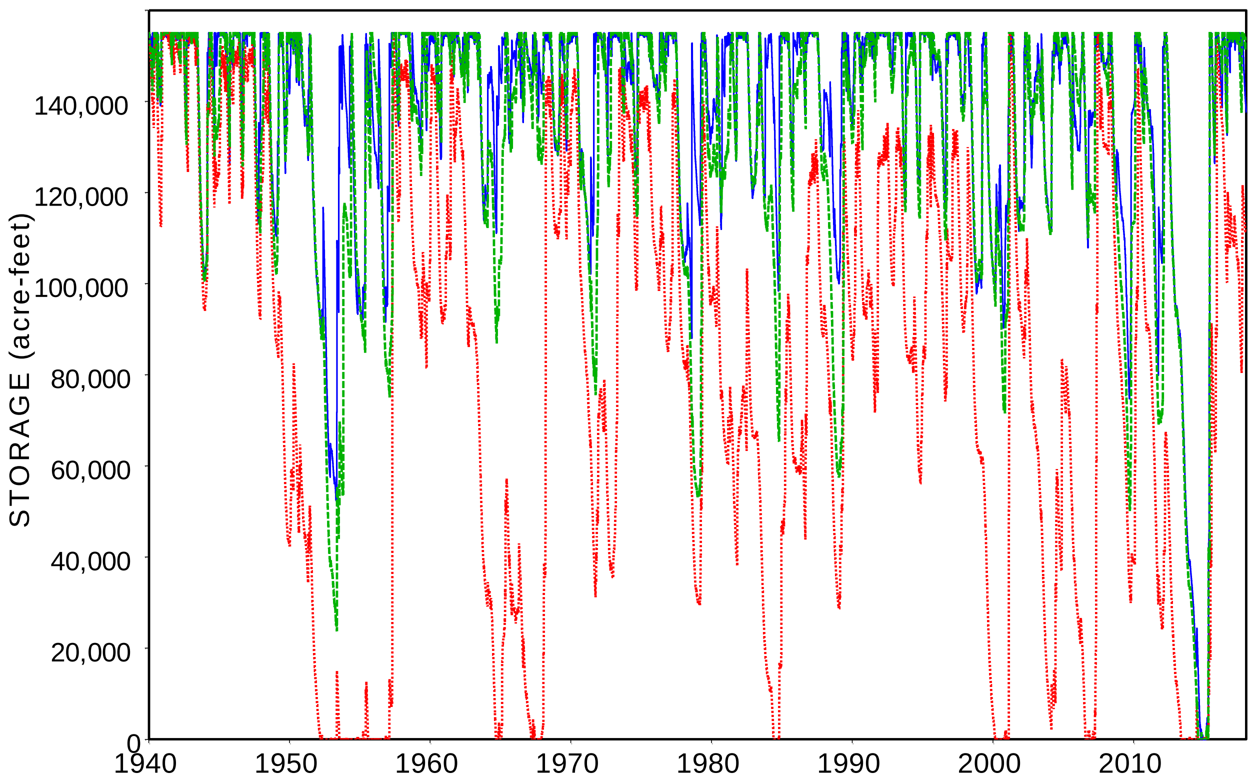

Figure 10.49 Granbury Reservoir Storage for Simulations D5 (green dashed line), D6 (red dotted line), and D7 (blue solid line)

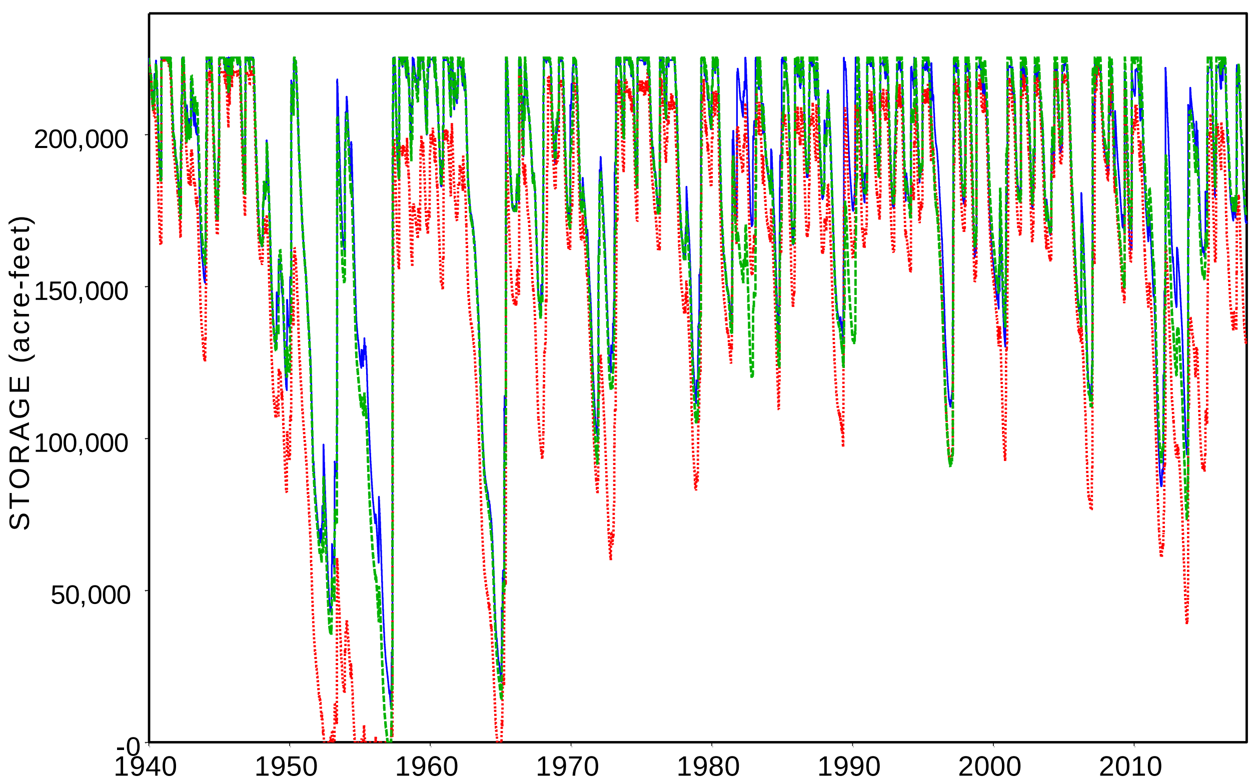

Figure 10.50 Limestone Reservoir Storage for Simulations D5, D6, and D7

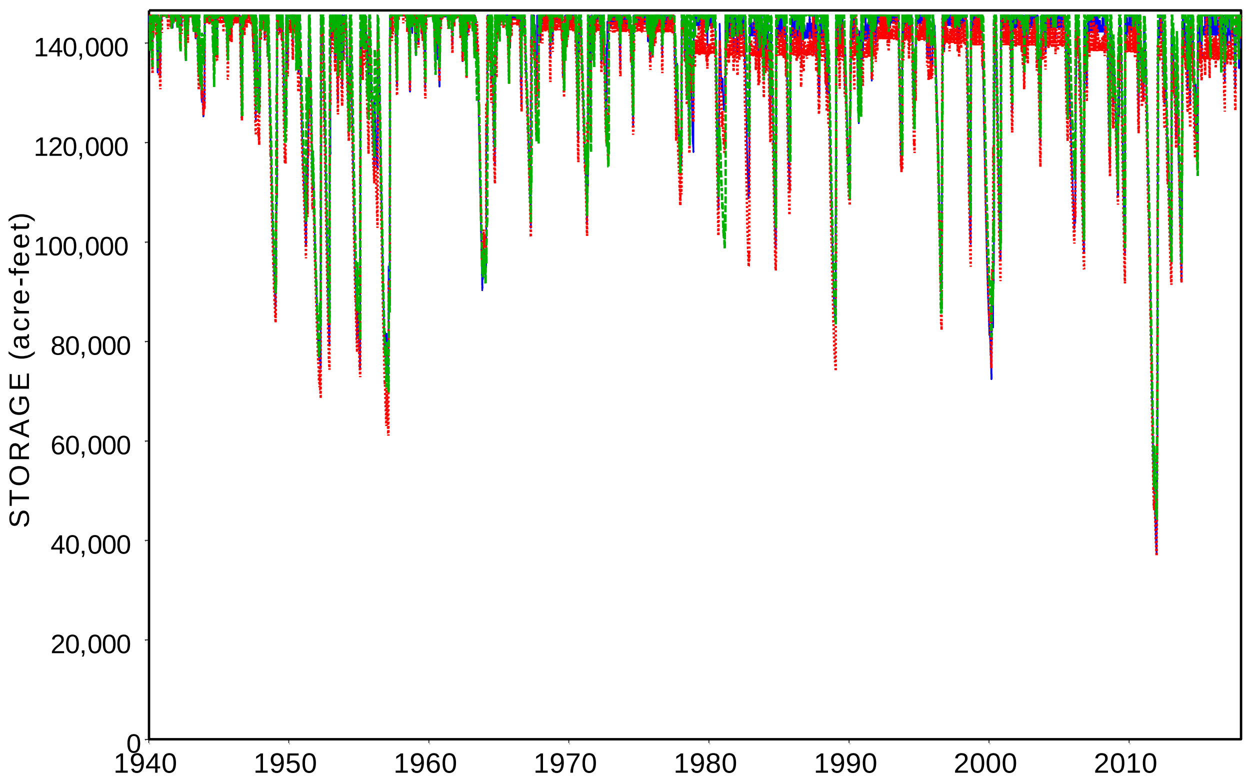

Figure 10.51 Allen's Creek Reservoir Storage for Simulations D5 (green dashed line), D6 (red dotted line), and D7 (blue solid line)

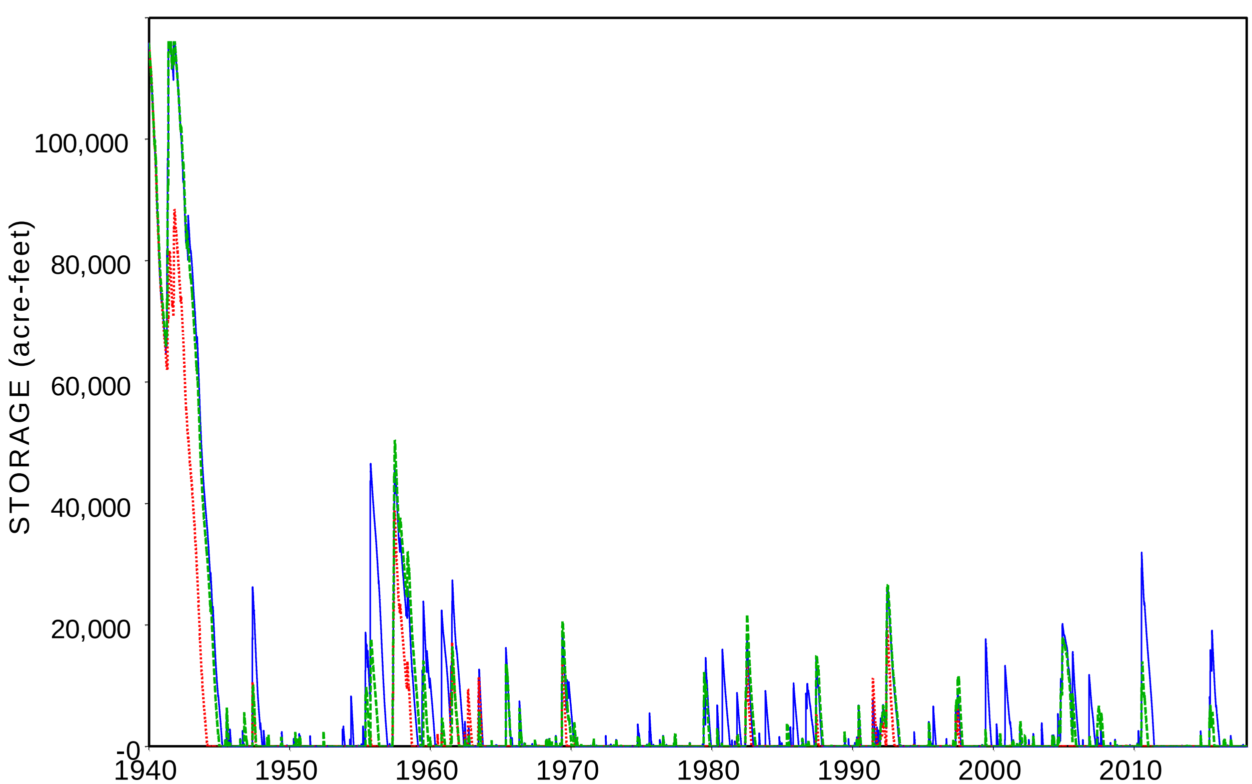

Figure 10.52 Alan Henry Reservoir Storage for Simulations D5, D6, and D7

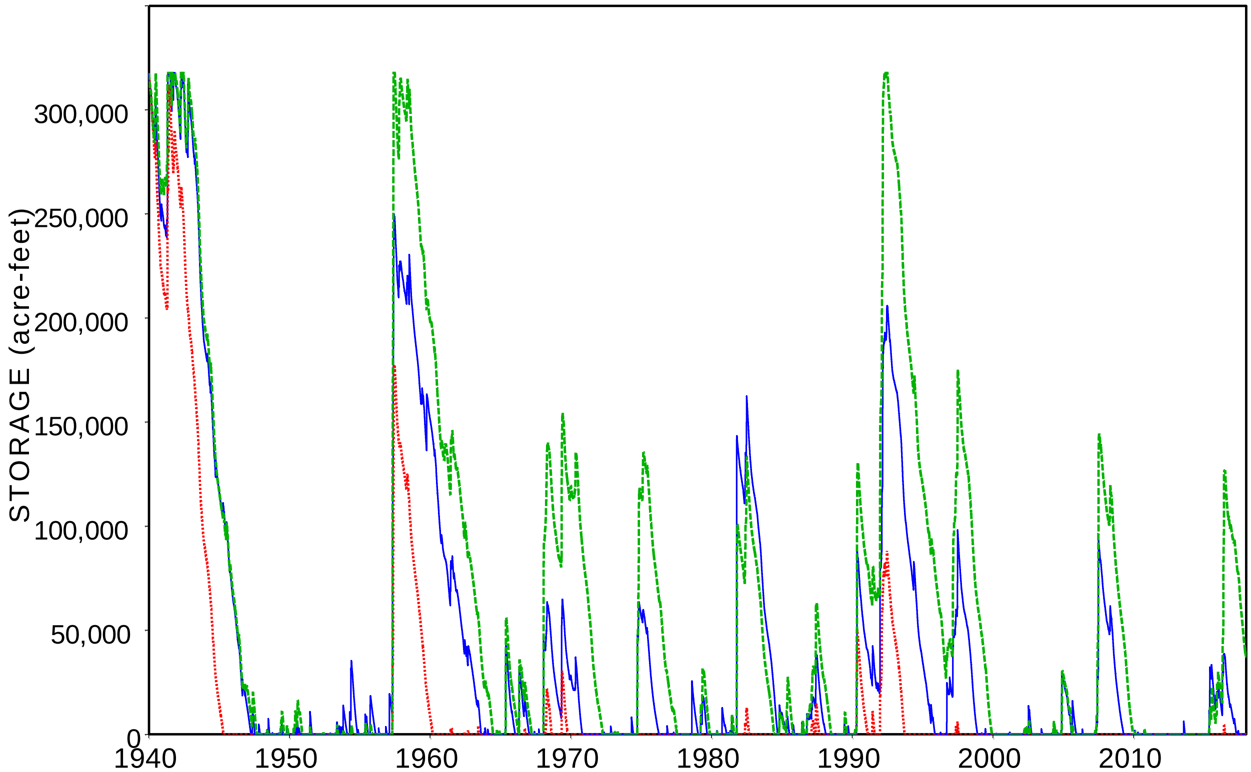

Figure 10.53 Hubbard Creek Reservoir Storage for Simulations D5 (green dashed line), D6 (red dotted line), and D7 (blue solid line)

Negative incremental flows and ADJINC adjustment options significantly affect the computation of stream flow availability in the water rights priority simulation. Flow forecasting significantly magnifies these effects by considering all days of the forecast period. Option 4 is generally the best ADJINC option but is not applicable to the future days in the forecast simulation. ADJINC option 7 is employed with forecasting to deal with the future forecast simulation days.

Forecasting of future stream flow is highly uncertain in actual real-time water management, with inaccuracies increasing with the length into the future of the forecast period. The selection of a *SIMD* forecast period is largely arbitrary. Routing parameters are inherently highly uncertain and inaccurate. Routing inaccuracies contribute to forecasting inaccuracies. Tradeoffs between dealing with modeling issues inherent in negative incremental flow adjustments, routing, forecasting, and other *SIMD* options may vary between WAMs and between different WAM applications.

Simulation D7 includes routing, flood control, and SB3 EFS but does not include forecasting. Without forecasting, simulation D7 employs ADJINC option 4. Simulation D6 has the same input dataset as D7 except forecasting is employed with a forecast period of 15 days. Simulation D5 has the same input as simulations D7 and D6 except both routing and forecasting are deactivated.

In general, routing does not appear to greatly impact simulation results. Forecasting does greatly impact simulation results. The daily WAM would be a valid model without both routing and forecasting (simulation D5). However, addition of routing (D7), though very approximate, probably improves model validity. Forecasting (D6) adversely affects WAM accuracy and validity.

Water Right Priorities

The SB EFS, as published in the Texas Water Code [23], are assigned a priority of March 1, 2012. The 19 instream flow *IF* record water rights that model the SB3 EFS are assigned priority numbers of 20120301 (March 1, 2012). The *FR* record flood control storage and release rights are assigned priorities that vary between 90100000 and 90980000. Storage-refilling water rights for Whitney Reservoir, Waco Reservoir, and a small reservoir with identifier RP5447 are assigned priorities of 99999999. The SB3 EFS rights should not directly affect senior rights but may affect these or other existing water rights with assigned priority numbers greater than 20120301.

As indicated in Tables 10.2 and 10.3, daily simulations D5, D6, and D7 include the SB3 EFS with priority numbers of 20120301 entered on their *IF* records. Simulation D8 is identical to simulation D7 except the priorities for the *IF* record rights that model the 19 SB3 EFS are changed from 20120301 to 99999999 for simulation D8. Thus, the SB3 IFS are junior to all other rights including flood control rights in simulation D8.

The 1949-2017 means of regulated and unappropriated flows at the 19 SB3 EFS sites for simulations D7 and D8 along with ten other simulations are tabulated in Tables 10.6 and 10.7. Means of SB3 EFS targets and shortages for simulations D7 and D8 and three other simulations are tabulated below in Table 10.9. Naturalized flow averages in cfs are also included in the table. The two columns labeled "*No FC*" are for a simulation identical to simulation D7 except flood control operations are removed. Shifting SB3 EFS priorities from 20120301 to 99999999 making them junior to flood control has only minimal effects on simulation results. Removing flood control storage/operations has only minimal effects on SB3 EFS instream flow targets and shortages.

Table 10.9
Mean Naturalized Flow and Means of SB3 EFS Instream Flow Targets and Shortages

Control Point	Natural Flow	SB3 EFS Instream Flow Targets (cfs)					SB3 EFS Instream Flow Shortages (cfs)				
		No FC	D6	D7	D8	M3	No FC	D6	D7	D8	M3
SFAS06	89.58	5.56	5.554	5.554	5.56	5.54	0.99	0.986	0.986	0.99	0.32
DMAS09	135.8	9.42	9.41	9.41	9.42	9.37	2.77	2.756	2.756	2.77	0.84
BRSE11	304.7	30.24	30.24	30.24	30.24	30.18	8.37	8.380	8.380	8.38	2.20
CFNU16	112.0	9.12	9.119	9.119	9.11	9.11	1.15	1.151	1.151	1.15	0.93
CON026	130.5	9.01	9.008	9.008	9.01	9.01	1.91	1.912	1.912	1.90	1.15
BRSB23	806.9	82.62	82.62	82.62	82.62	82.48	20.70	20.66	20.66	20.67	6.33
BRPP27	992.3	181.8	181.8	181.8	181.8	181.2	92.21	92.21	92.21	91.94	94.06
BRGR30	1,400	300.0	300.4	300.4	300.3	299.3	147.8	147.9	147.9	148.1	123.7
NBCL36	224.4	22.95	22.95	22.95	22.95	22.91	1.94	1.941	1.941	1.94	1.18
BRWA41	2,569	511.5	511.3	511.3	511.5	508.9	267.1	266.5	266.5	270.7	142.3
LEGT47	347.1	29.34	29.34	29.34	29.34	29.28	7.97	8.015	8.015	8.00	3.38
LAKE50	165.3	36.85	36.85	36.85	36.85	36.80	3.87	3.874	3.874	3.87	2.97
LRLR53	1,165	205.0	205.3	205.3	205.2	204.7	71.64	70.57	70.57	71.11	49.99
LRCA58	1,841	408.9	410.3	410.3	410.1	408.8	139.1	136.4	136.4	136.6	94.26
BRBR59	5,474	1,330	1,330	1,330	1,330	1,328	474.8	472.0	472.0	473.5	257.8
NAEA66	464.7	34.23	34.23	34.23	34.22	34.15	5.50	5.517	5.517	5.49	3.07
BRHE68	7,378	2,158	2,158	2,158	2,158	2,155	738.7	732.1	732.1	734.0	368.1
BRRI70	8,061	2,373	2,374	2,374	2,373	2,372	808.1	797.0	797.0	796.4	365.2
BRRO72	8,445	2,668	2,669	2,669	2,669	2,670	1,011	504.4	504.4	1,000	608.4

Simulations With-and-Without Senate Bill 3 Environmental Flow Standards

Simulation 7 is considered to represent the best strategy for computing SB3 EFS instream flow targets. Flow forecasting is excluded from simulation D7. Forecasting was found in the simulation study to overly constrain stream flow availability for reservoir storage and water supply diversions and channel flow capacity for releasing flood waters from flood control pools.

The SB3 EFS are assigned priority numbers of 20120301 (March 1, 2012) in simulation D7, which makes the 19 *IF* record rights for the SB3 EFS junior to the *FR* record flood control storage and release rights. Storage-refilling water rights for Whitney Reservoir, Waco Reservoir, and the small reservoir RP5447 have priorities of 99999999. The SB3 EFS rights may affect senior water rights with assigned priority numbers greater than 20120301.

Simulation D7 employs the version of the daily Brazos WAM adopted in this study for computing instream flow targets for the 19 SBS EFS. Simulation D9 is identical to simulation D7 except for removal from the DAT file of the 19 *IF* record instream flow rights that model the SB3 EFS. The storage contents in each of the 15 reservoirs at the end of each of the 28,490 days of the 1940-2017 simulation for simulations D7 and D9 are plotted in Figures 10.54 through 10.68. The corresponding storage frequency metrics are tabulated in Table 10.8. Means of regulated and unappropriated flows are tabulated in Tables 10.6 and 10.7. Simulations D7 and D9 result in almost the same but not exactly identical reservoir storage sequences. Regulated flows are likewise almost but not absolutely identical in simulations D7 and D9, with and without SB3 EFS. Unappropriated flows at the 19 SB3 EFS sites are decreased significantly by the SB3 EFS.

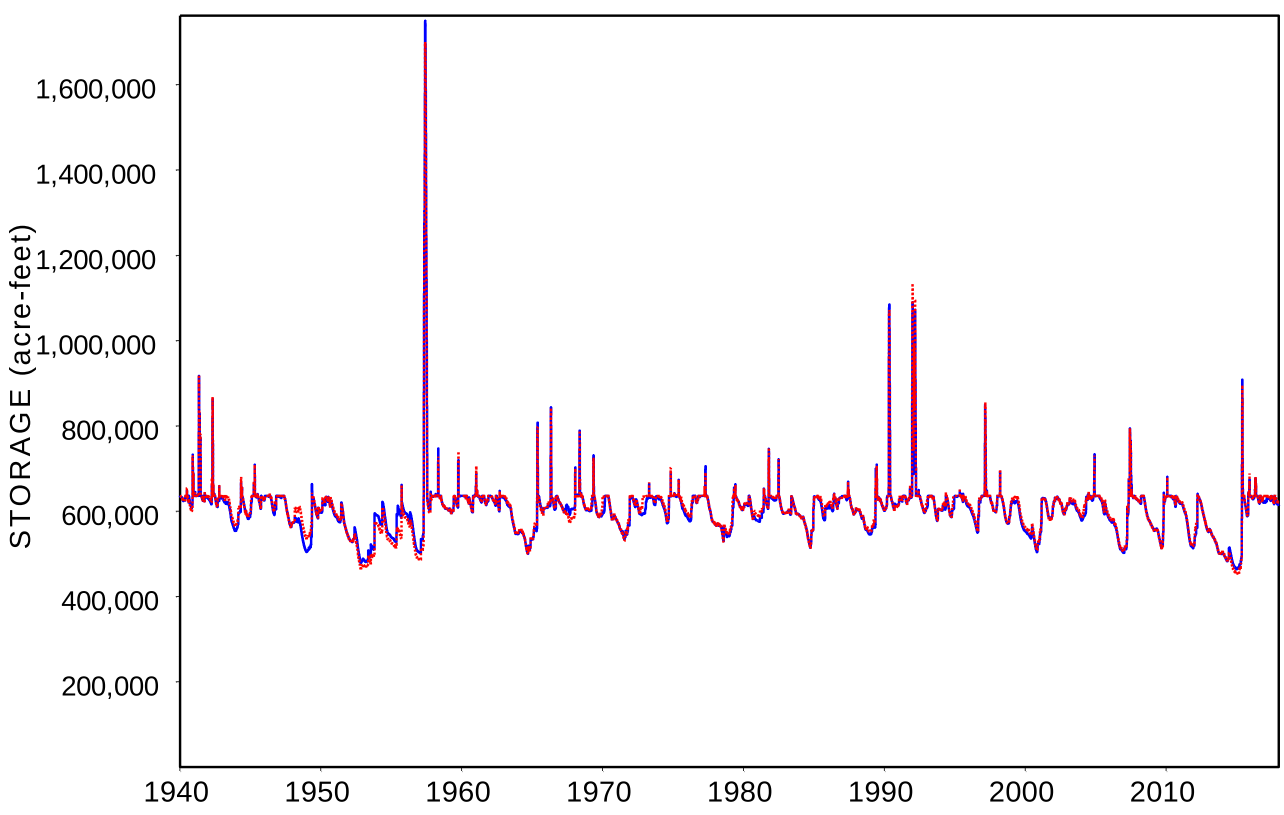

Figure 10.54 Whitney Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

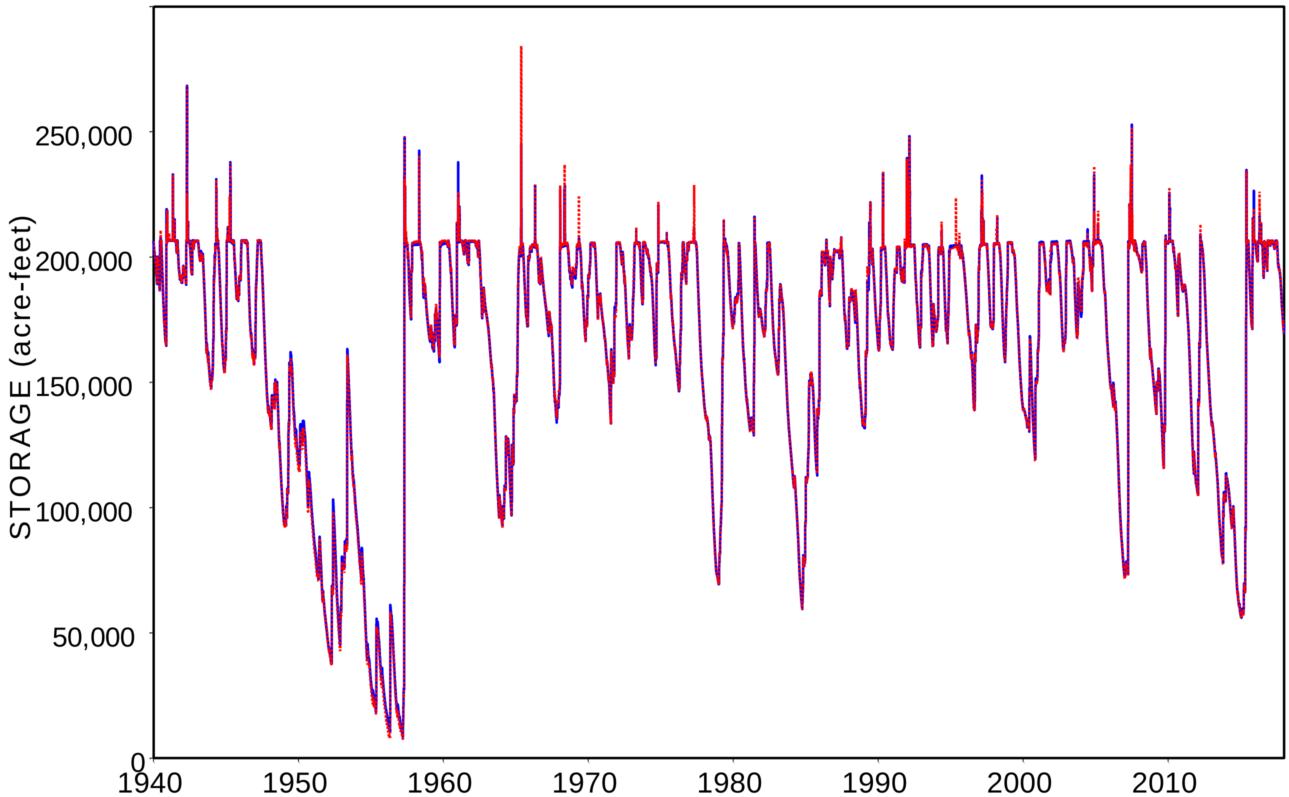

Figure 10.55 Waco Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

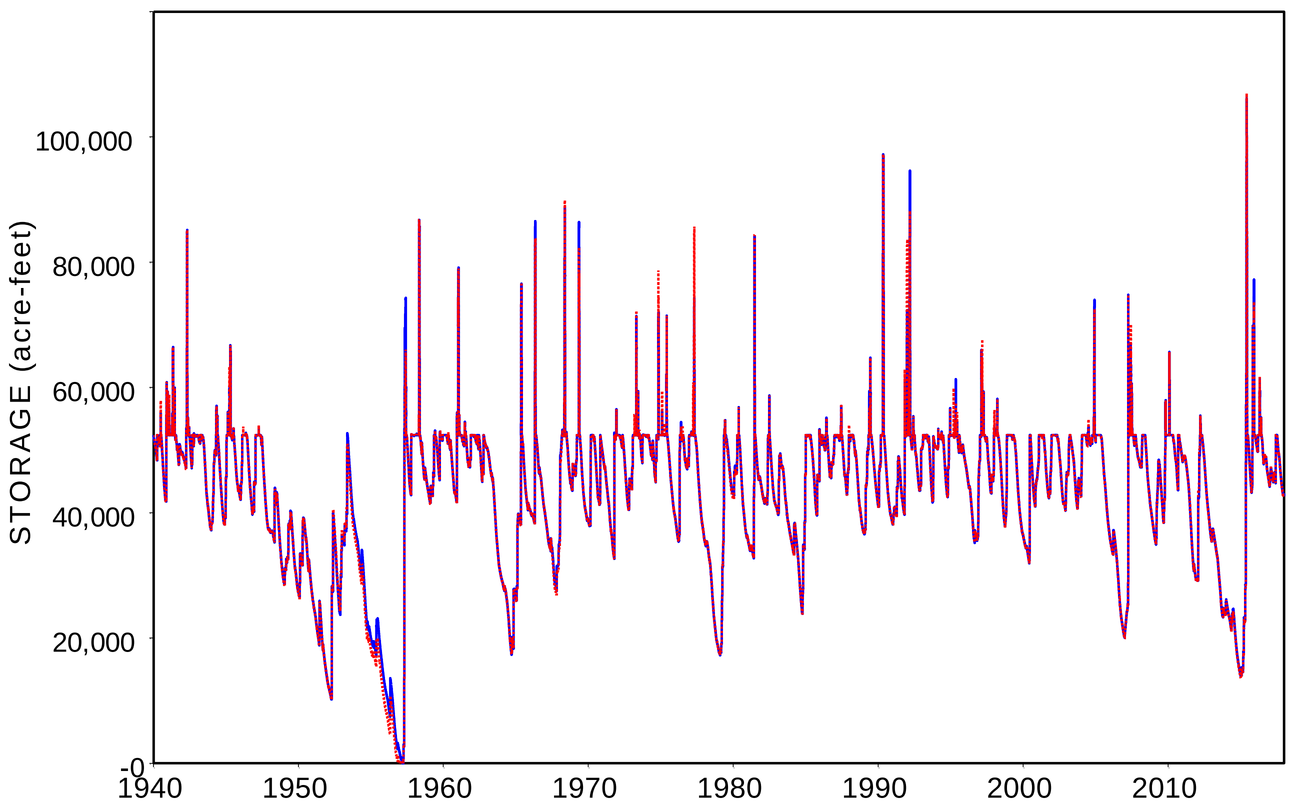

Figure 10.56 Aquilla Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

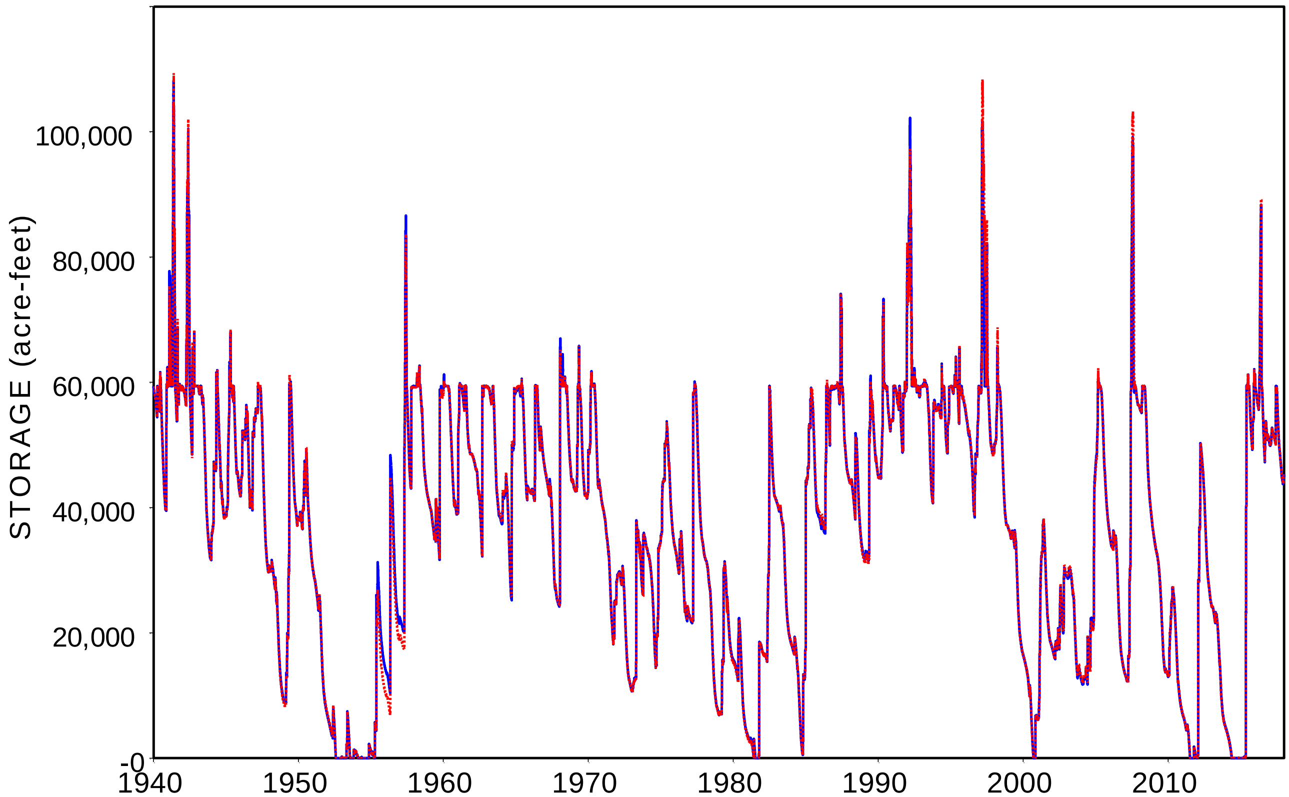

Figure 10.57 Proctor Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

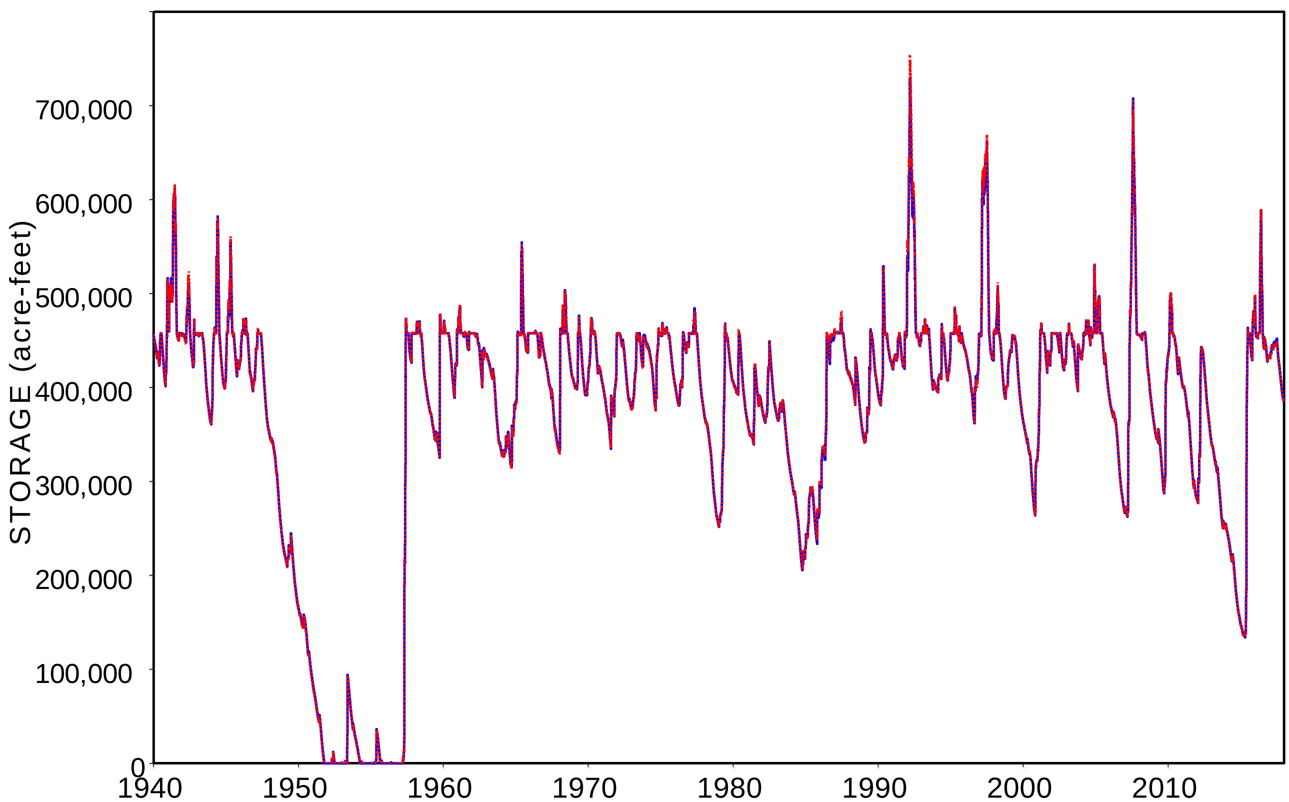

Figure 10.58 Belton Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

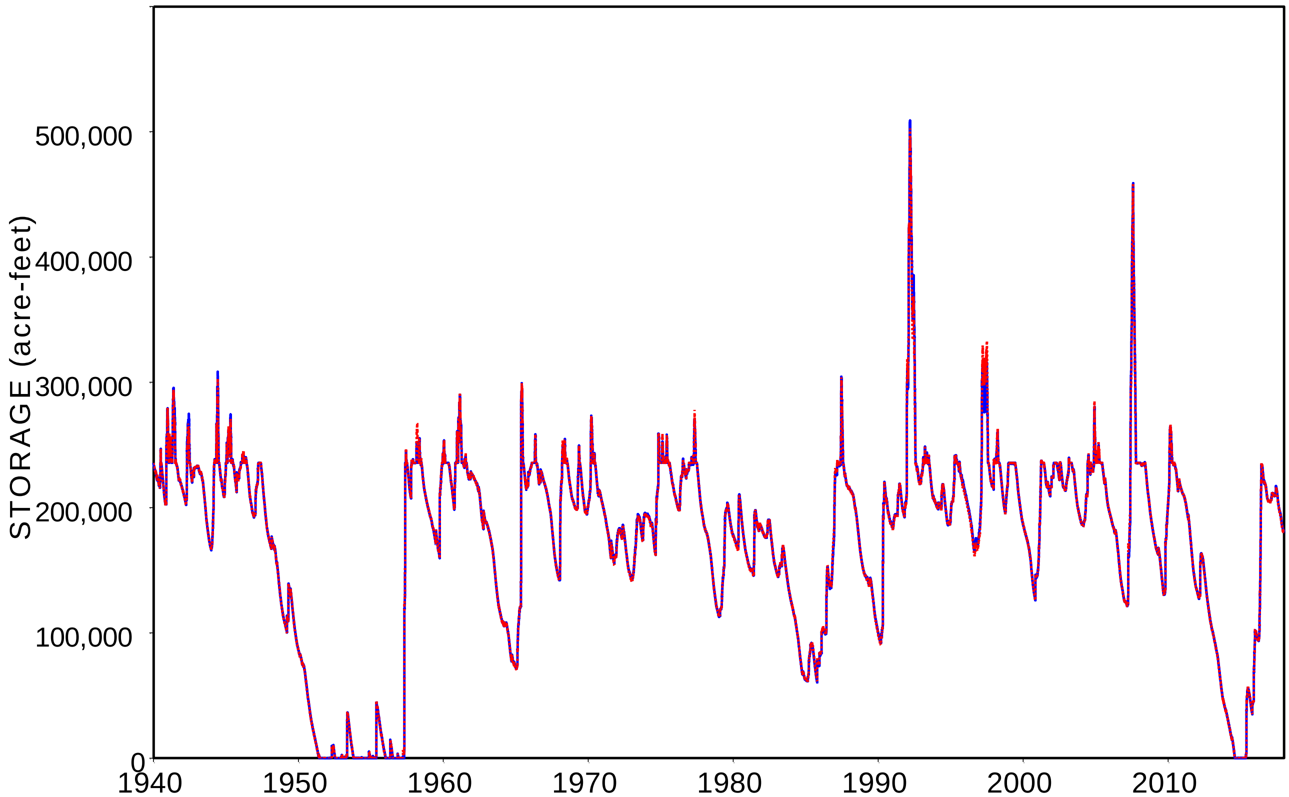

Figure 10.59 Stillhouse Hollow Storage With (blue solid) and Without (red dotted) SB3 EFS

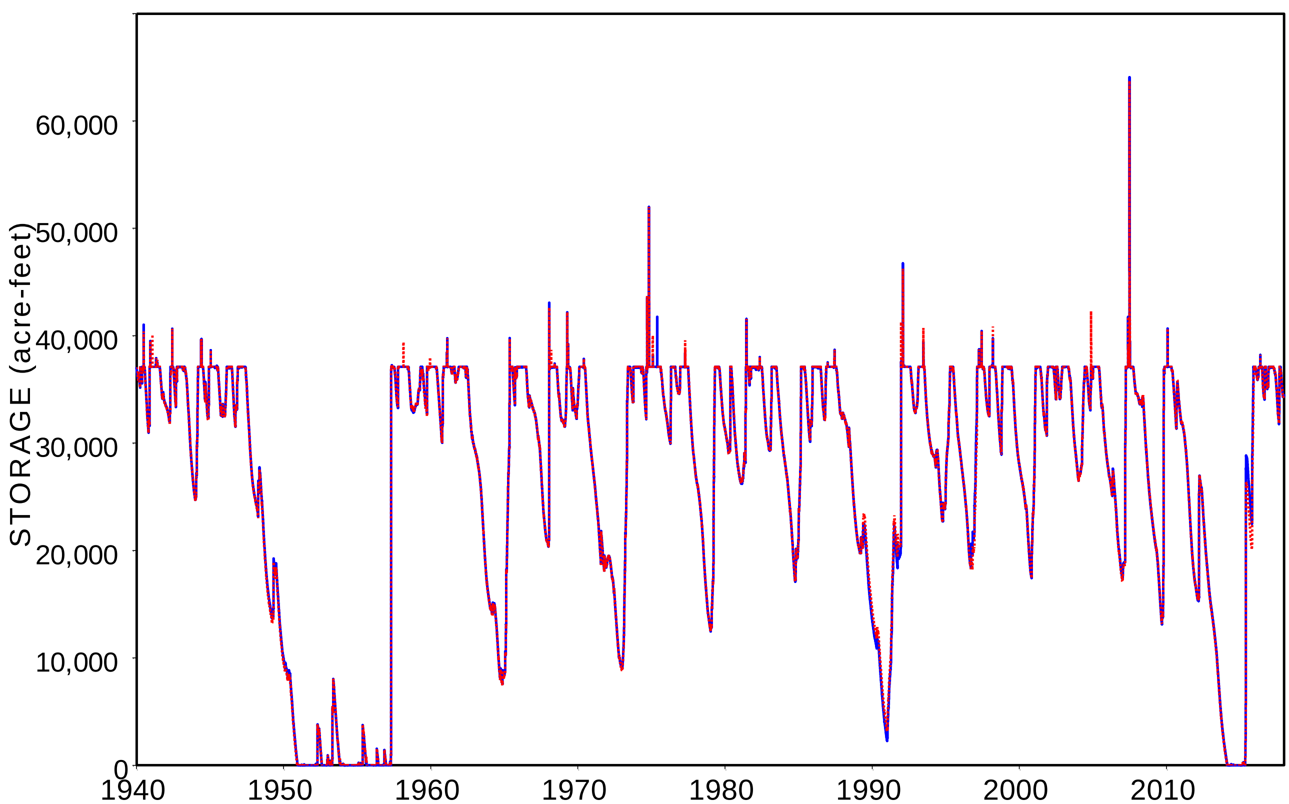

Figure 10.60 Georgetown Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

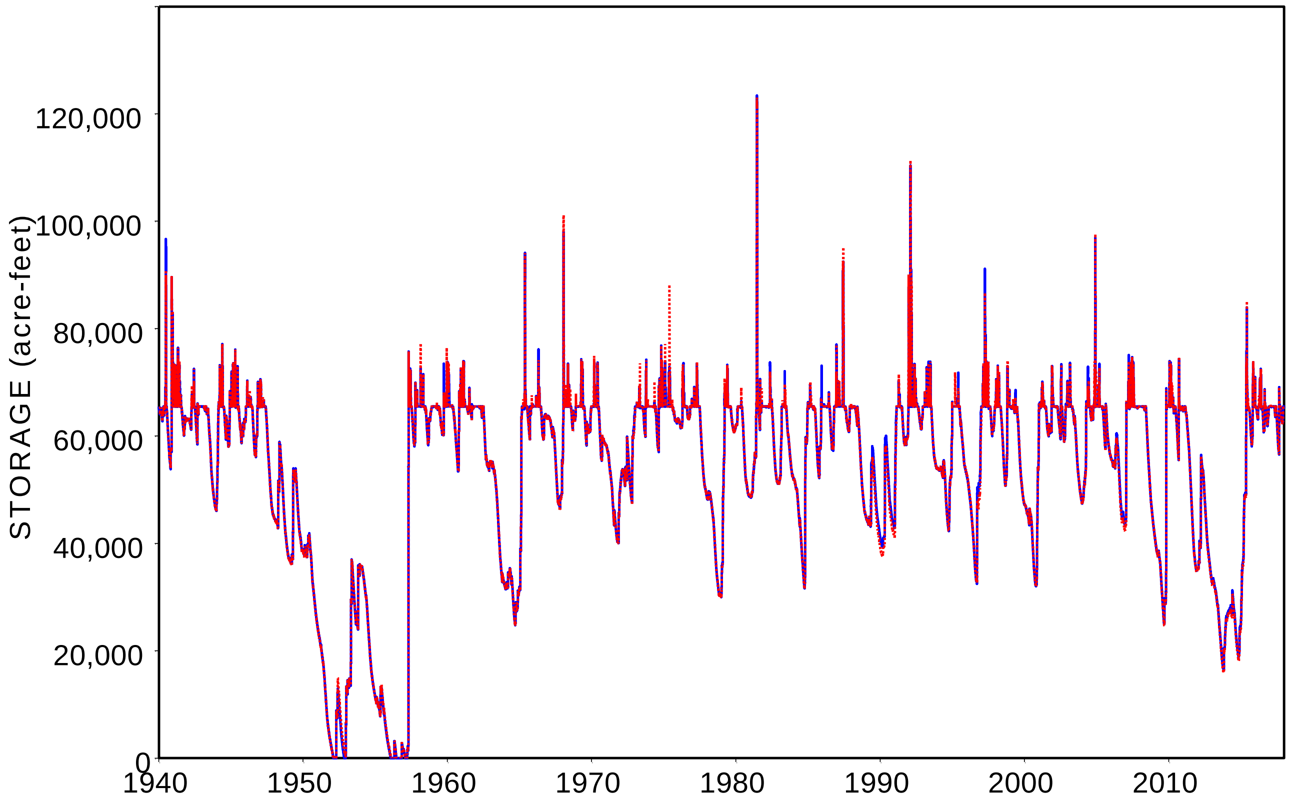

Figure 10.61 Granger Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

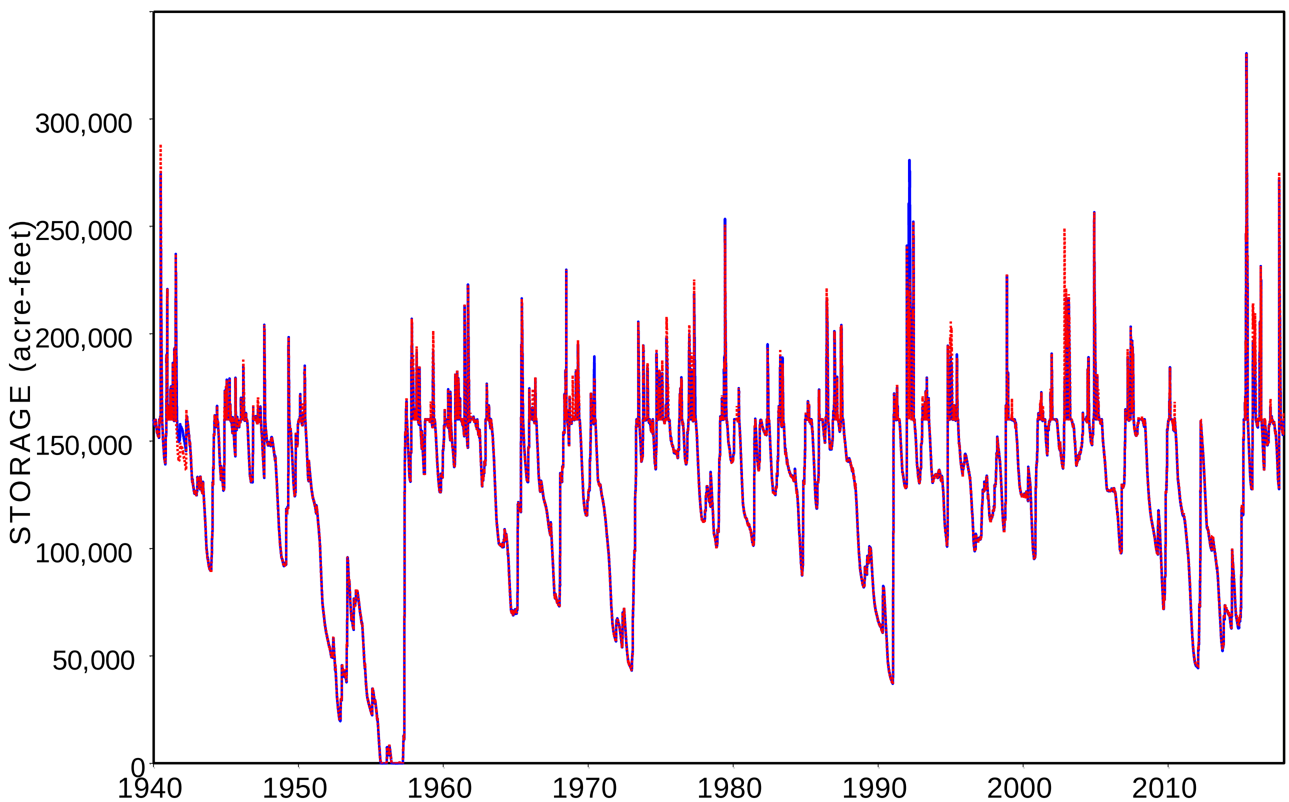

Figure 10.62 Somerville Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

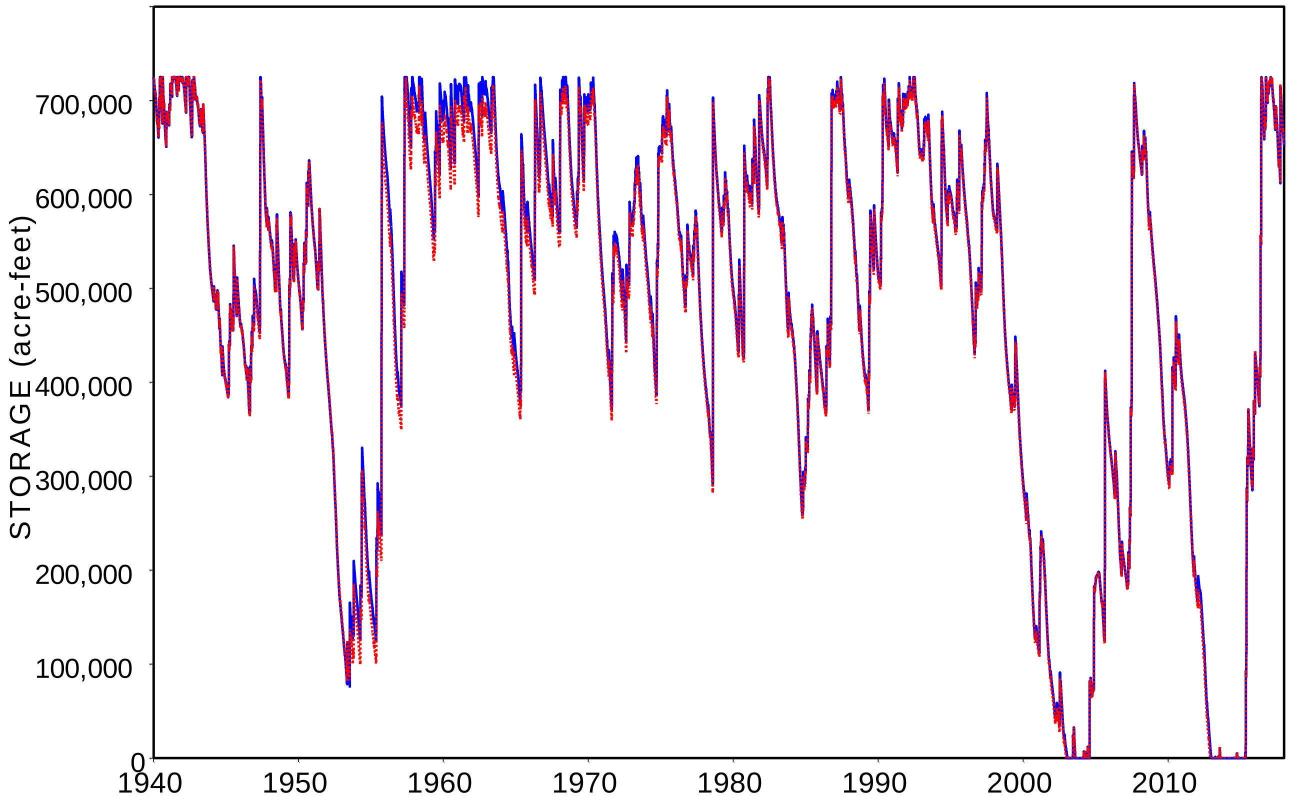

Figure 10.63 Possum Kingdom Storage With (blue solid) and Without (red dotted) SB3 EFS

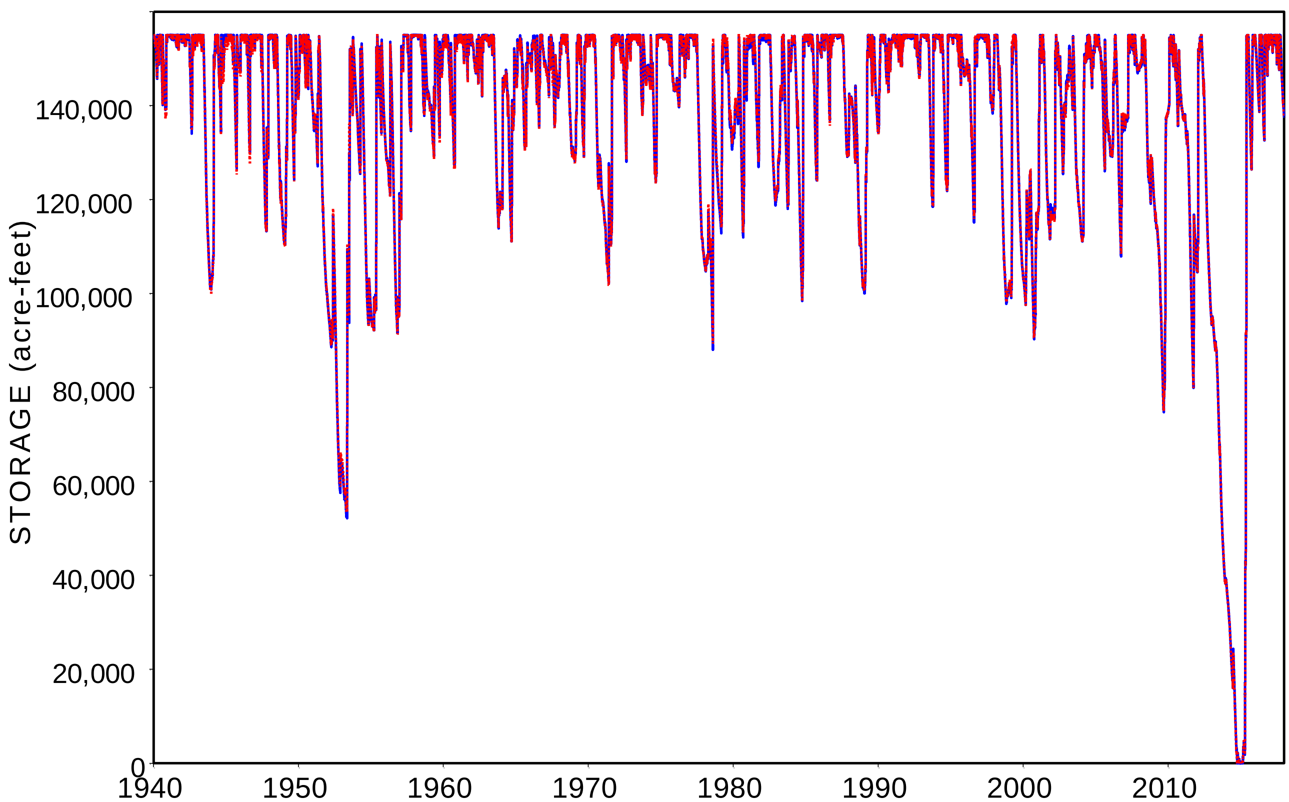

Figure 10.64 Granbury Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

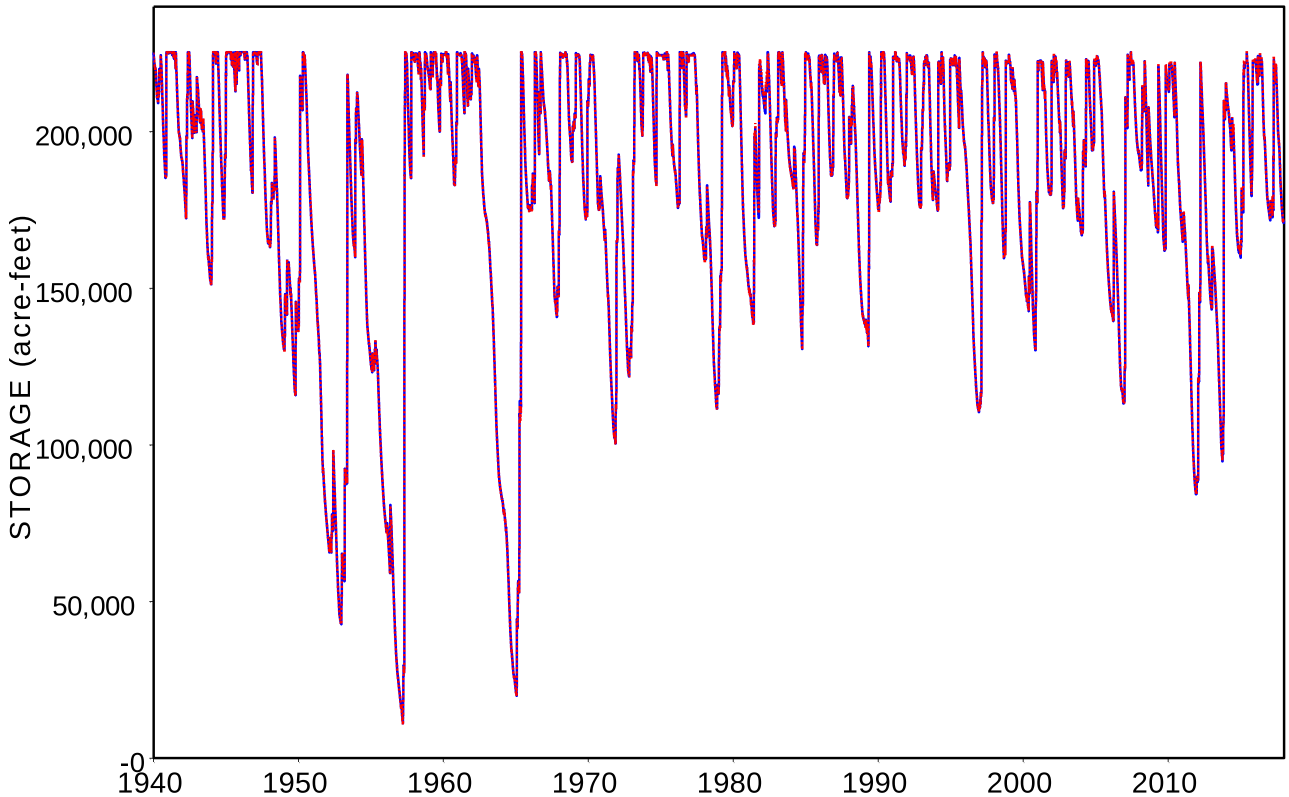

Figure 10.65 Limestone Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

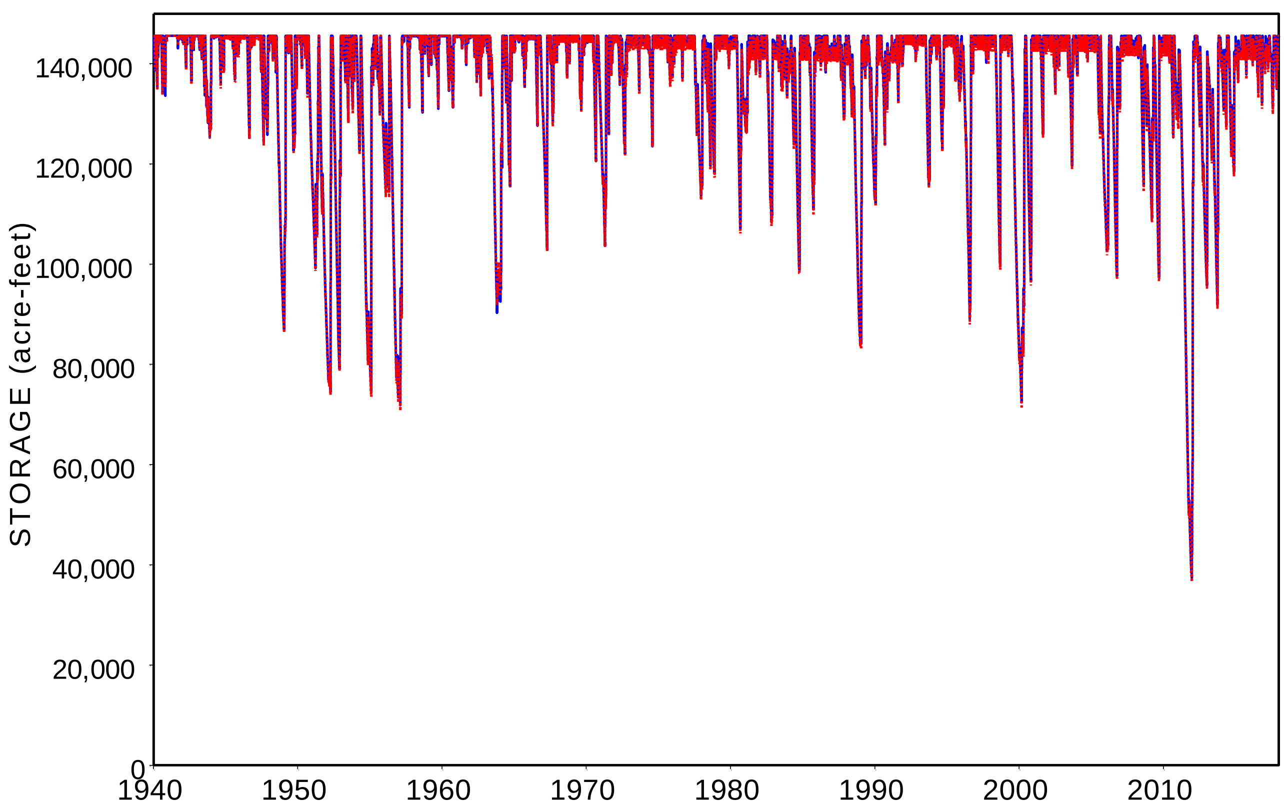

Figure 10.66 Allen's Creek Storage With (blue solid) and Without (red dotted) SB3 EFS

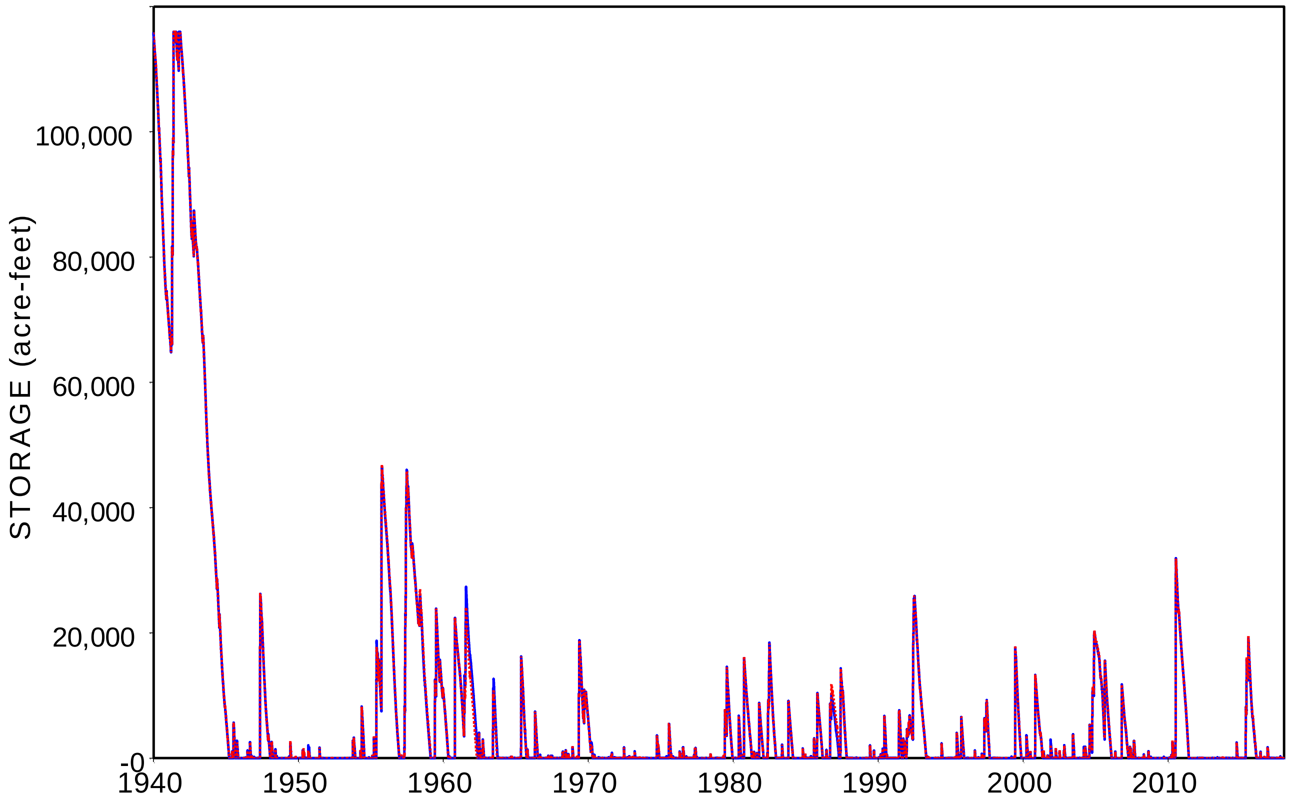

Figure 10.67 Alan Henry Reservoir Storage With (blue solid) and Without (red dotted) SB3 EFS

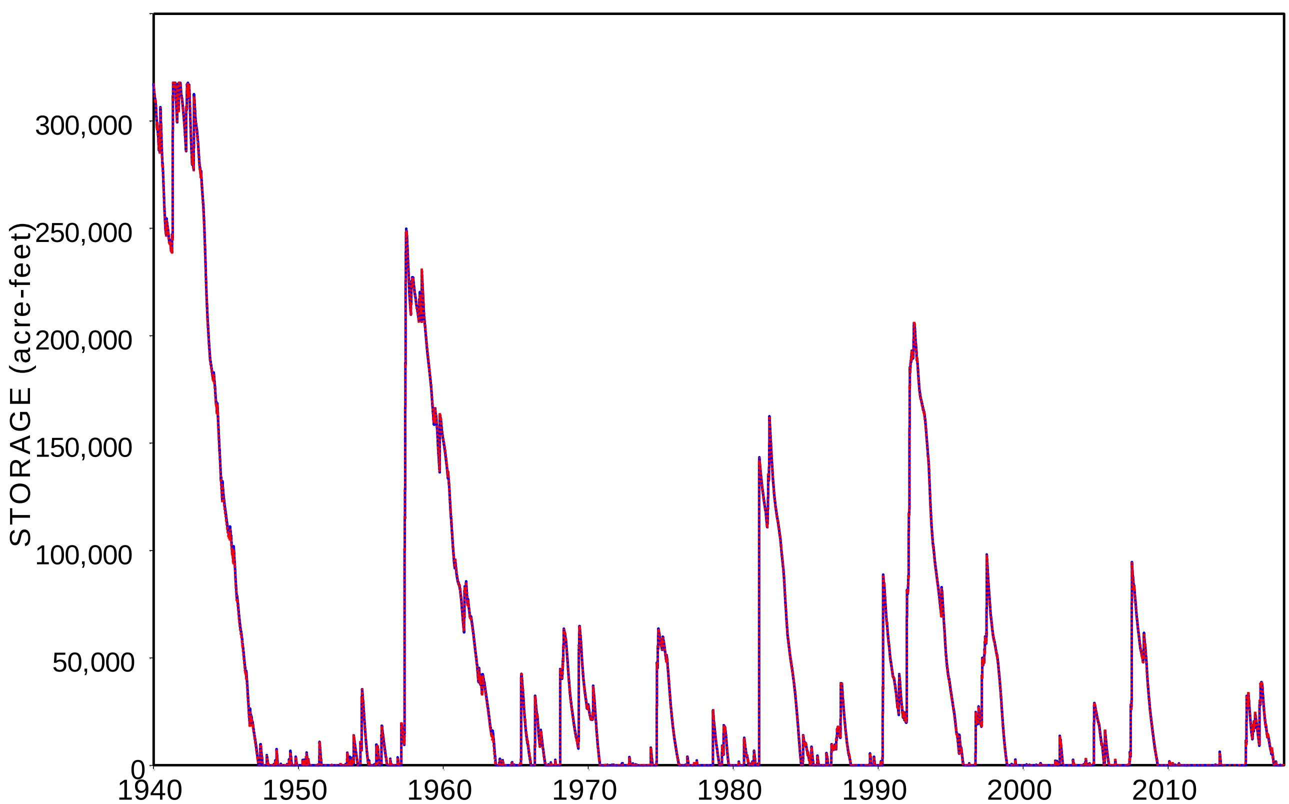

Figure 10.68 Hubbard Creek Storage With (blue solid) and Without (red dotted) SB3 EFS

Final Daily and Monthly WAMs

The daily Brazos WAM can be employed for a variety of different types of applications. This report focuses on applying the daily WAM to develop instream flow targets for the Senate Bill 3 (SB3) environmental flow standards (EFS) for incorporation in the monthly Brazos WAM following the procedure outlined in Chapter 5. The last section of Chapter 10, which follows directly after this section, focuses specifically on SB3 EFS instream flow targets. Based on considerations discussed in the preceding sections of this chapter, simulation D7 is selected as the best modeling strategy for simulating the SB3 EFS. The SB3 EFS instream flow targets generated by simulation D7 are inserted into the monthly WAM (simulation M1) to create the *SIM* input dataset employed in simulation M3. These final recommended daily and monthly versions of the Brazos WAM are employed in simulations D7 and M3, which are defined in Tables 10.2 and 10.3 along with the other alternative simulations discussed in Chapter 10.

The remainder of Chapter 10 focuses on simulations D7 and M3, which employ the daily and monthly versions of the Brazos WAM that are considered to be the final proposed versions for purposes of the study documented by this report. The final recommended daily WAM includes routing, flood control operations, and SB3 EFS, but does not include forecasting. The monthly WAM incorporates SB3 IFS instream flow targets developed with the daily WAM. The sets of *IF*, *HC*, *ES*, and *PF* records that model the 19 sets of SB3 EFS in the daily WAM are replicated in Table 5.8 of Chapter 5. The *IF* and *TS* records in the DAT file of the monthly WAM reproduced in Table 5.10 reference *TS* record target sequences stored in the DSS input file as DSS records with the pathnames listed in Table 5.9.

Statistical frequency metrics and time series plots for observed, naturalized, regulated, and unappropriated flows and instream flow targets and shortages at selected WAM control points representing sites of USGS gaging stations and SB3 EFS are presented in this chapter. Daily means of observed flows at USGS gaging stations were downloaded from the National Water Information System (NWIS) website maintained by the USGS. The WAM hydrology input dataset includes the monthly and daily naturalized flows discussed in Chapters 6 and 7. Regulated and unappropriated stream flows for each month and/or day of the 1940-2017 hydrologic period-of-analysis at each of the over 3,800 control points are computed in each *SIM* or *SIMD* simulation.

Stream flow statistics for all 12 alternative simulations are tabulated in Tables 10.6 and 10.7. Reservoir storage frequency metrics are presented in Table 10.8. Means of SB3 EFS targets and shortages are compared in the preceding Table 10.9 and in other tables presented later. Averages of 936 monthly flow means are compared with averages of 28,490 mean daily flows. The daily instream flow targets plotted in later in this chapter in Figures 10.92-10.112 were summed to monthly totals within the *SIMD* simulation (D7) and incorporated in the input read by the monthly simulation (M3).

Monthly flow volumes in acre-feet/month are computed in *SIM* simulations. Daily volumes in acre-feet/day are computed in daily *SIMD* simulations. *SIMD* sums the simulated daily flow volumes in acre-feet/day to monthly volumes in acre-feet/month and records both daily and monthly quantities in its output files.

The tables and plots of this chapter switch between flow volumes in acre-feet per day, month, or year and mean flow rates in cubic feet per second (cfs) during days, months, or years. One acre-foot per day is equivalent to exactly 0.50416667 cubic feet per second (cfs). An acre-foot/month is equal to approximately 0.0165639 cfs, realizing that months have different numbers of days. The number of days in each month (28, 29 for leap years, 30, or 31 days) are considered in *SIMD*, *TABLES*, and *HEC-DSSVue* computations and, in this chapter, in precisely converting between monthly and daily flow rates in individual months and days. Regardless of the units used, 1940-2017 period-of-analysis averages of 936 monthly flows versus 1940-2017 period-of-analysis averages of 28,490 daily flows vary slightly due to the differences in the number of days in the months of the year.

Simulated end-of-day reservoir storage contents from the daily *SIMD* simulation D7 and end-of-month storage contents from the monthly *SIM* simulation M3 for the 15 large reservoirs are compared in Figures 10.77 through 10.91. Encroachments into the flood control pools of the nine USACE reservoirs of course occurs only in the daily model. The comparisons indicate generally reasonable model behavior. As noted earlier in this chapter, the over-appropriated Alan Henry and Hubbard Creek Reservoirs on tributaries in the dry upper basin are empty or almost empty throughout most of the 1940-2017 hydrologic period-of-analysis in all of the simulations. The differences between D7 and M3 simulated storages are large in these two reservoirs. The differences in Possum Kingdom Reservoir on the upper Brazos River are also large. The daily D7 and monthly M3 conservation pool storage plots match closest for Limestone Reservoir and, with the exceptions of Alan Henry and Hubbard Creek Reservoirs, are reasonably close for the other reservoirs.

In general, as discussed earlier in this chapter, the daily model is expected to more severely constrain stream flow availability for refilling storage and supplying water right targets than the monthly model. The storage plots show this to be the case for the majority of the reservoirs. Draw-downs in most of the reservoirs tend to be greater in the daily than the monthly simulation. However, the draw-downs in Lakes Granbury and Allen Creek are greater in the monthly than the daily model.

The plots of Figures 10.69, 10.71, 10.73, and 10.75 of January 1, 1940 through December 31, 2017 daily regulated flow from simulation D7 illustrate the tremendous variability of stream flow at these sites and throughout the Brazos River Basin and state of Texas. The plots of simulation D7 annual volumes of observed, naturalized, simulated regulated and unappropriated stream flows and SB3 EFS instream flow targets and shortages of Figures 10.70, 10.72, 10.74, and 10.76 provide a visual comparison of the relative magnitude of these quantities and their great variation of time.

The legend for Figures 10.70, 10.72, 10.74, and 10.76 is as follows.

blue solid line	1920-2018 annual observed flows at USGS gaging stations (ac-ft)
red dotted line	1940-2017 annual naturalized flow volumes (acre-feet)
green dashed	1940-2017 annual regulated flow volumes (acre-feet)
purple dotted	1940-2017 annual unappropriated flow volumes (acre-feet)
black solid	1940-2017 annual SB3 EFS instream flow targets (acre-feet)
dark red dotted	1940-2017 annual SB3 EFS instream flow shortages (acre-feet)

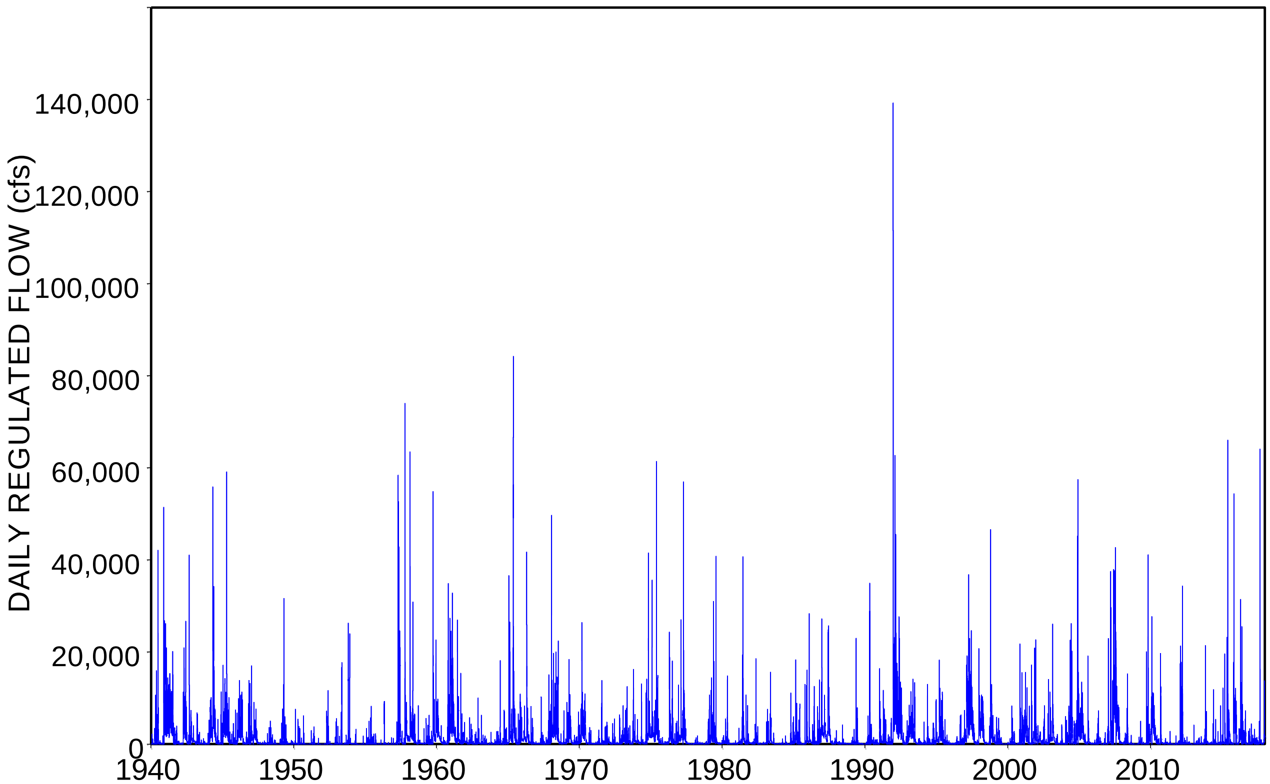

Figure 10.69 Daily Regulated Flow (cfs) of Little River at Cameron (Control Point LRCA58)

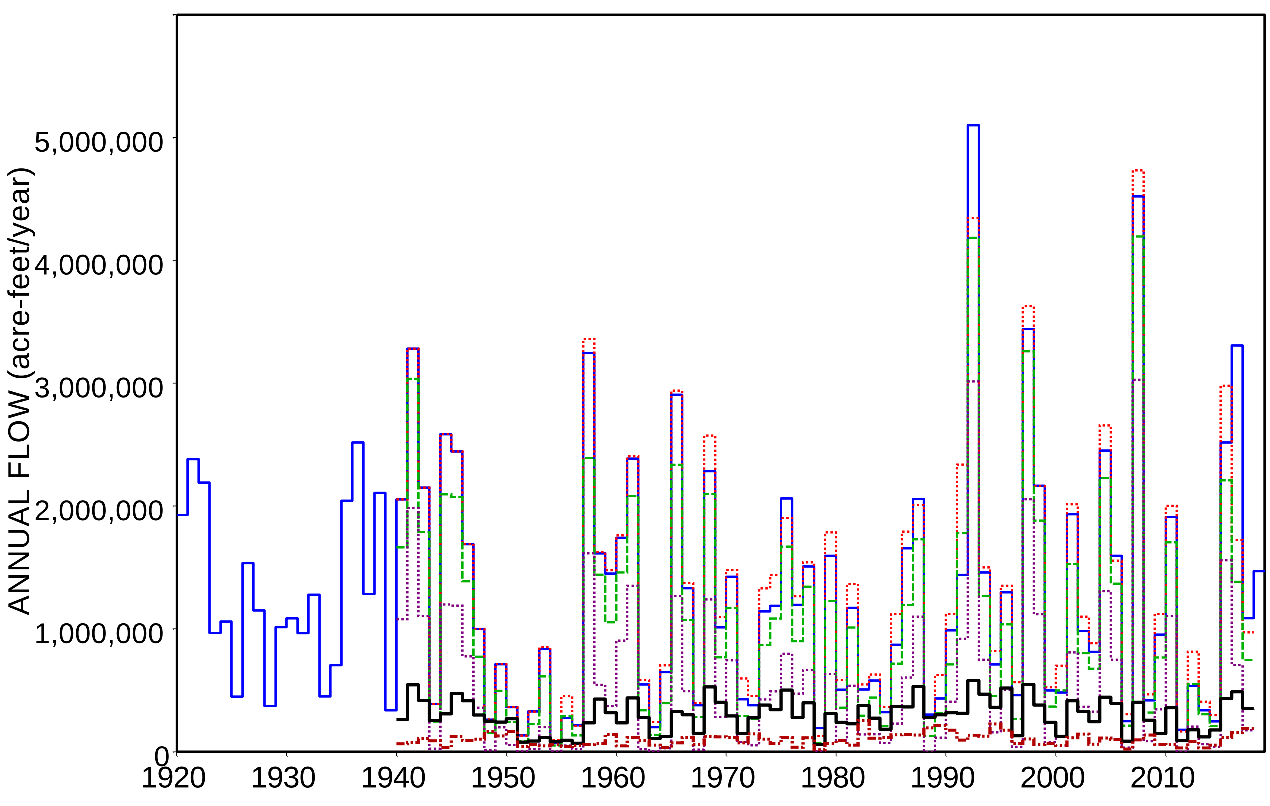

Figure 10.70 Annual Flow and SB3 EFS Target and Shortage Volumes (acre-feet) at LRCA58

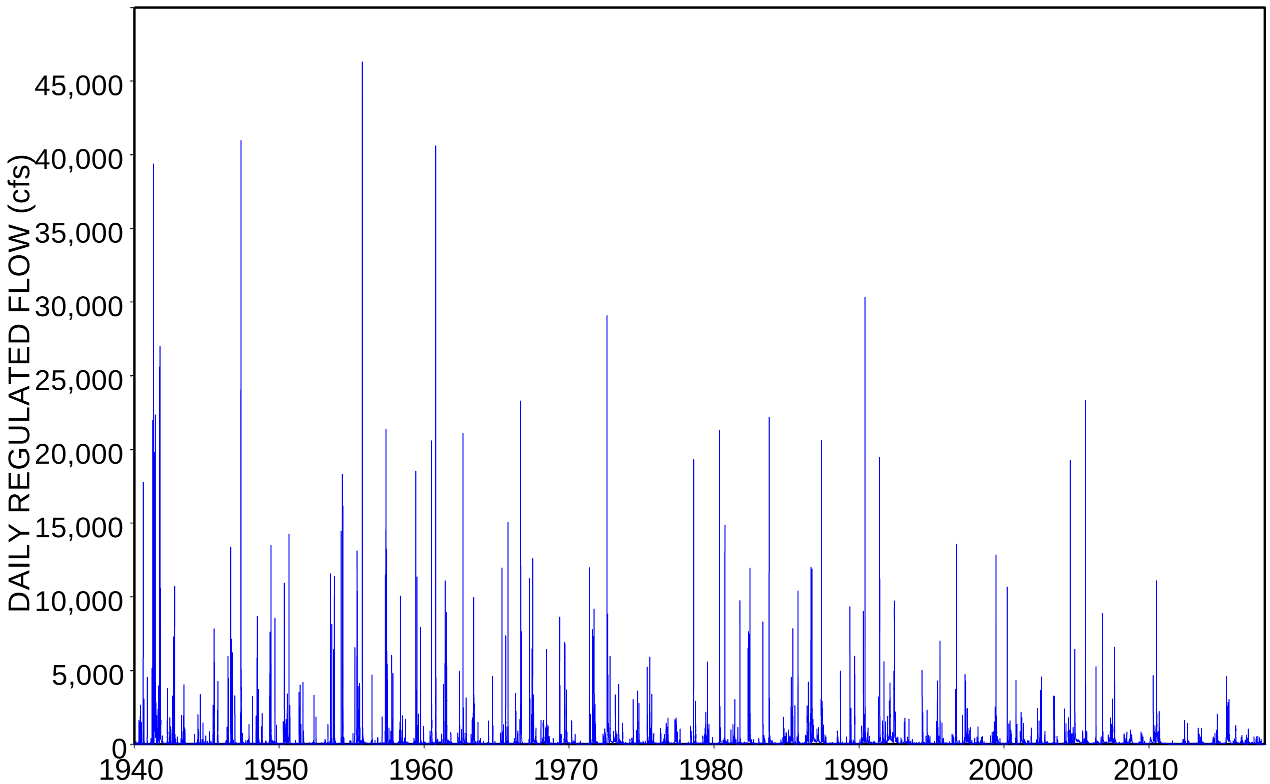

Figure 10.71 Daily Regulated Flow (cfs) of Brazos River at Seymour (Control Point BRSE11)

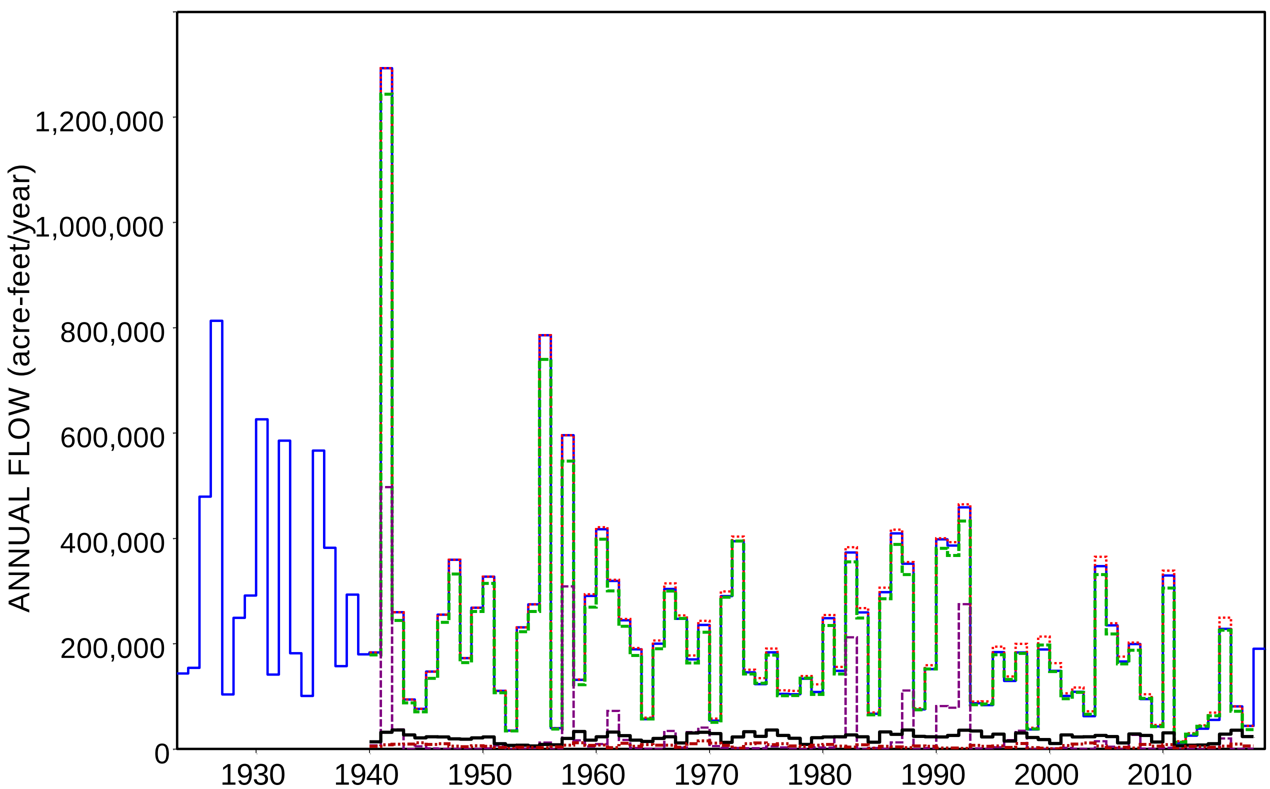

Figure 10.72 Annual Flow and SB3 EFS Target and Shortage Volumes (acre-feet) at BRSE11

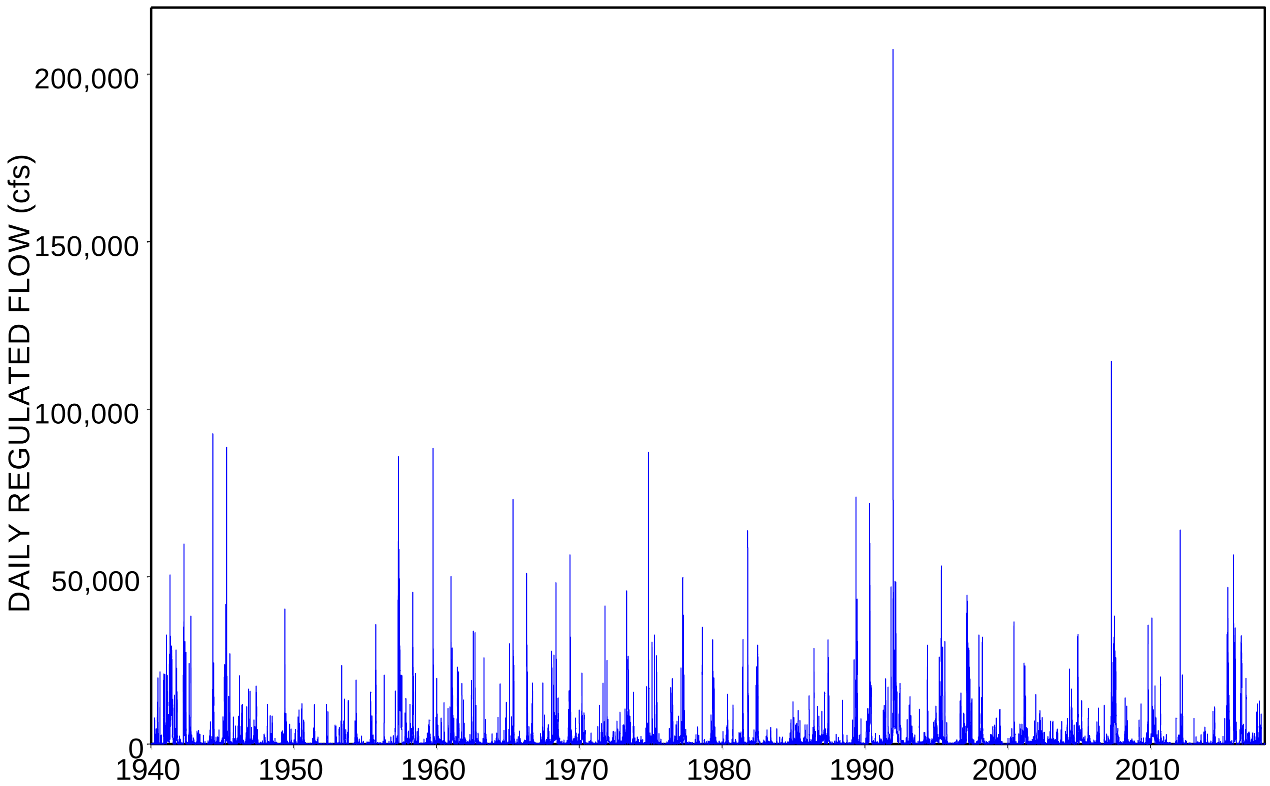

Figure 10.73 Daily Regulated Flow (cfs) of Brazos River at Waco (Control Point BRWA41)

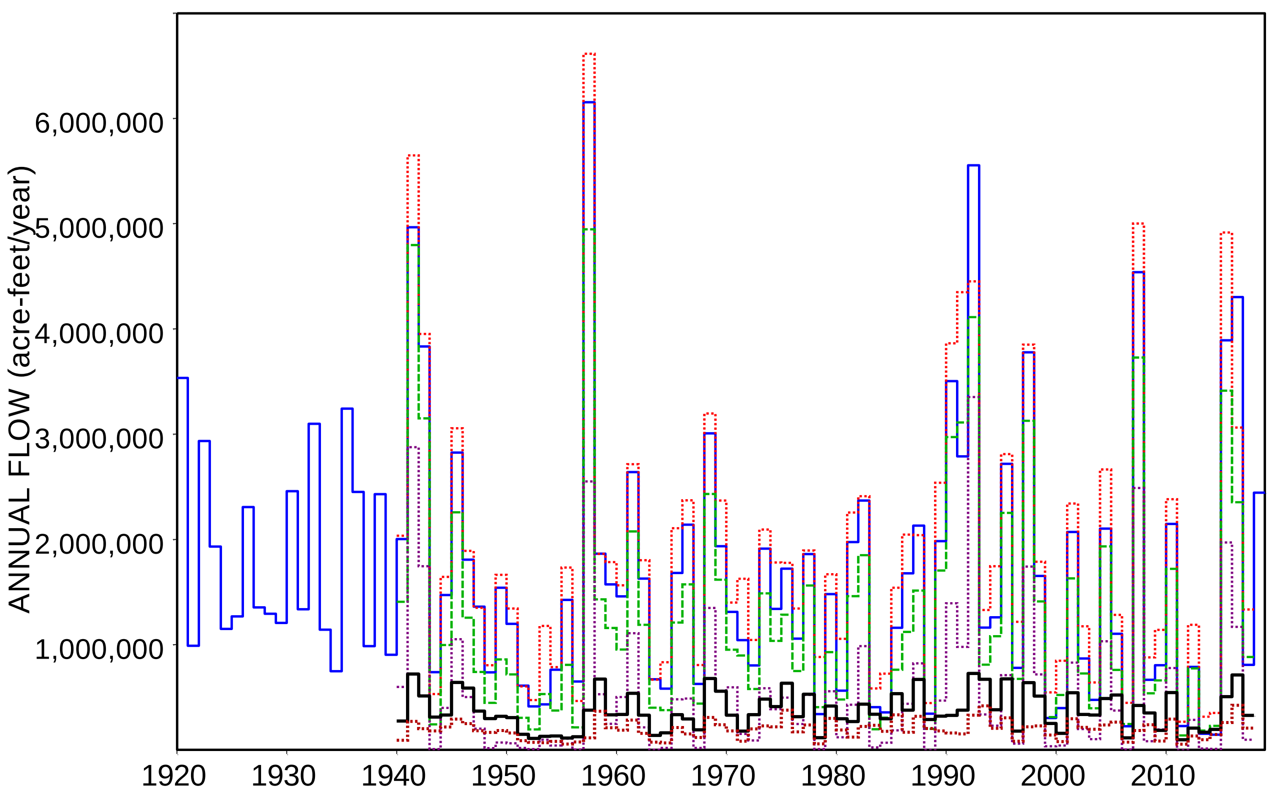

Figure 10.74 Annual Flow and SB3 EFS Target and Shortage Volumes (acre-feet) at BRWA41

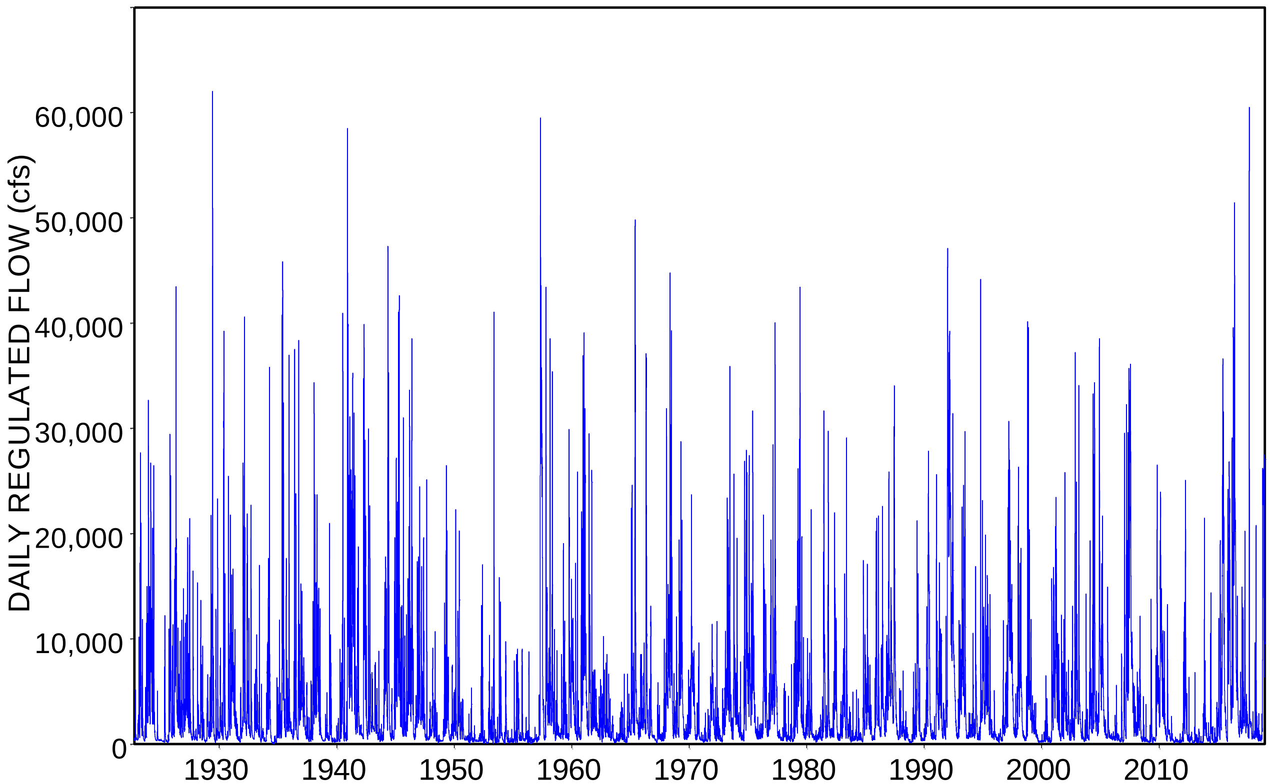

Figure 10.75 Daily Regulated Flow (cfs) of Brazos River at Richmond (Control Point BRRI70)

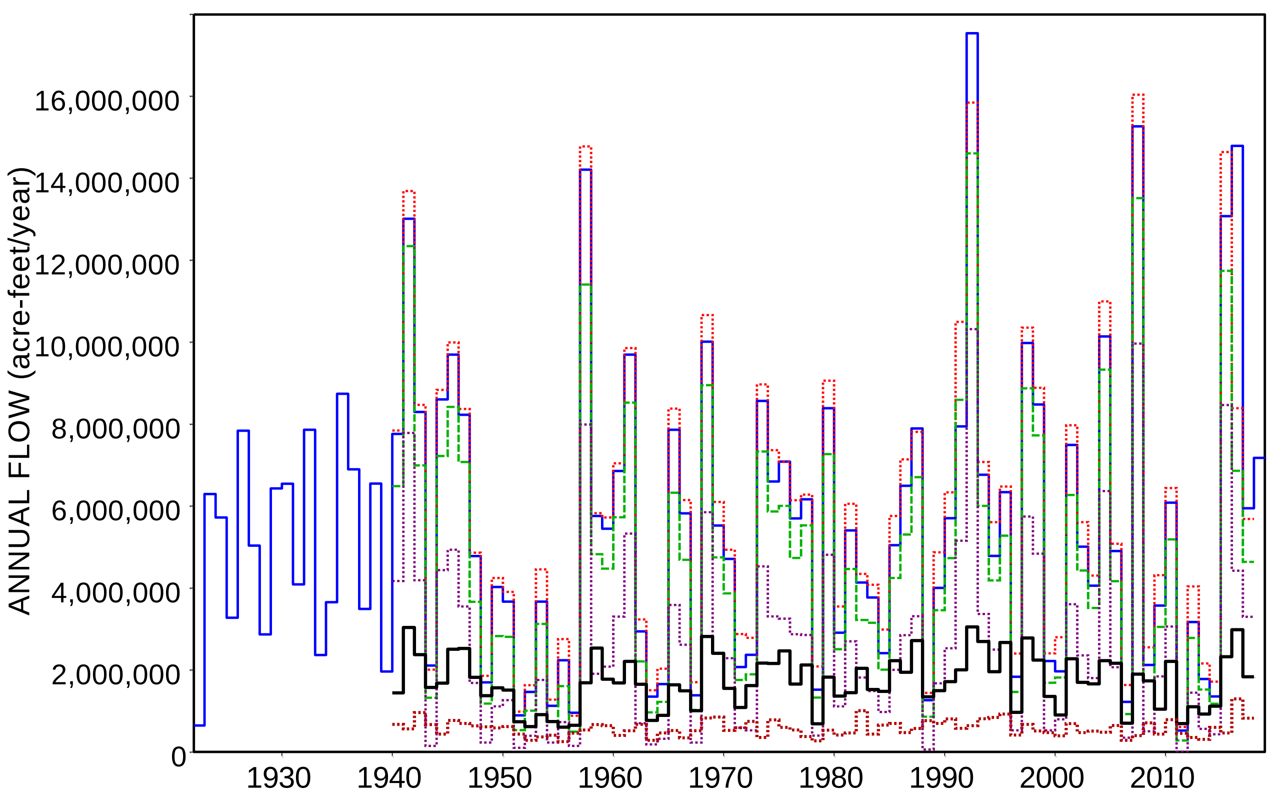

Figure 10.76 Annual Flow and SB3 EFS Target and Shortage Volumes (acre-feet) at BRRI70

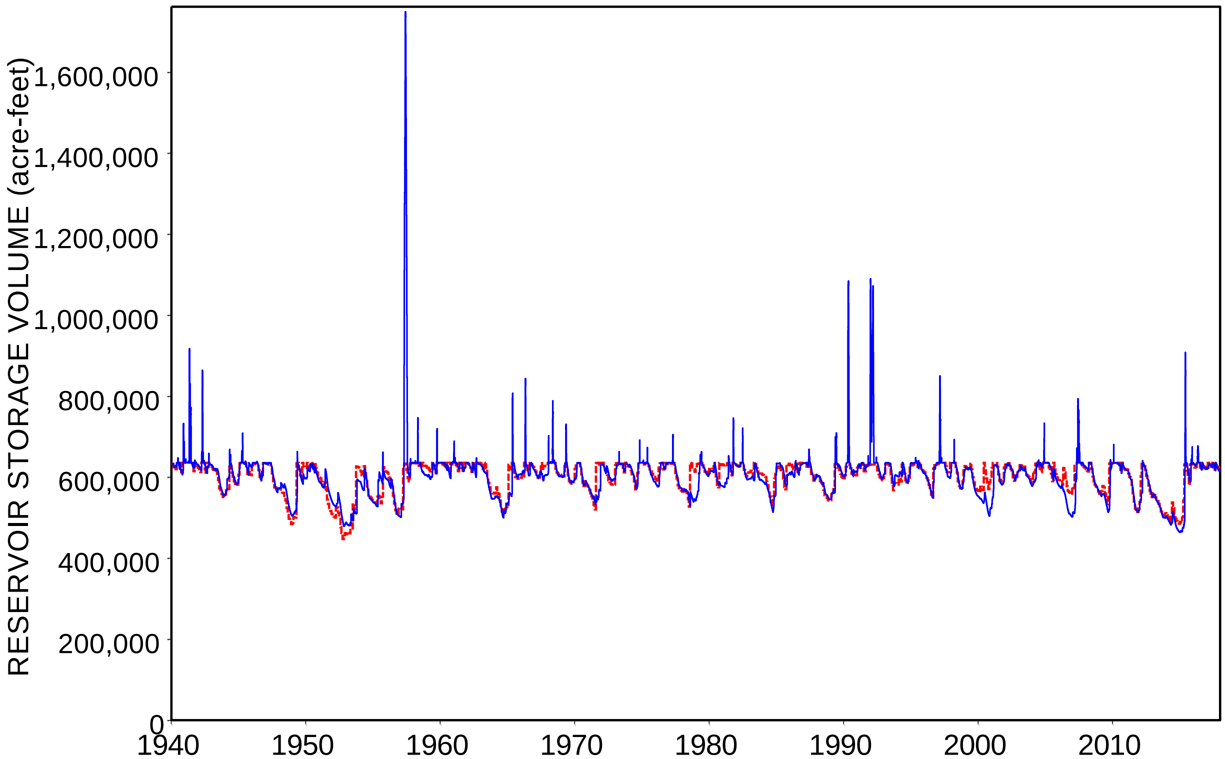

Figure 10.77 Whitney Reservoir Storage for Daily D7 (blue solid line) and Monthly M3 (red dashed line) Simulations

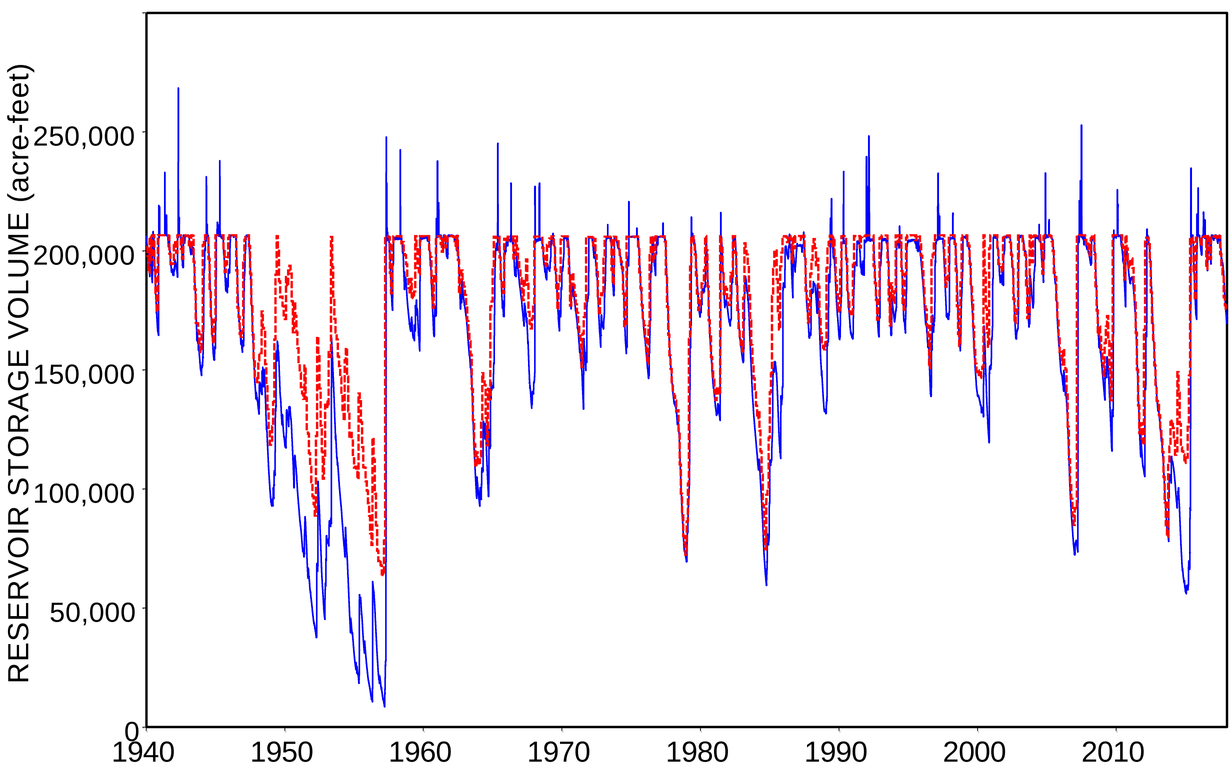

Figure 10.78 Waco Reservoir Storage for Daily D7 (blue solid line) and Monthly M3 (red dashed line) Simulations

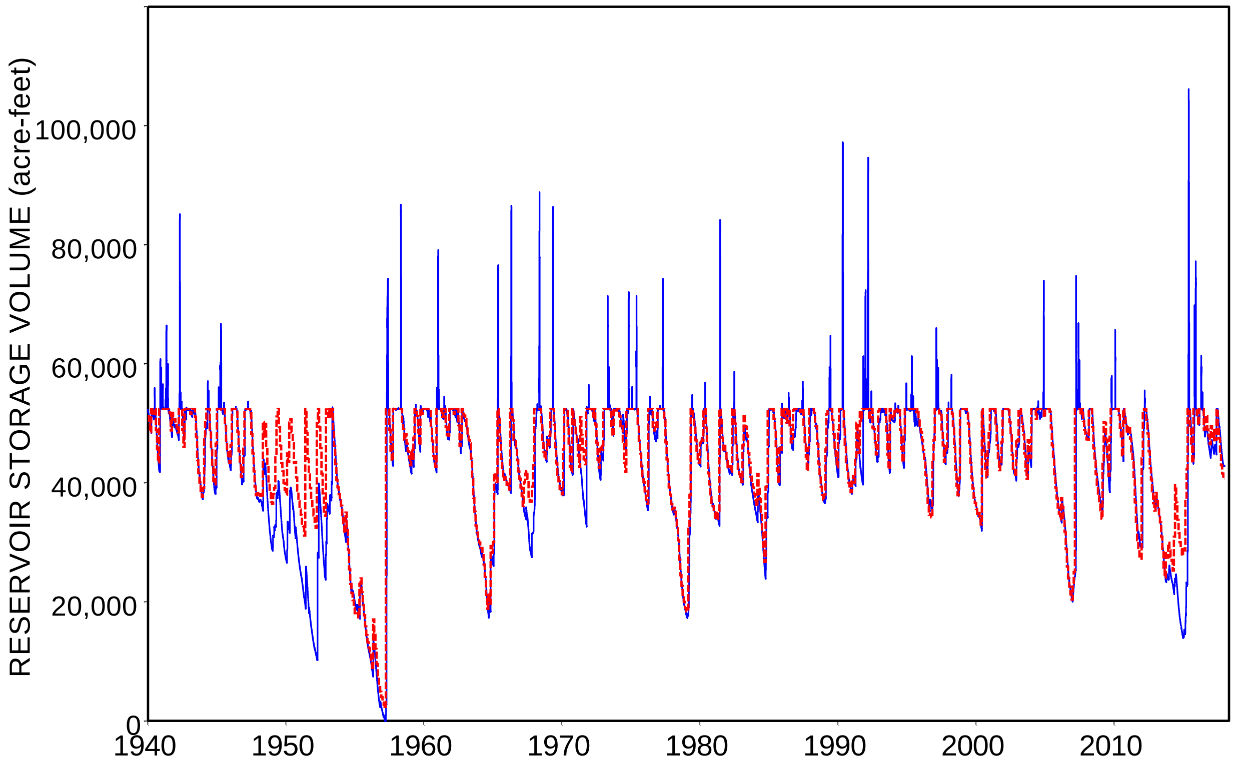

Figure 10.79 Aquilla Reservoir Storage for Daily D7 (blue solid)
and Monthly M3 (red dashed line) Simulations

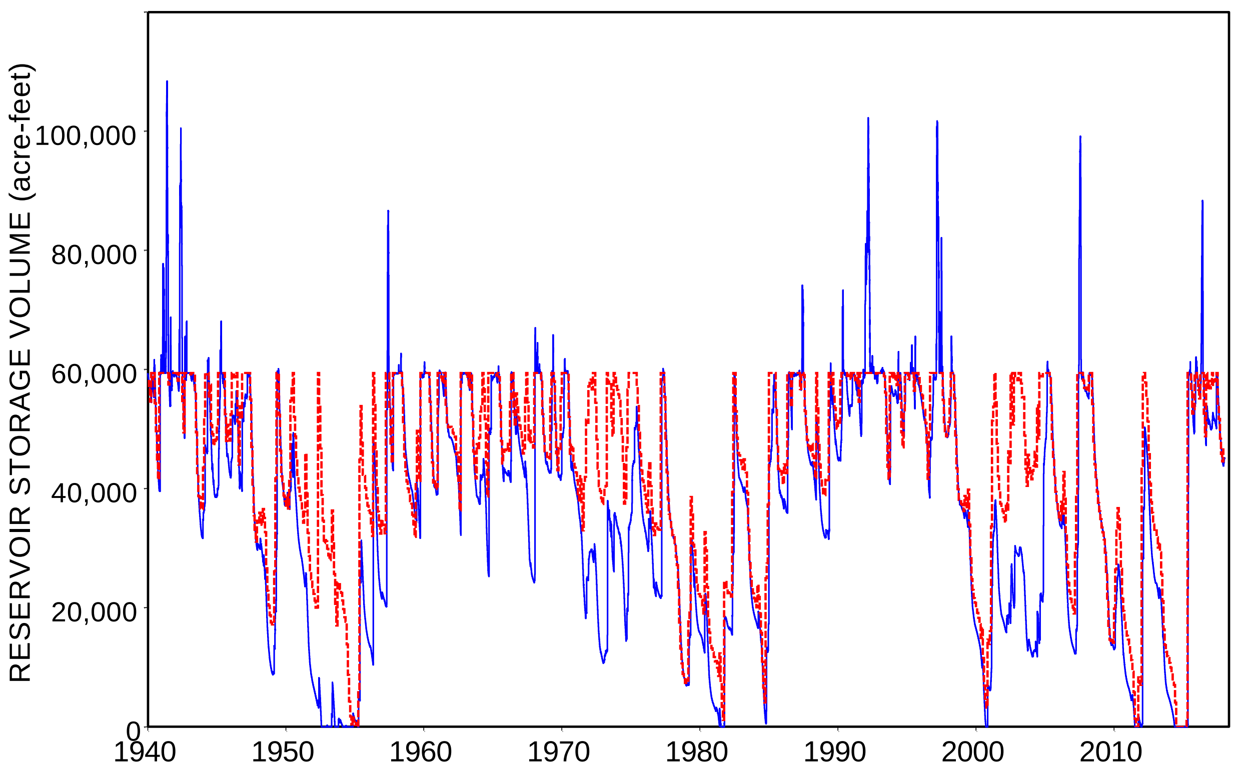

Figure 10.80 Proctor Reservoir Storage for Daily D7 (blue solid)
and Monthly M3 (red dashed) Simulations

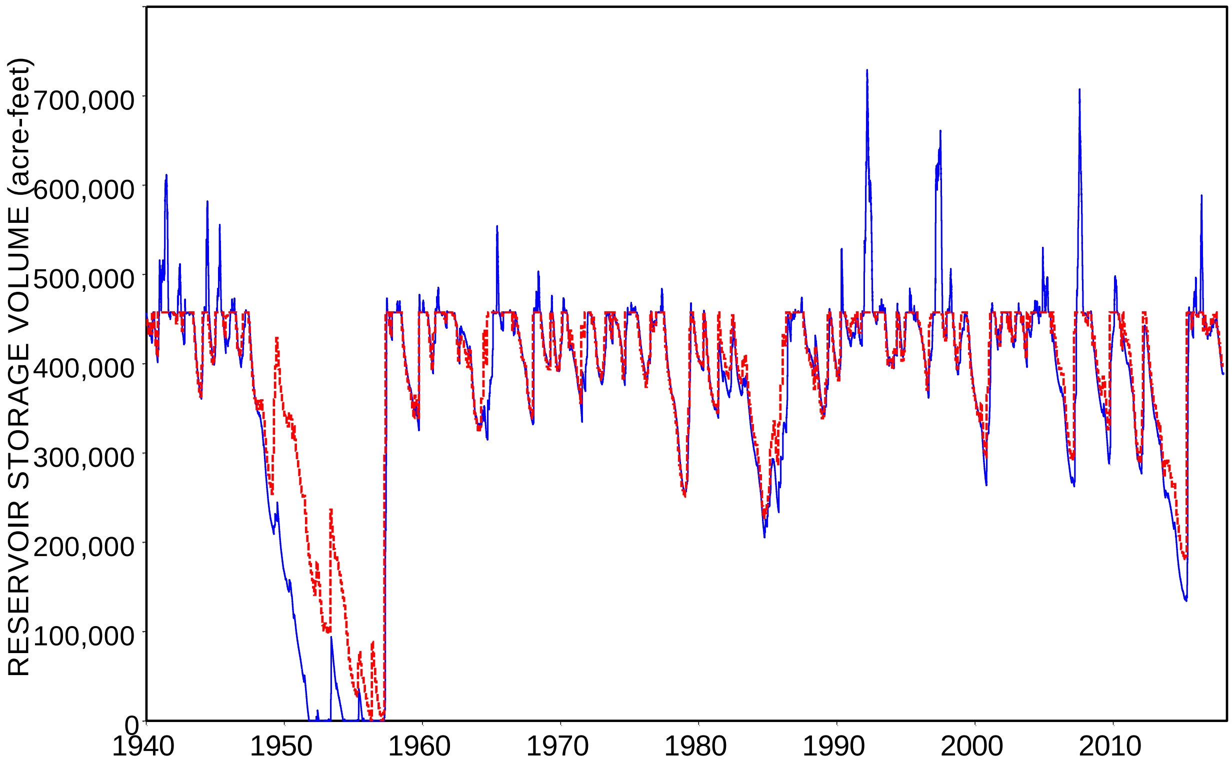

Figure 10.81 Belton Reservoir Storage for Daily D7 (blue solid)
and Monthly M3 (red dashed) Simulations

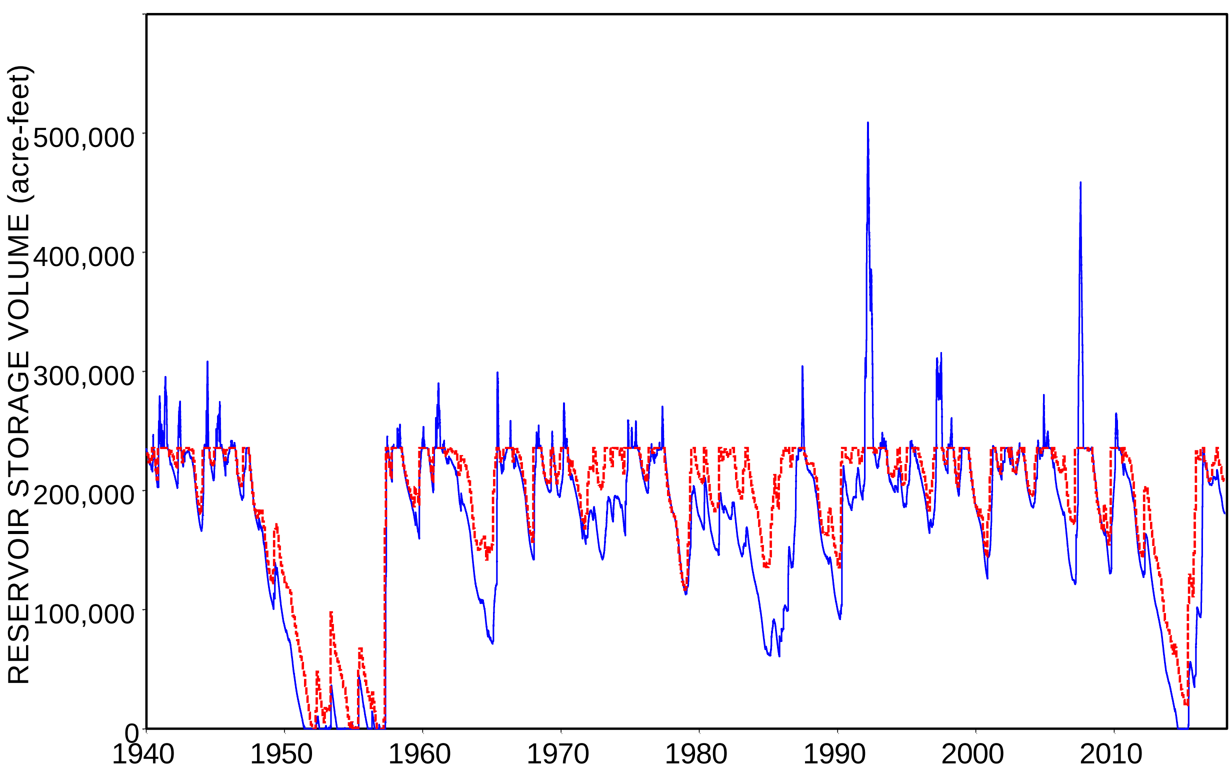

Figure 10.82 Stillhouse Hollow Storage for Daily D7 (blue solid)
and Monthly M3 (red dashed) Simulations

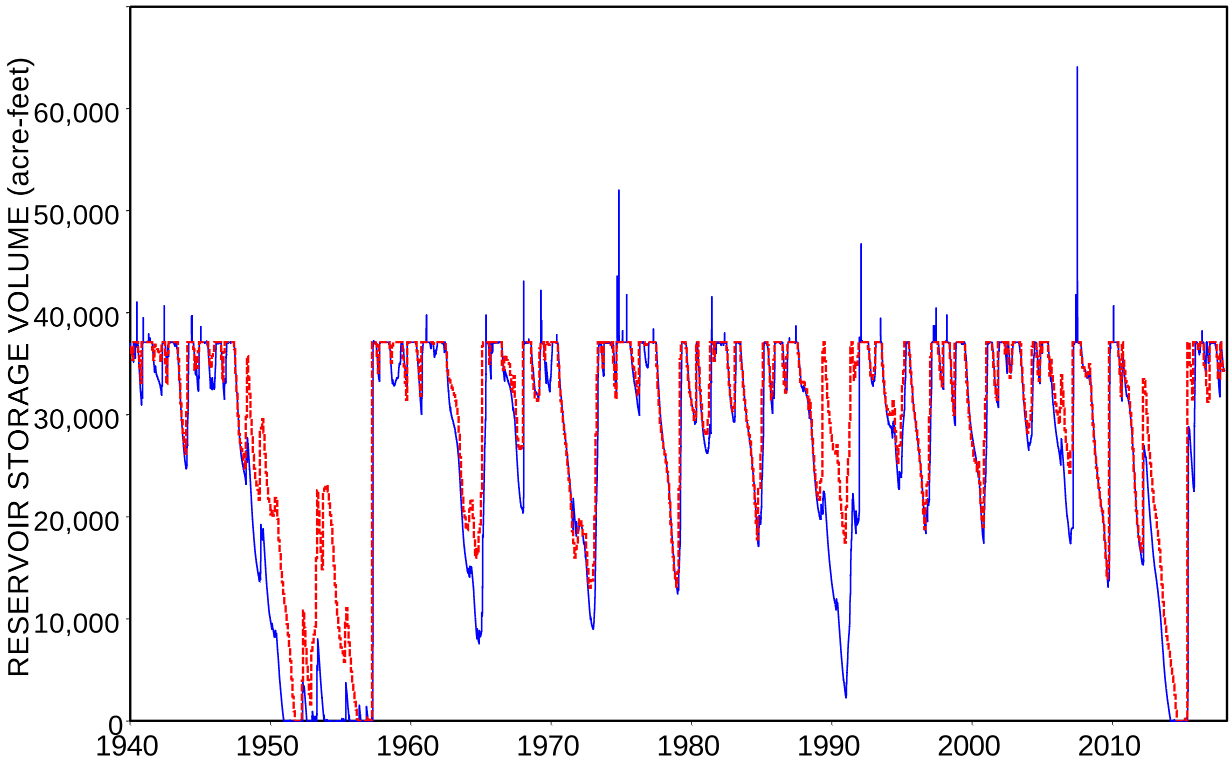

Figure 10.83 Georgetown Reservoir Storage for Daily D7 (blue solid)
and Monthly M3 (red dashed) Simulations

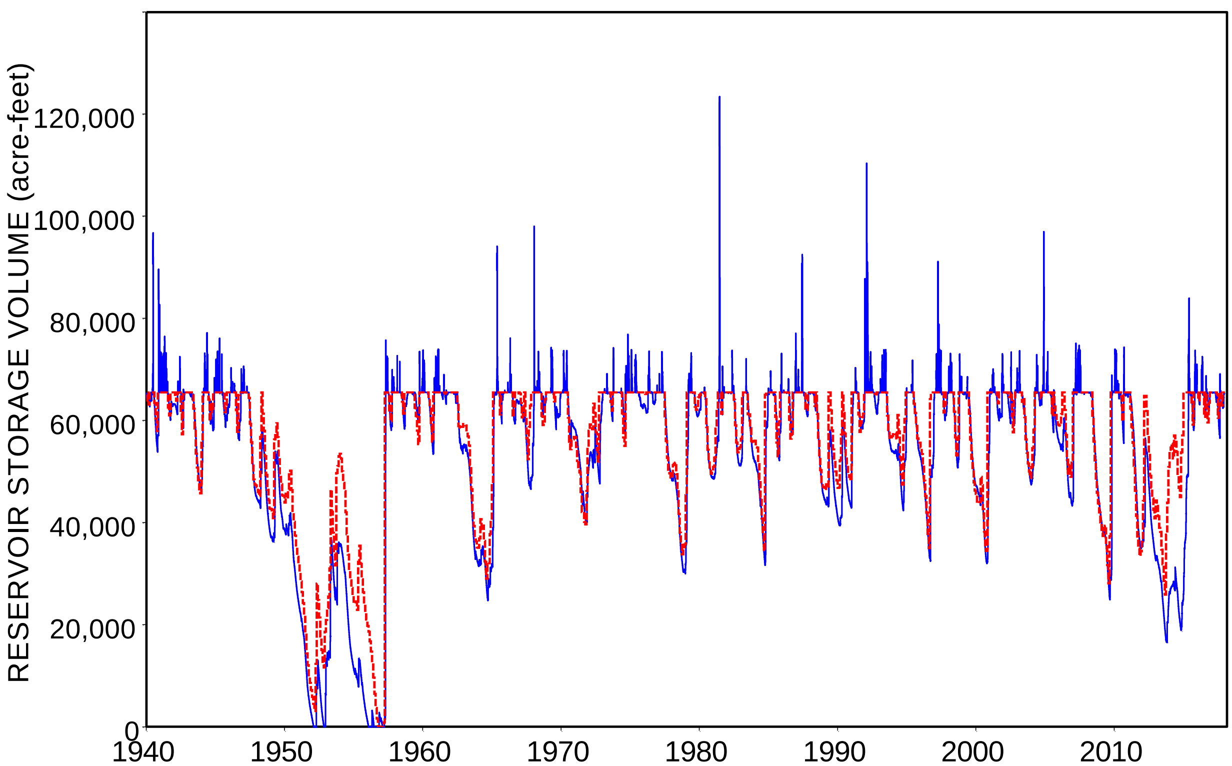

Figure 10.84 Granger Reservoir Storage for Daily D7 (blue solid)
and Monthly M3 (red dashed) Simulations

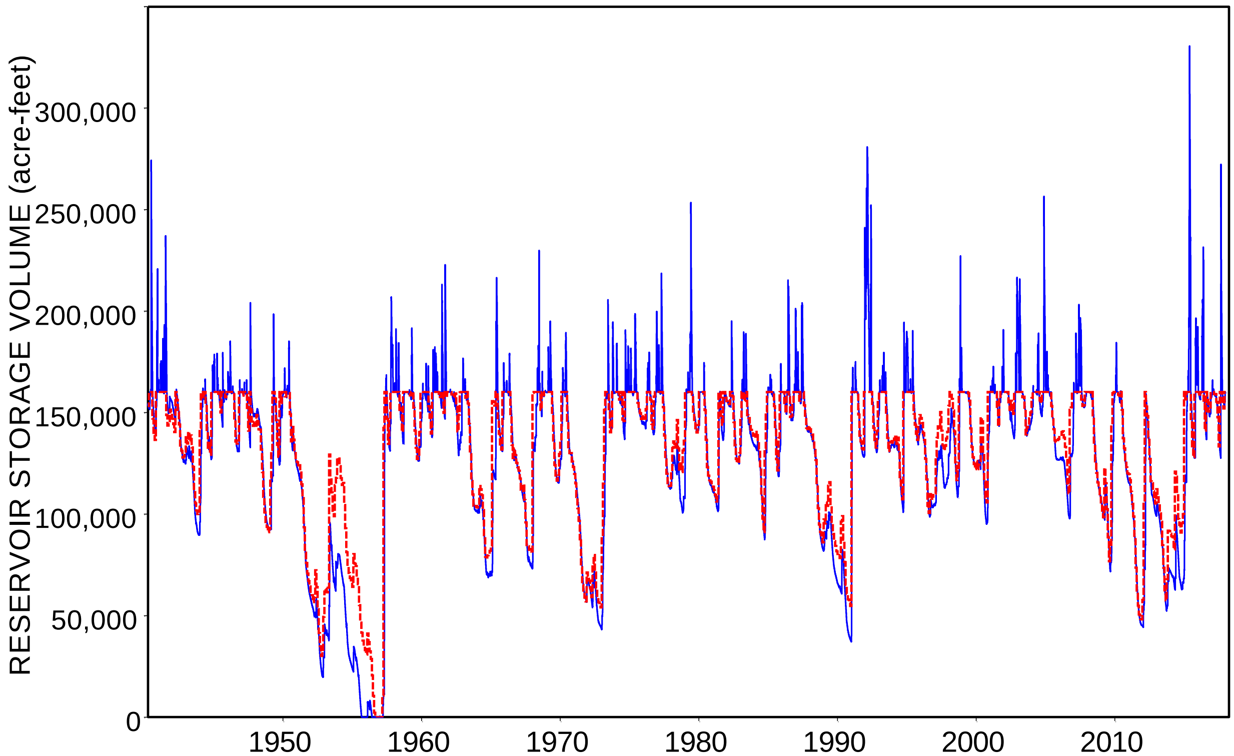

Figure 10.85 Somerville Reservoir Storage for Daily D7 (blue solid) and Monthly M3 (red dashed) Simulations

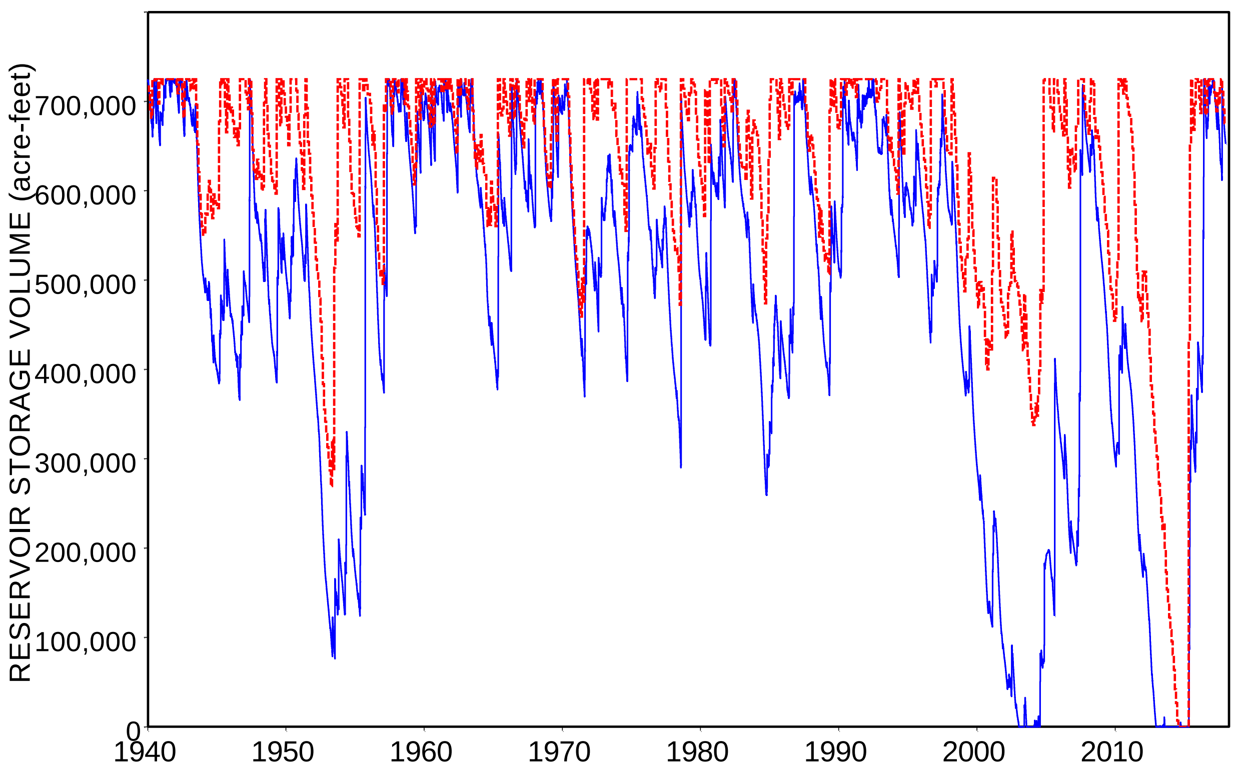

Figure 10.86 Possum Kingdom Storage for Daily D7 (blue solid) and Monthly M3 (red dashed) Simulations

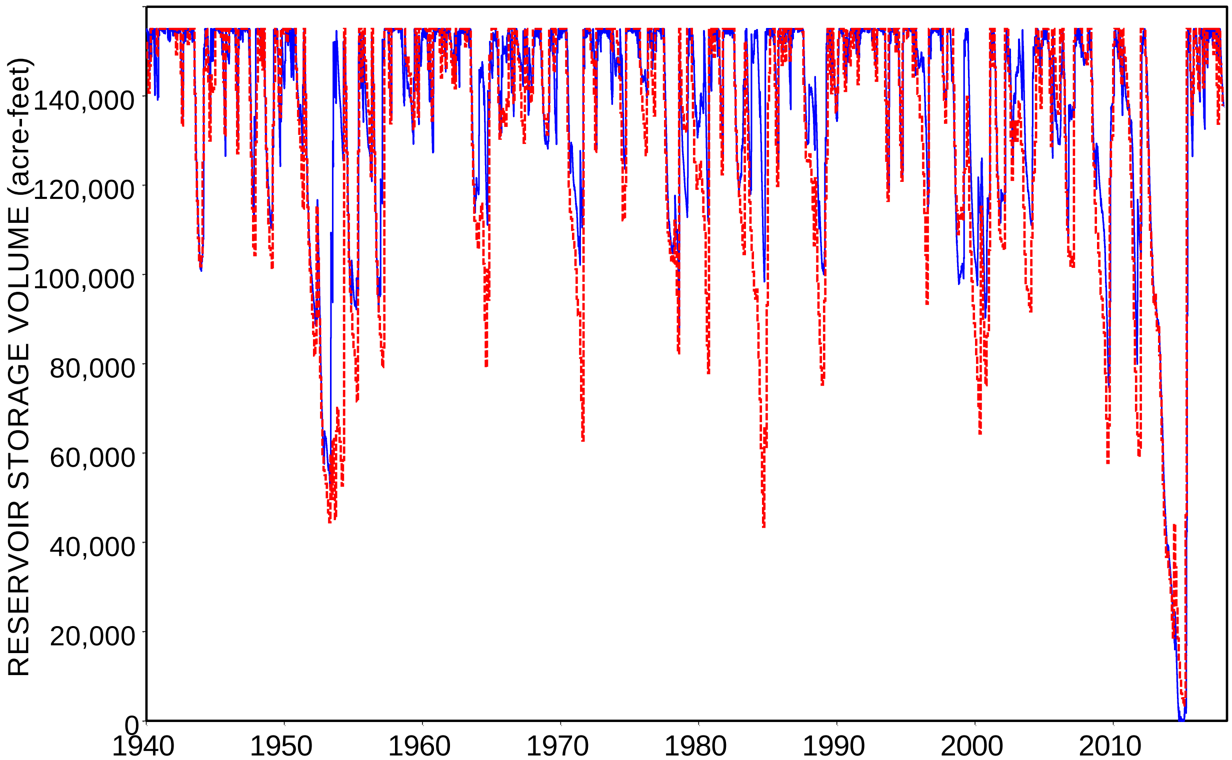

Figure 10.87 Granbury Reservoir Storage for Daily D7 (blue solid) and Monthly M3 (red dashed) Simulations

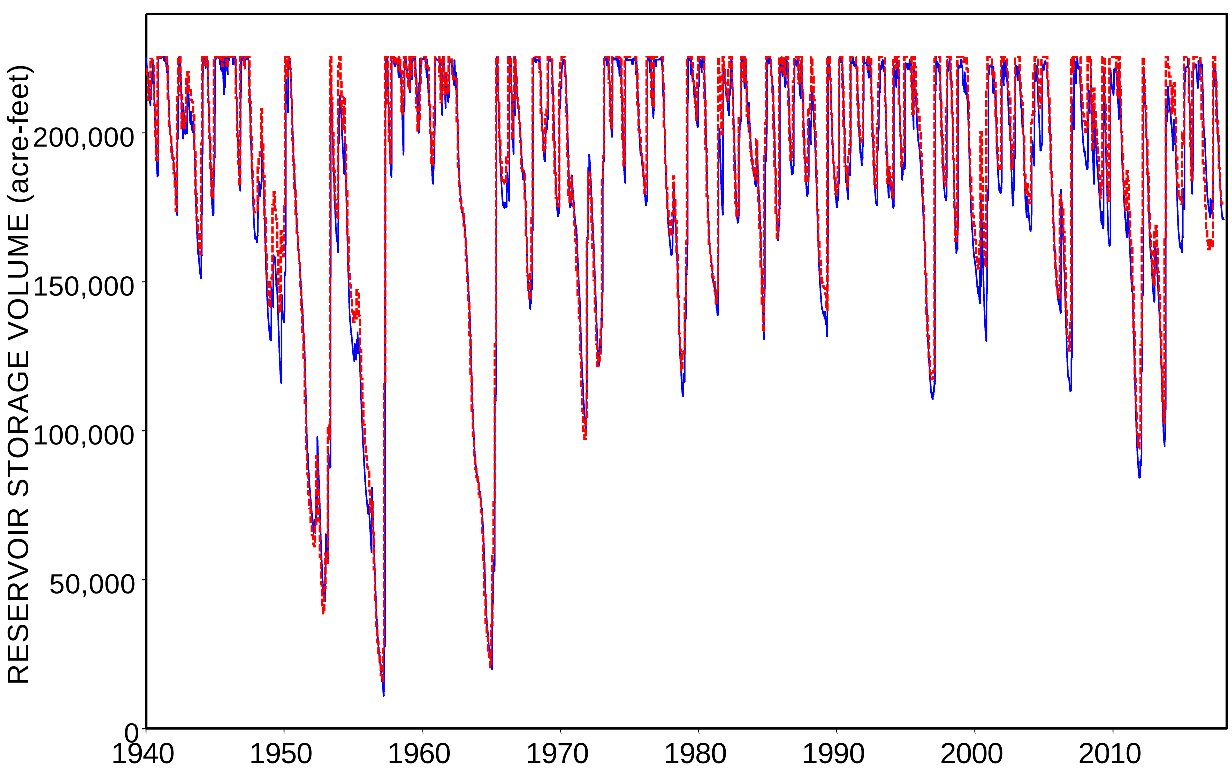

Figure 10.88 Limestone Reservoir Storage for Daily D7 (blue solid) and Monthly M3 (red dashed) Simulations

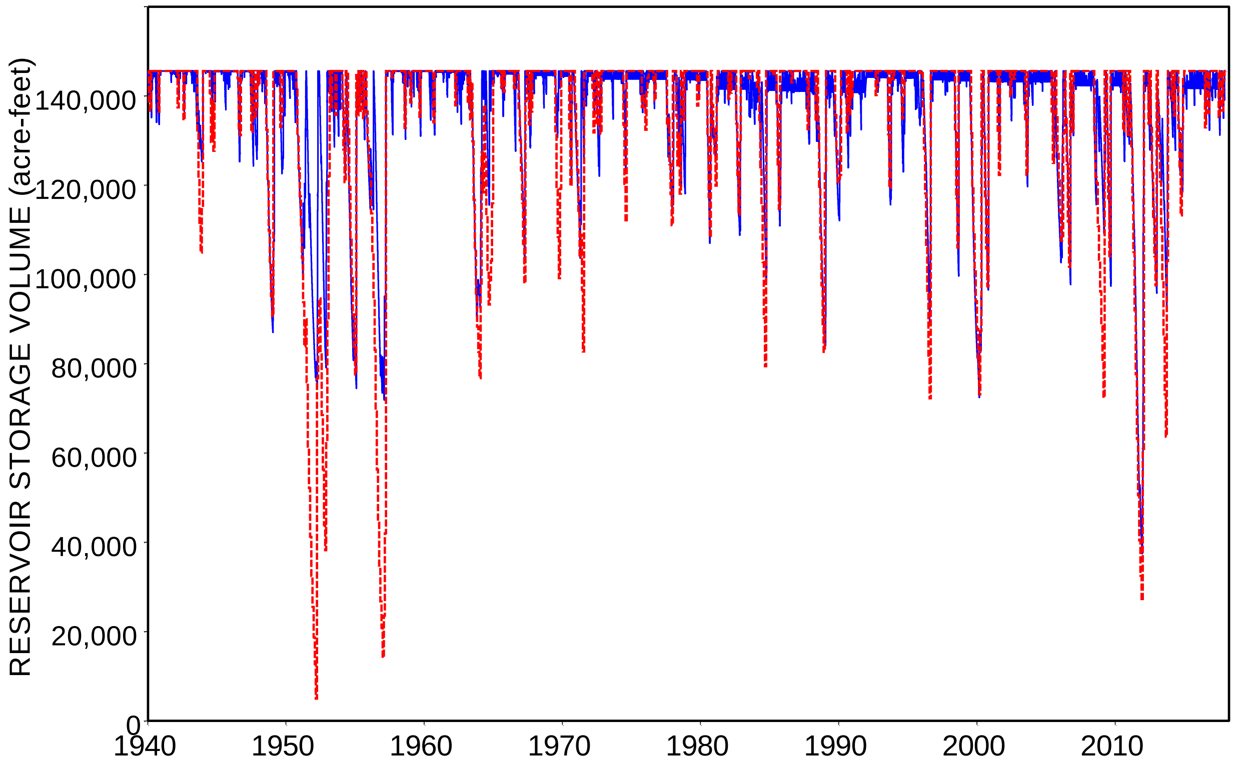

Figure 10.89 Allen's Creek Reservoir Storage for Daily D7 (blue solid) and Monthly M3 (red dashed) Simulations

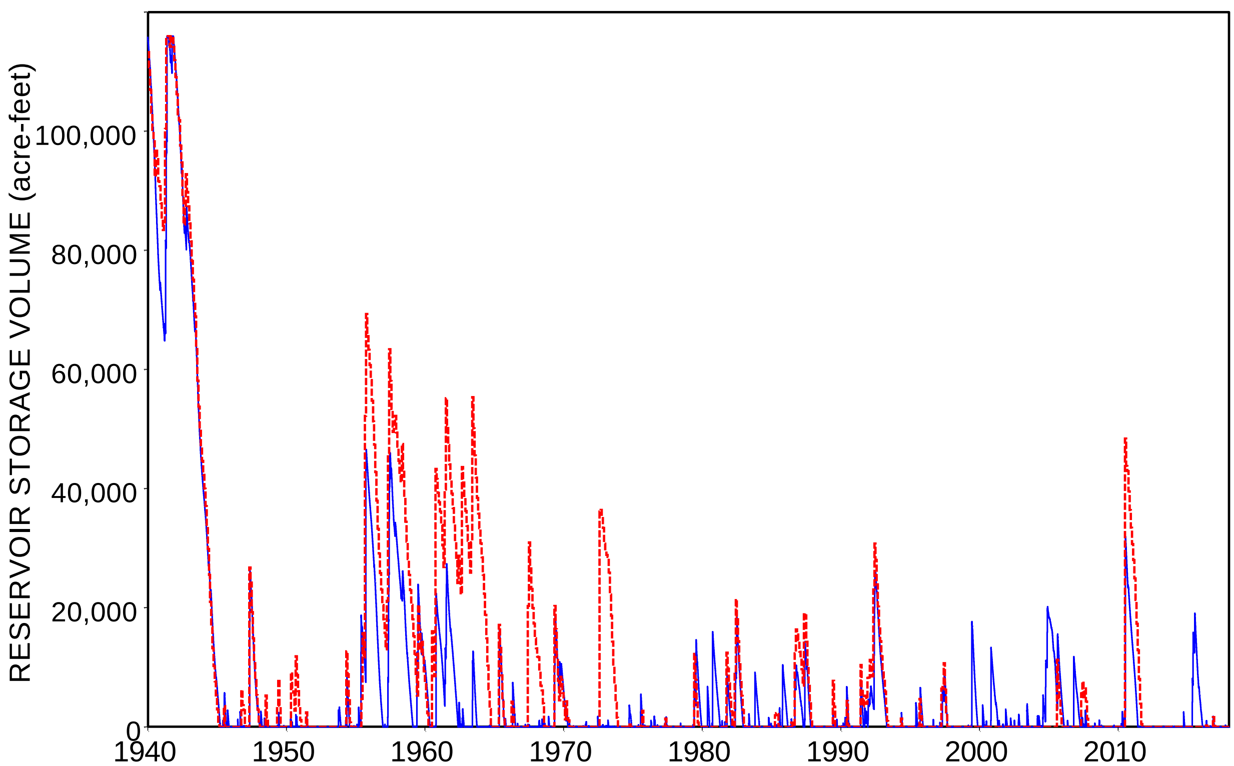

Figure 10.90 Alan Henry Reservoir Storage for Daily D7 (blue solid) and Monthly M3 (red dashed) Simulations

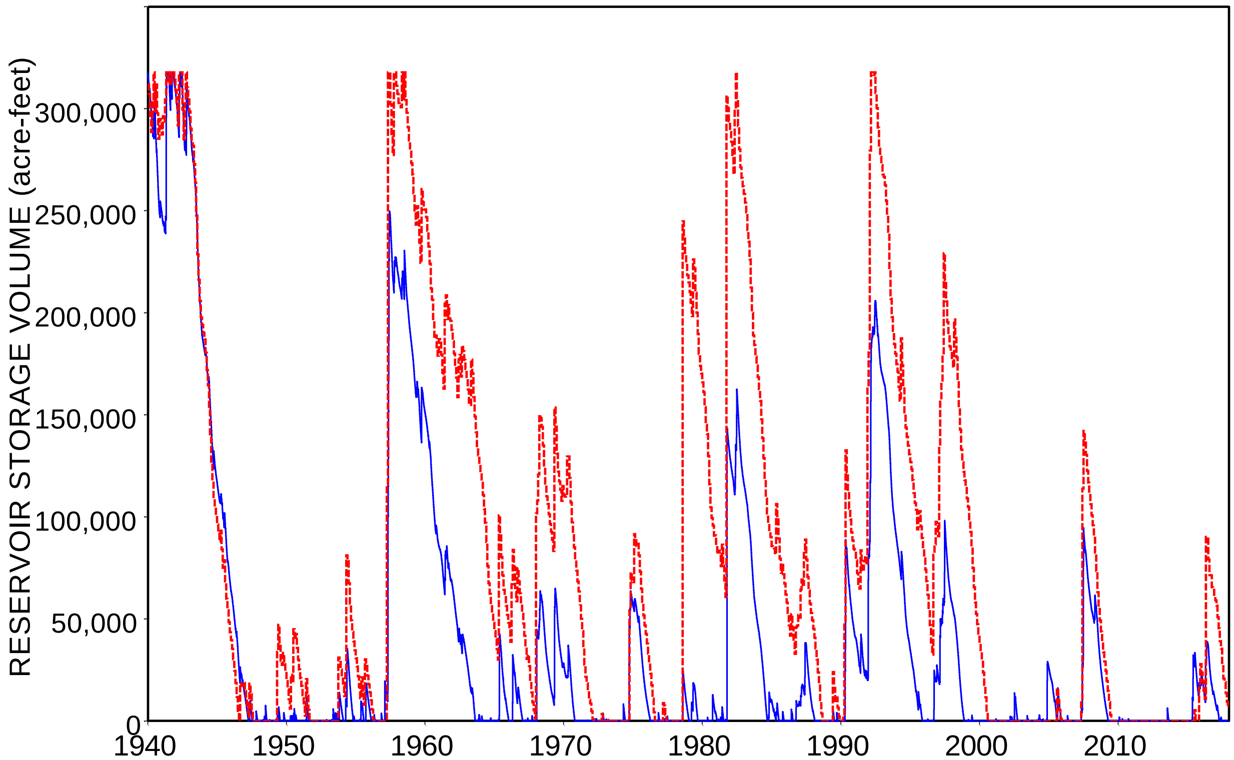

Figure 10.91 Hubbard Creek Reservoir Storage for Daily D7 (blue solid) and Monthly M3 (red dashed) Simulations

Instream Flow Targets for SB3 Environmental Flow Standards

The daily Brazos WAM can be employed for a variety of different types of applications. This report focuses on applying the daily WAM to develop instream flow targets for the SB3 Senate Bill 3 (SB3) environmental flow standards (EFS) for incorporation in the monthly Brazos WAM following the procedure outlined in Chapter 5. The SB3 EFS located at 19 gaging stations are described in Chapter 5. Based on considerations discussed in the preceding sections of this chapter, simulation D7 defined in Tables 10.2 and 10.3 is selected as the best modeling strategy for simulating the SB3 EFS. The SB3 EFS instream flow targets generated by simulation D7 are inserted into the monthly WAM (simulation M1) to create the *SIM* input dataset employed in simulation M3. This final section of Chapter 10 focuses on instream flow targets and associated shortages in meeting the targets for the SB3 EFS.

SB3 EFS Instream Flow Targets at 19 Sites

This final section of Chapter 10 is based on simulations D7 and M3, which employ the daily and monthly versions of the Brazos WAM that are considered to be the final proposed versions for purposes of the study documented by this report. The sets of *IF*, *HC*, *ES*, and *PF* records that model the 19 sets of SB3 EFS in the daily WAM are replicated in Table 5.8 of Chapter 5. The *IF* and *TS* records in the DAT file of the monthly WAM reproduced in Table 5.10 reference *TS* record target sequences stored in the DSS input file as DSS records with the pathnames listed in Table 5.9.

Daily instream flow targets for the SB3 EFS at 19 control points are computed in the *SIMD* simulation for each day as the maximum of the computed subsistence and base flow target and pulse flow target as explained in Chapter 5. Shortages in meeting subsistence and base flow targets represent deficits between targeted minimum flow limits and regulated stream flow. The EFS high pulse flow component replicates regulated flow computed within the water rights priority sequence, which differs from the final regulated flow at the completion of the priority sequence. Thus, shortages can also occur in meeting pulse flow targets.

The 1940-2017 means of the observed, naturalized, simulated regulated, and unappropriated flows at the 19 SB3 EFS sites are tabulated in Tables 10.6 and 10.7. Means of SB3 EFS instream flow targets and shortages at these 19 sites computed in simulations D6, D7, D8, and M3 are compared in Table 10.9.

The daily instream flow targets in cfs at 19 sites plotted in Figures 10.92 through 10.110 were computed in simulation D7 in units of acre-feet/day and aggregated within *SIMD* to monthly targets in acre-feet/month for output to the *SIMD* output OUT and DSS files. The *SIMD* computed monthly SB3 EFS instream flow targets were converted within HEC-DSSVue to target series *TS* records and copied into the hydrology input file BrazosHYD.DSS read by *SIM* and *SIMD*. The pathnames for the *TS* records in the DSS input file are listed in Table 5.9 of Chapter 5. The *IF* and *TS* records replicated in Table 5.10 are inserted in the DAT file read by *SIM* for simulation M3.

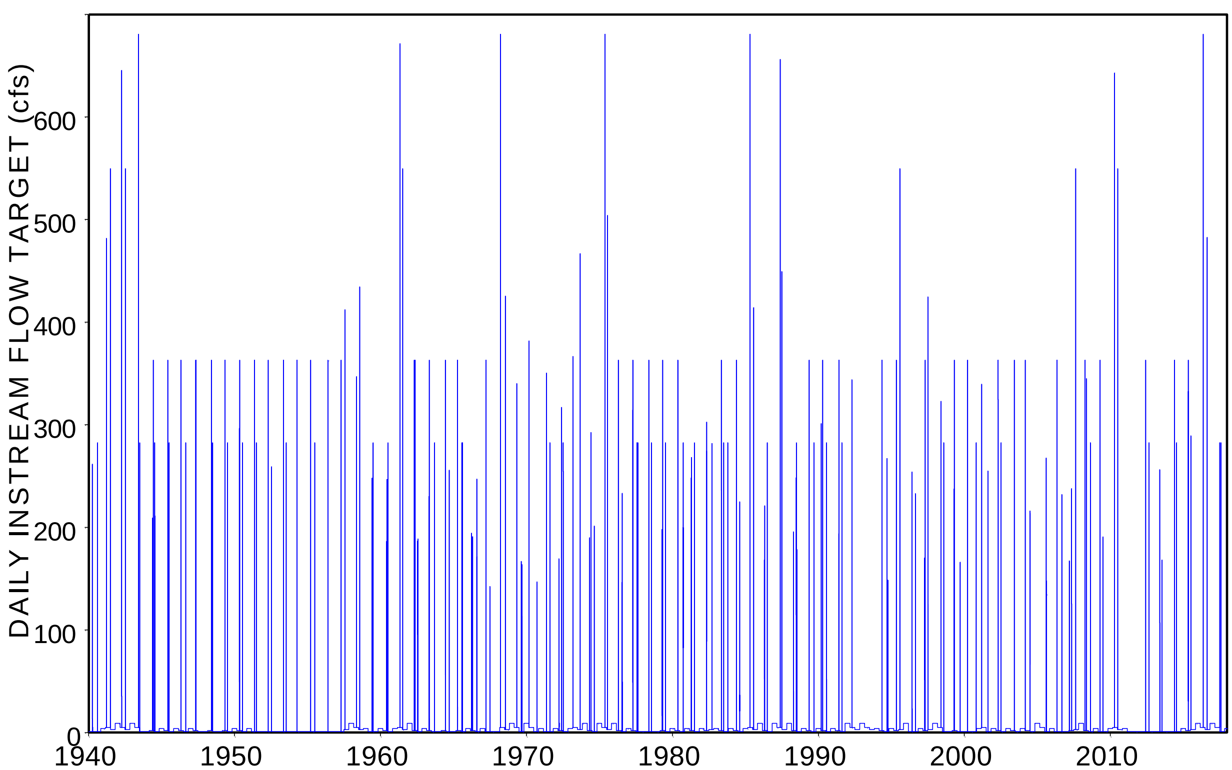

Figure 10.92. Daily Instream Flow Targets for Salt Fork of Brazos River at Aspermont (SFA06)

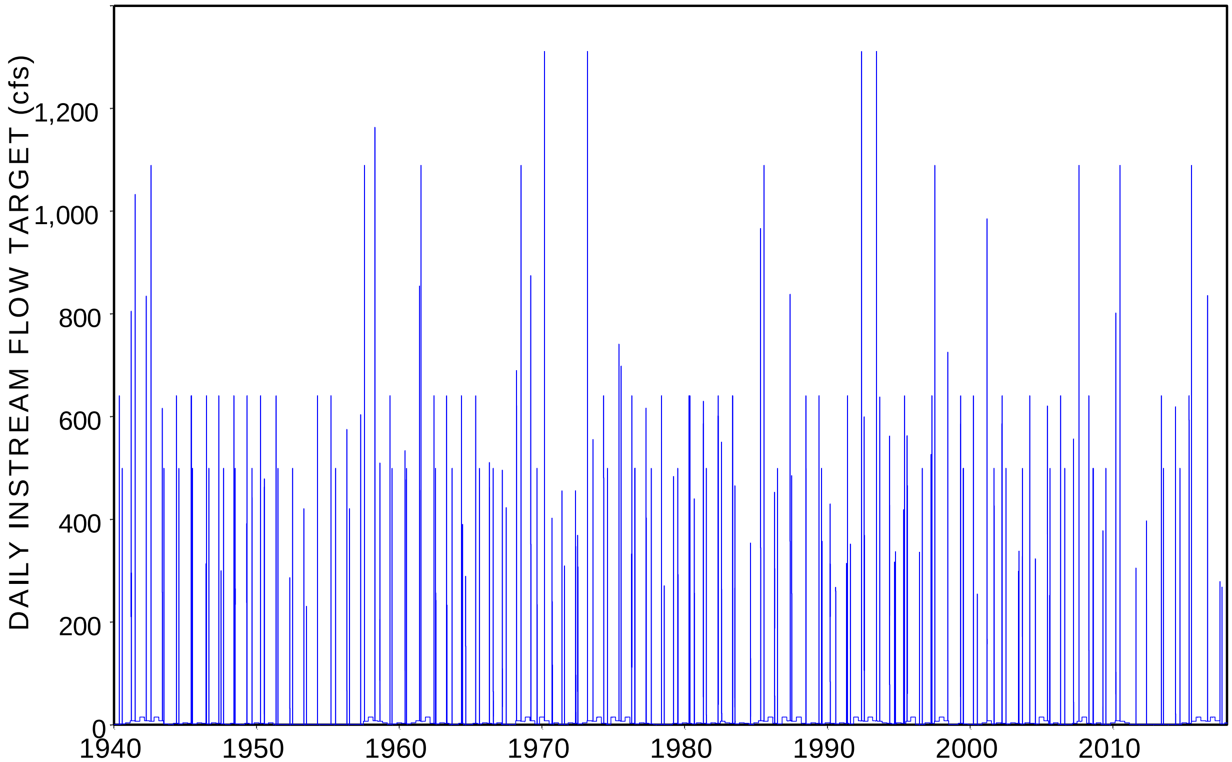

Figure 10.93. Daily Instream Flow Targets for Double Mountain Fork at Aspermont (DMA09)

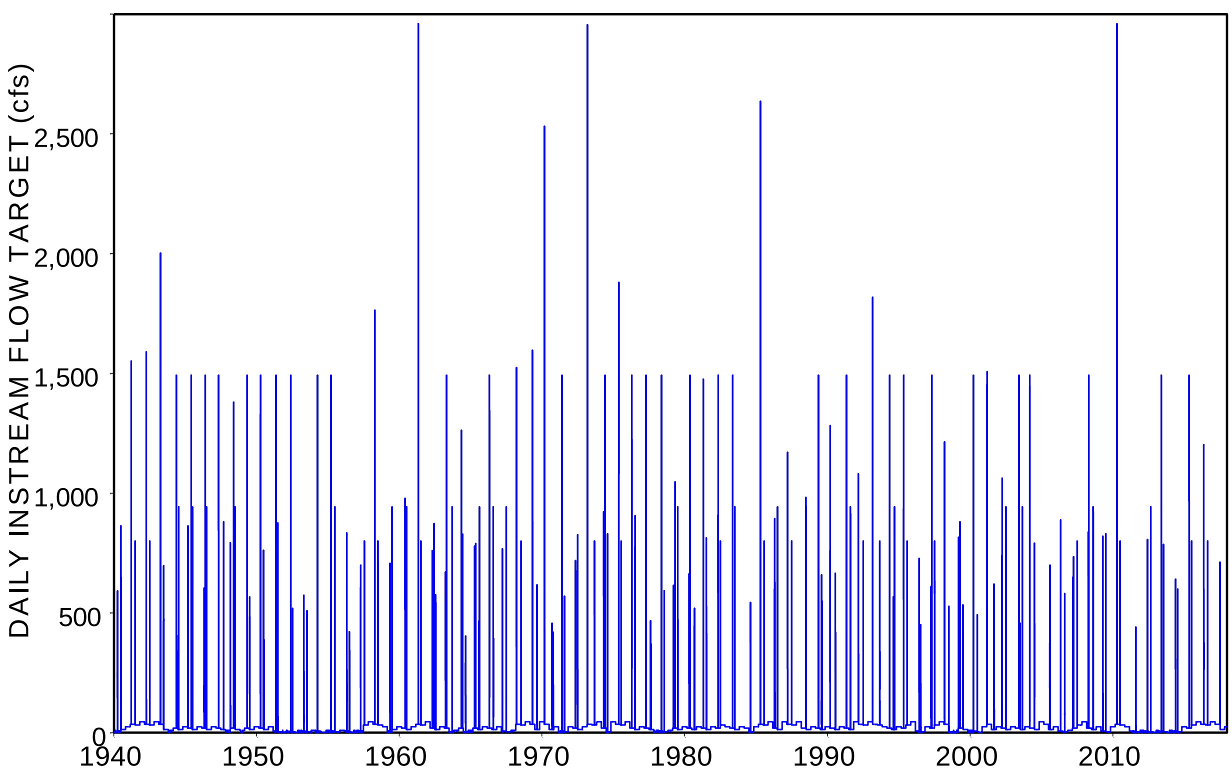

Figure 10.94 Daily Instream Flow Targets (cfs) for Brazos River at Seymour (BRSE11)

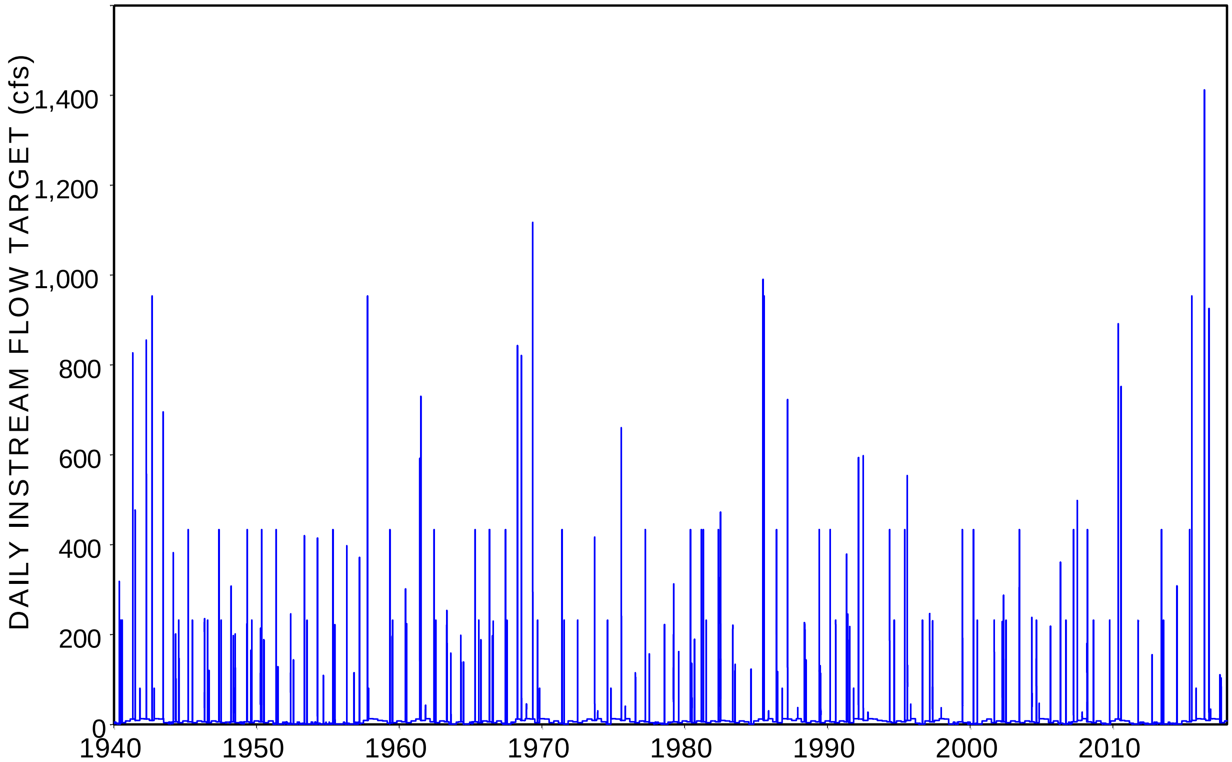

Figure 10.95 Daily Instream Flow Targets for Clear Fork Brazos River at Nugent (CFNU16)

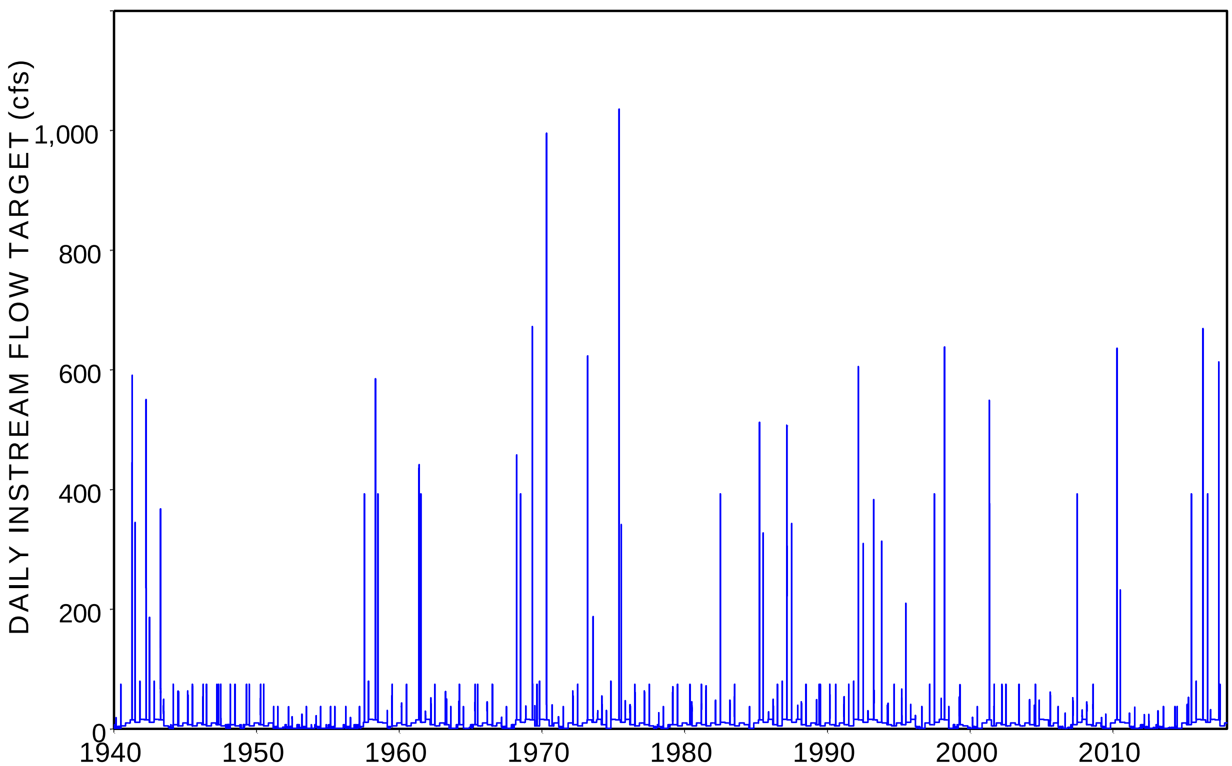

Figure 10.96 Daily Instream Flow Targets for Clear Fork Brazos River at Lueders (CON026)

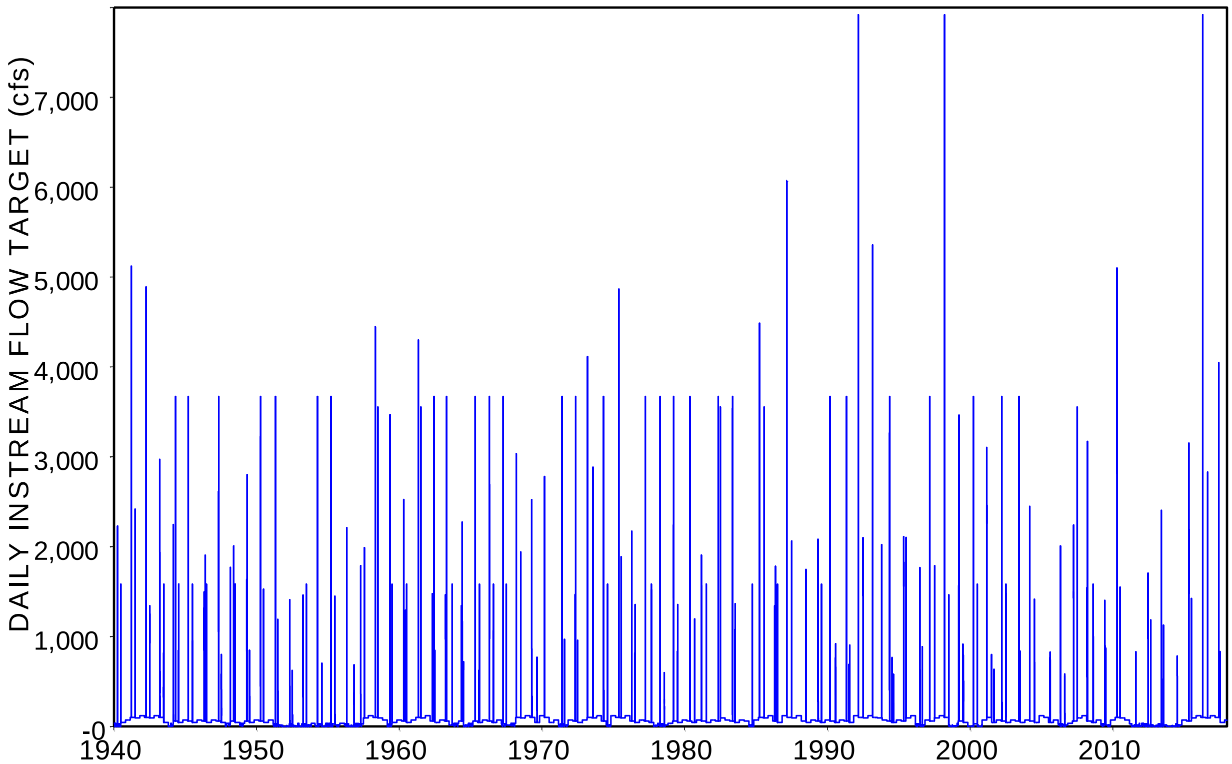

Figure 10.97 Daily Instream Flow Targets (cfs) for Brazos River at South Bend (BRSB23)

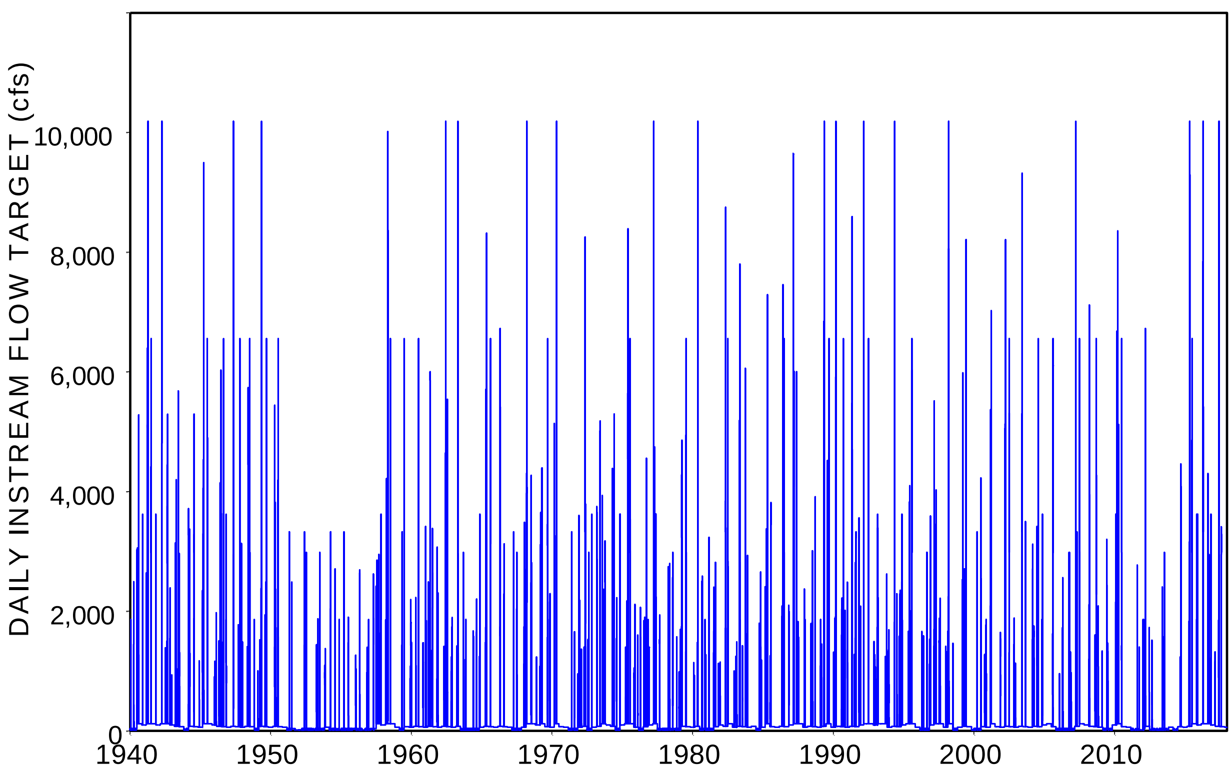

Figure 10.98 Daily Instream Flow Targets (cfs) for Brazos River at Palo Pinto (BRPP27)

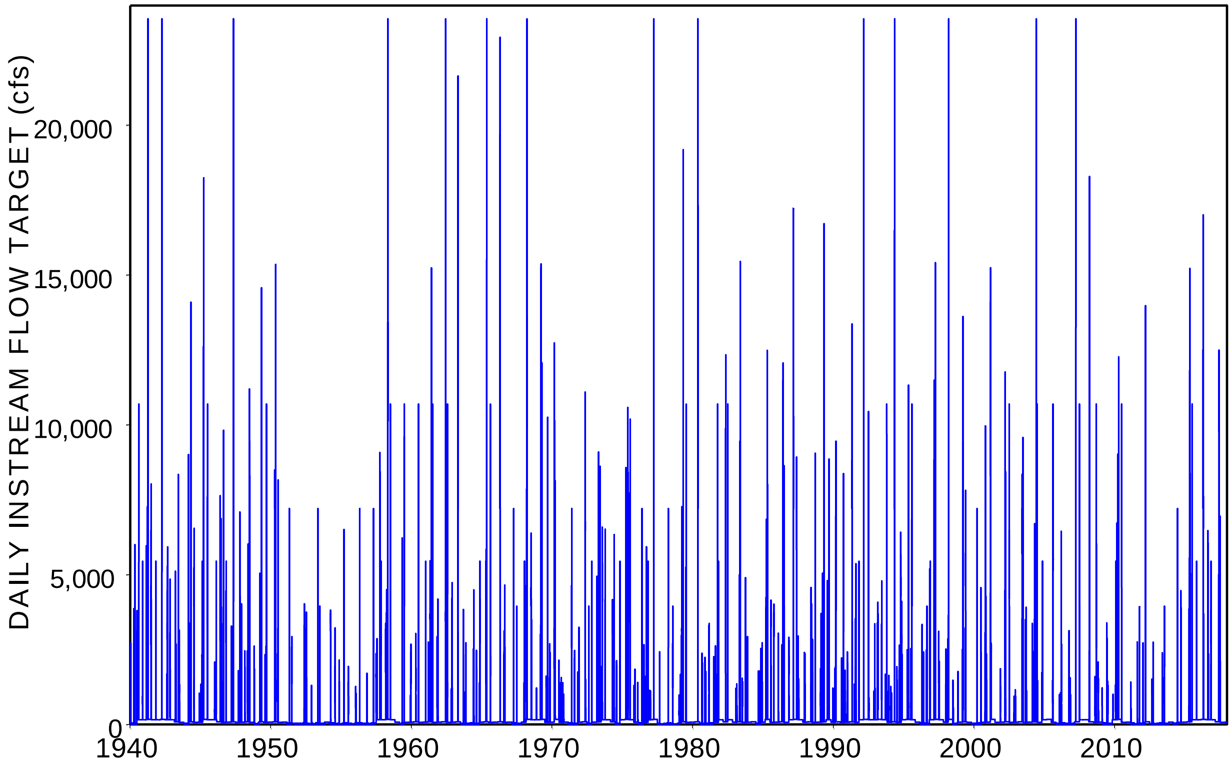

Figure 10.99 Daily Instream Flow Targets (cfs) for Brazos River at Glen Rose (BRGR30)

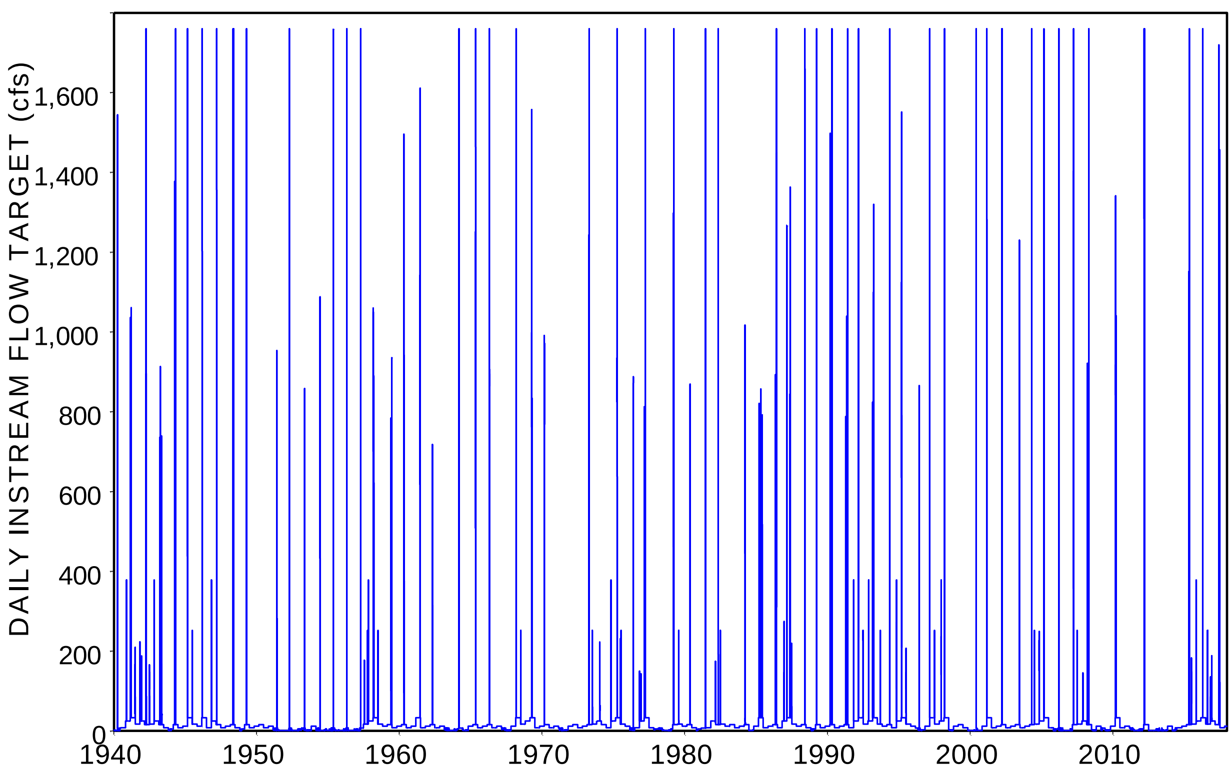

Figure 10.100 Daily Instream Flow Targets (cfs) for North Bosque River at Clifton (NBCL36)

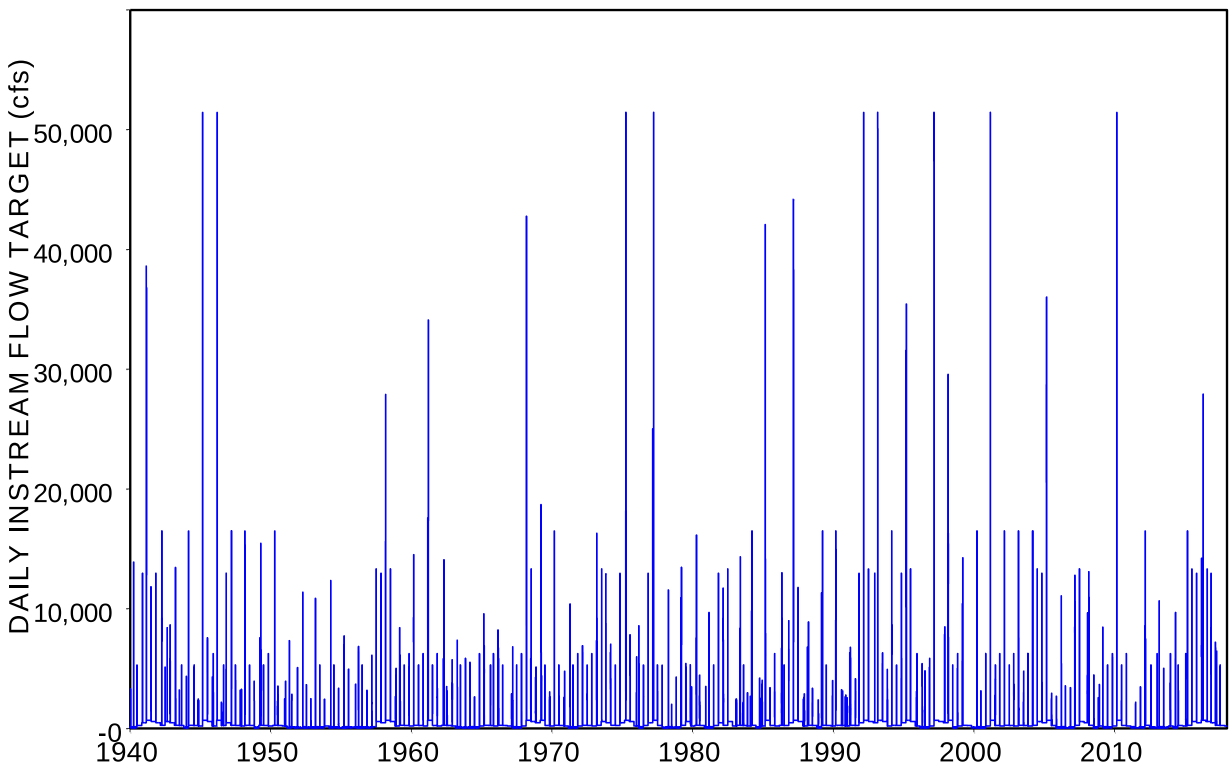

Figure 10.101 Daily Instream Flow Targets (cfs) for Brazos River at Waco (BRWA41)

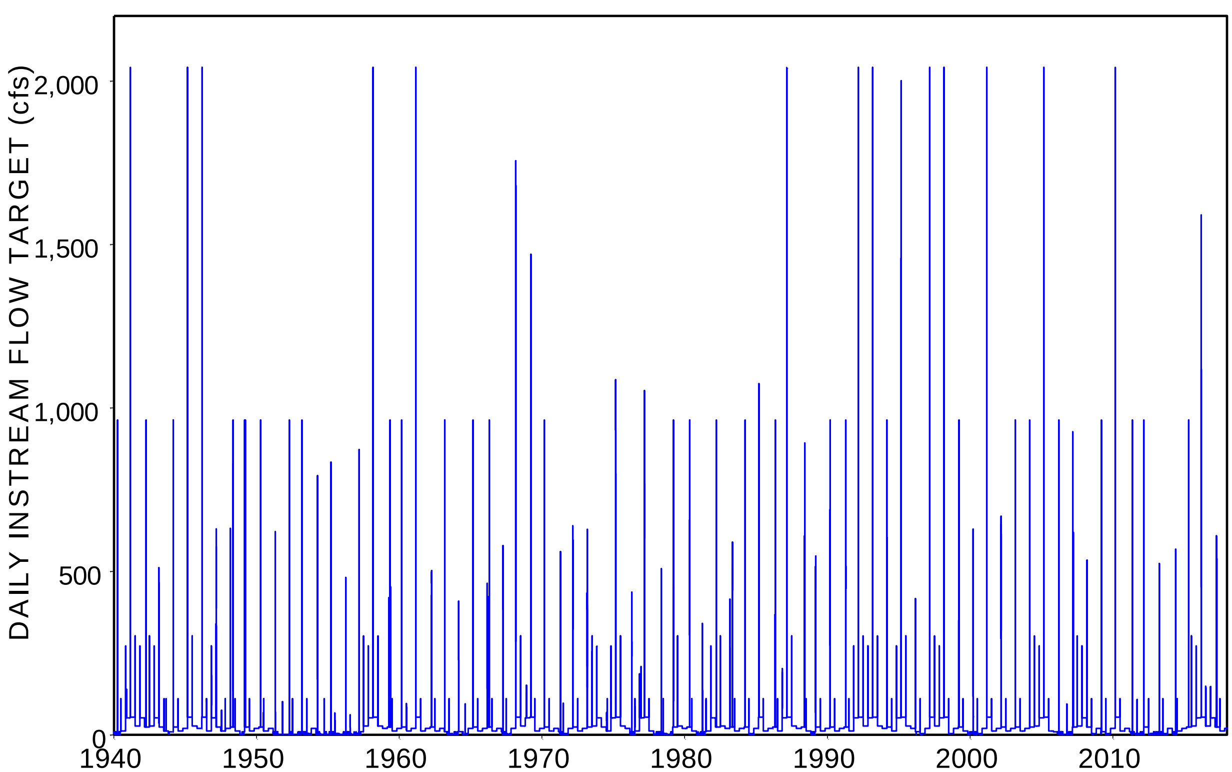

Figure 10.102 Daily Instream Flow Targets (cfs) for Leon River at Gatesville (LEGT47)

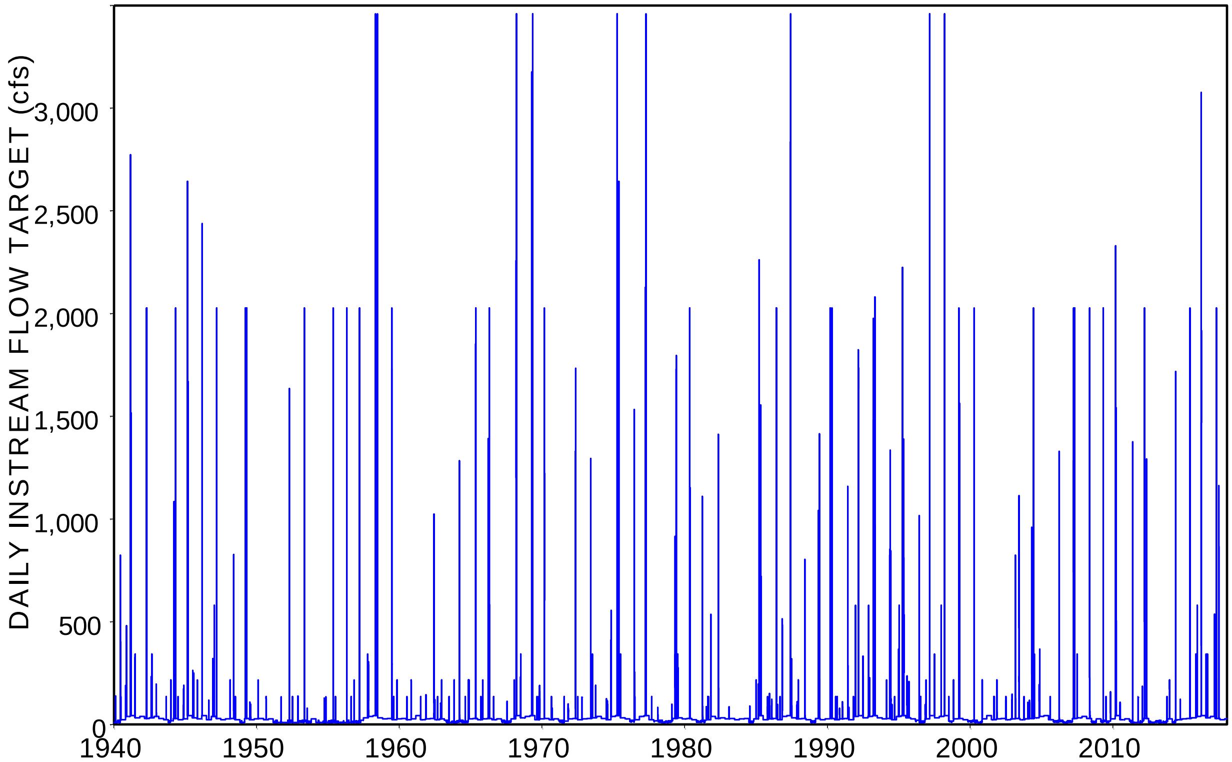

Figure 10.103 Daily Instream Flow Targets (cfs) for Lampases River at Kemper (LAKE50)

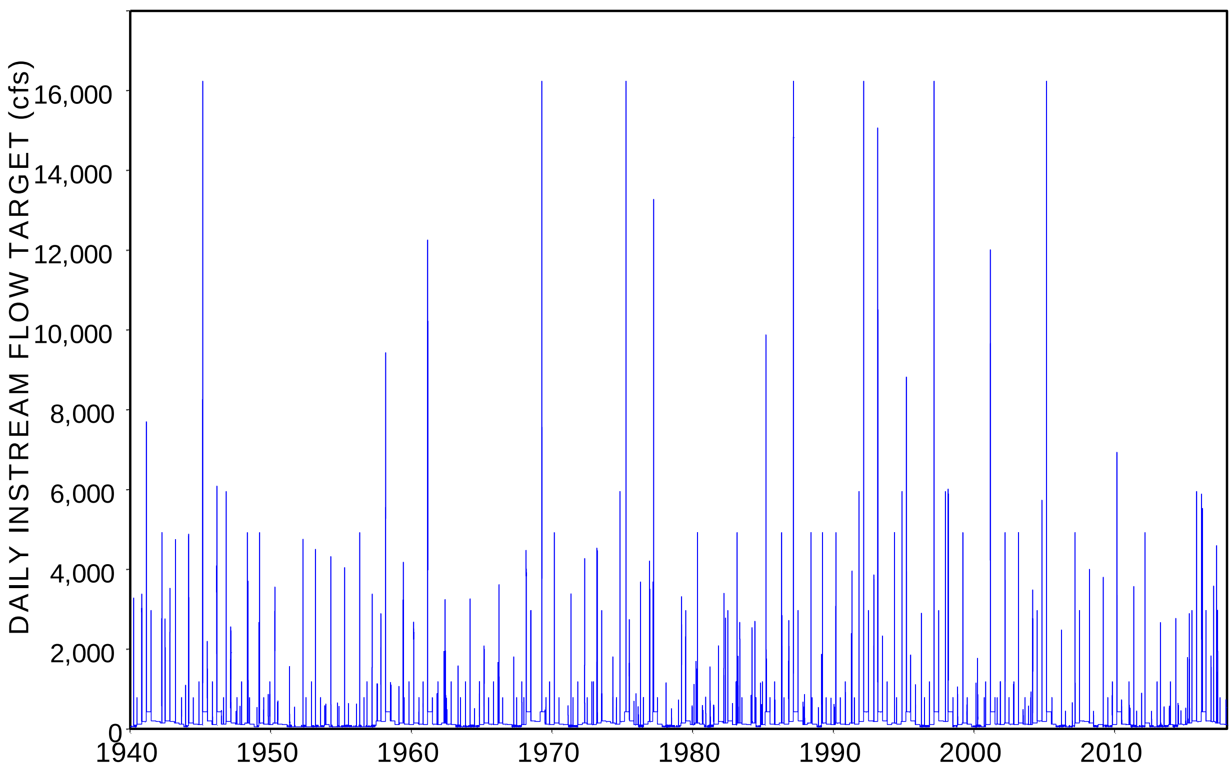

Figure 10.104 Daily Instream Flow Targets (cfs) for Little River at Little River (LRLR53)

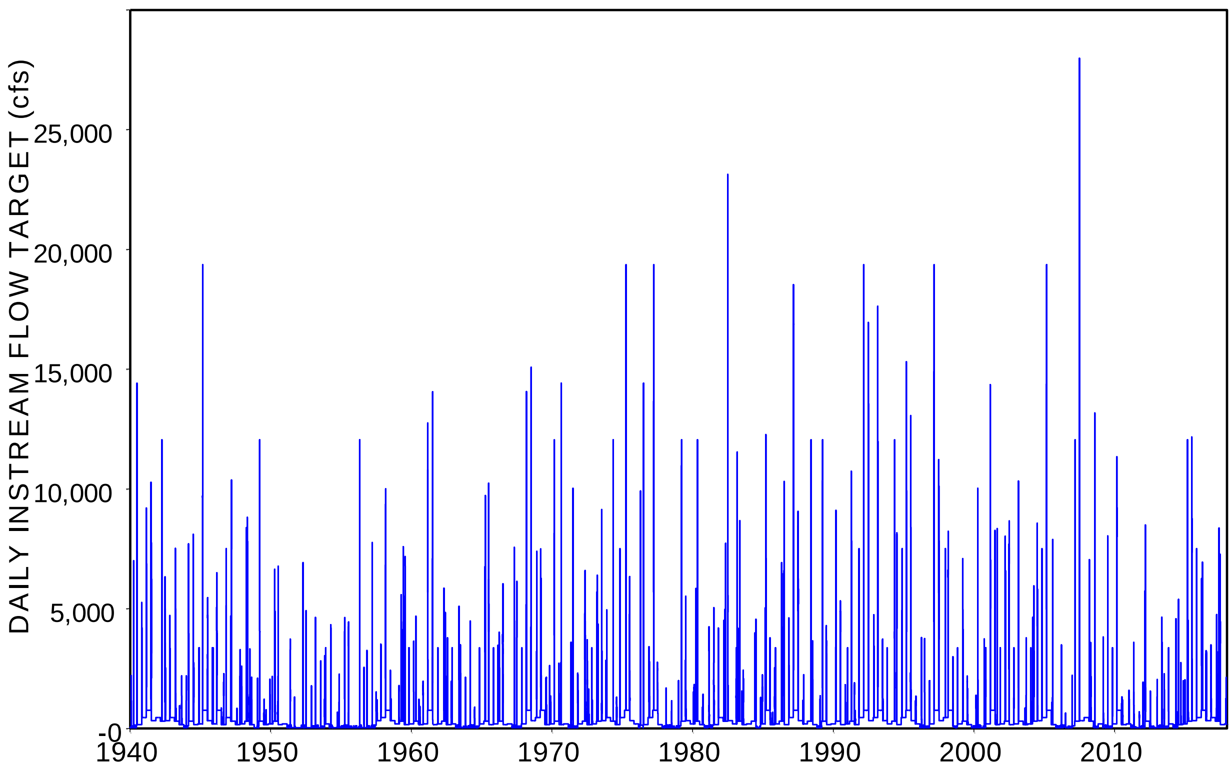

Figure 10.105 Daily Instream Flow Targets (cfs) for Little River at Cameron (LRCA58)

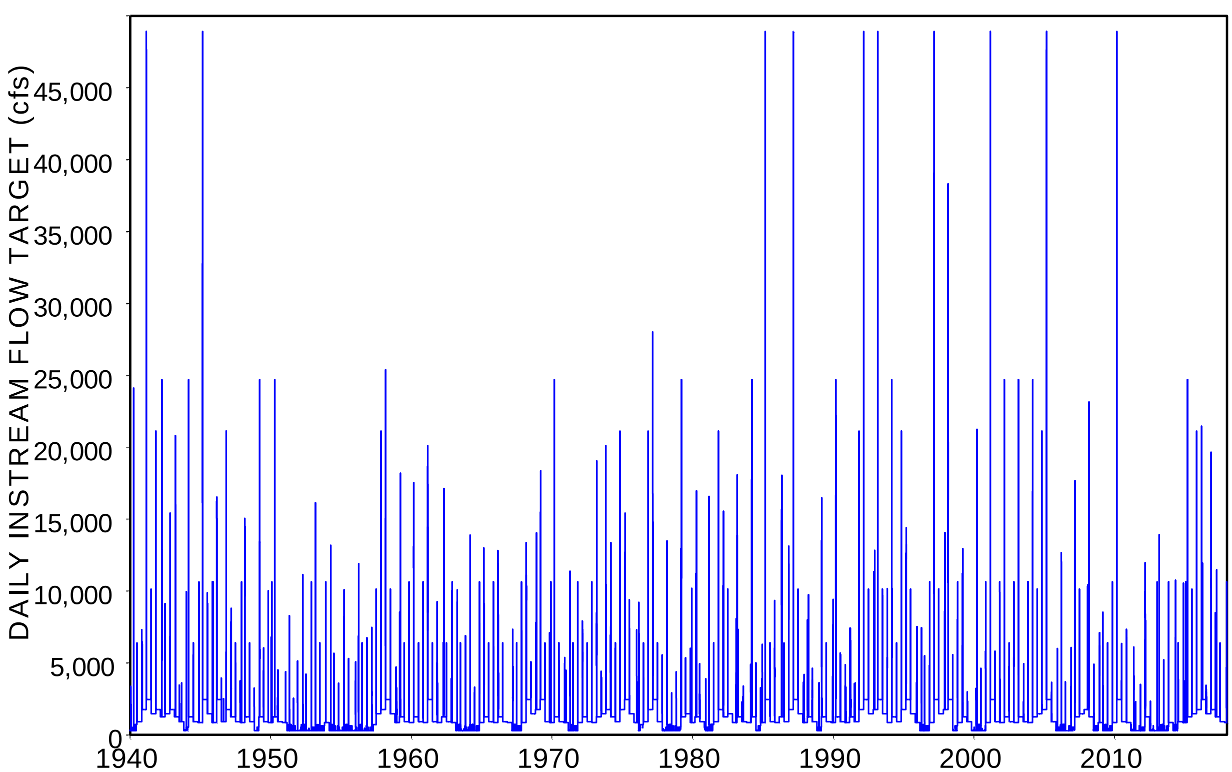

Figure 10.106 Daily Instream Flow Targets (cfs) for Brazos River at Bryan (BRBR59)

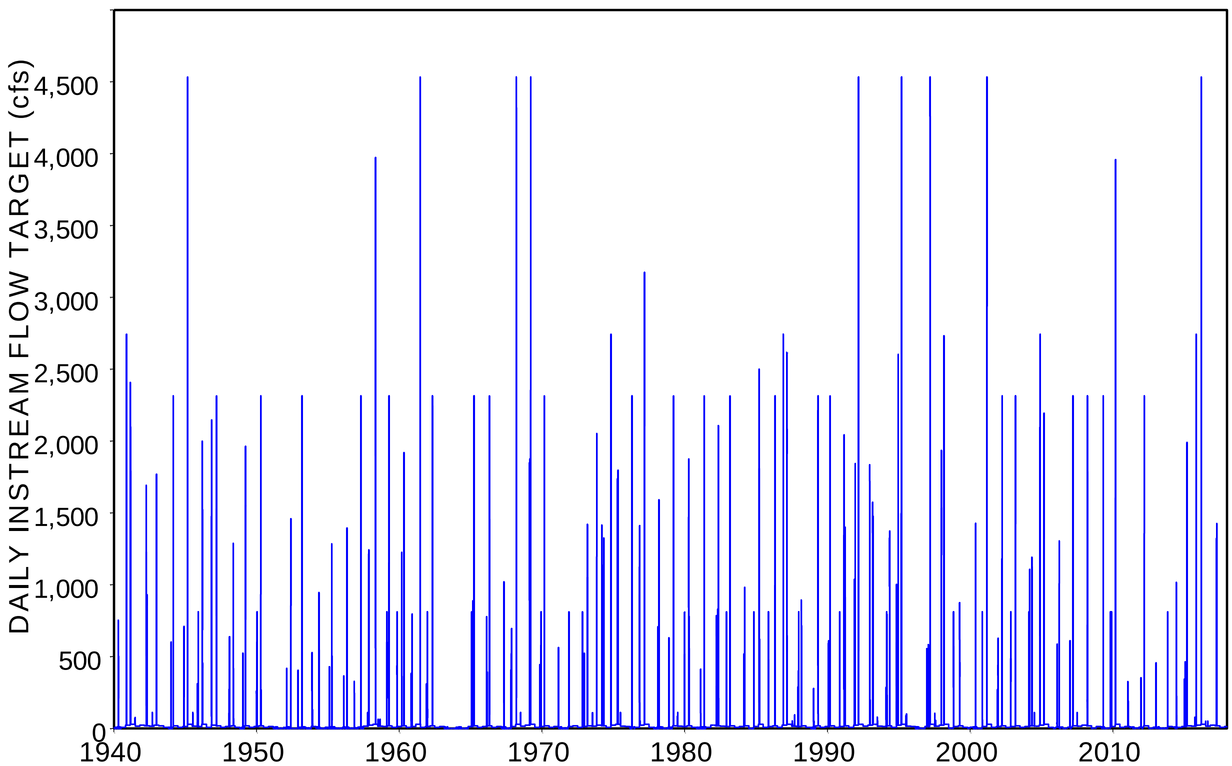

Figure 10.107 Daily Instream Flow Targets (cfs) for Navasota River at Easterly (NAEA66)

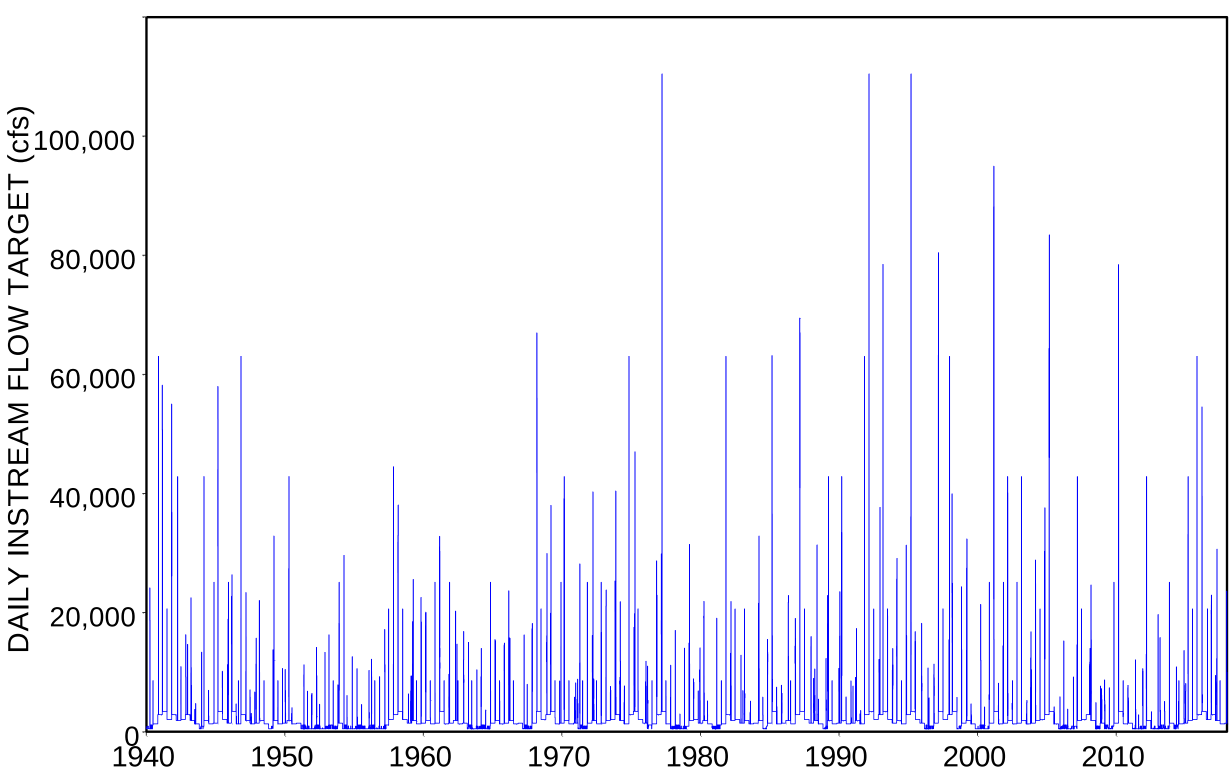

Figure 10.108 Daily Instream Flow Targets (cfs) for Brazos River at Hempstead (BRHE68)

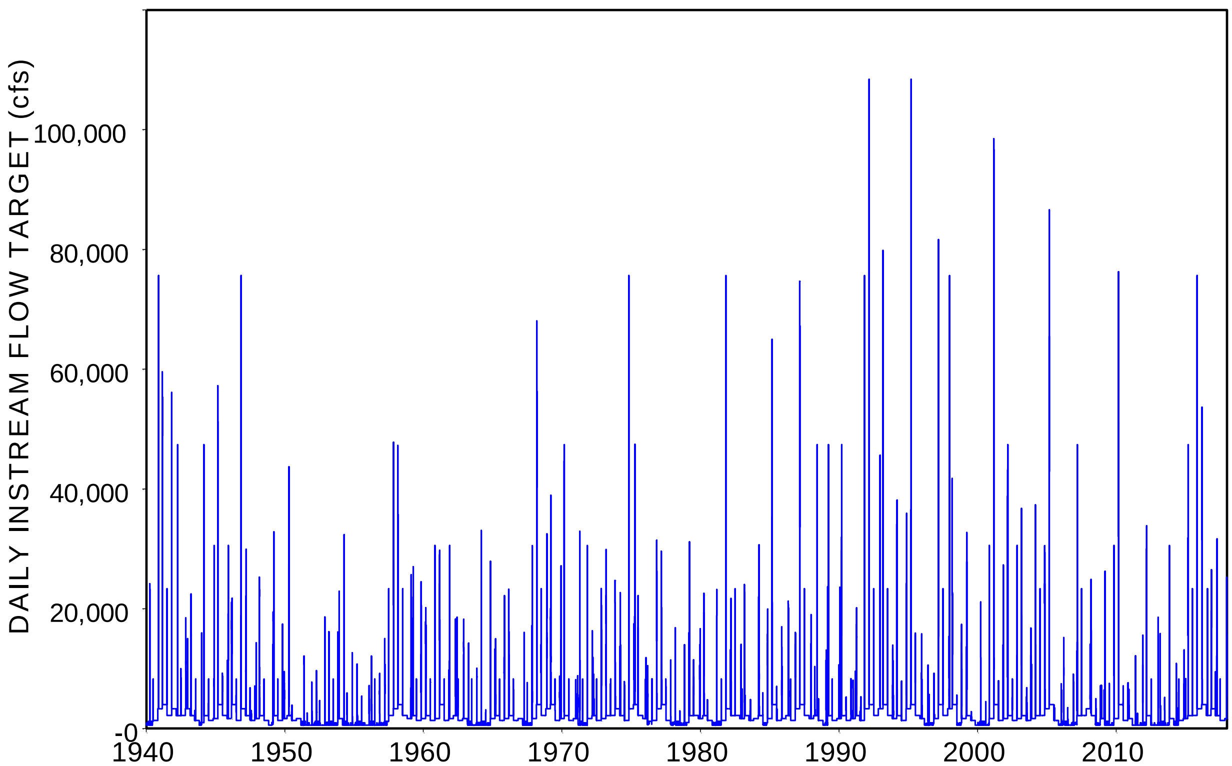

Figure 10.109 Daily Instream Flow Targets (cfs) for Brazos River at Richmond (BRRI70)

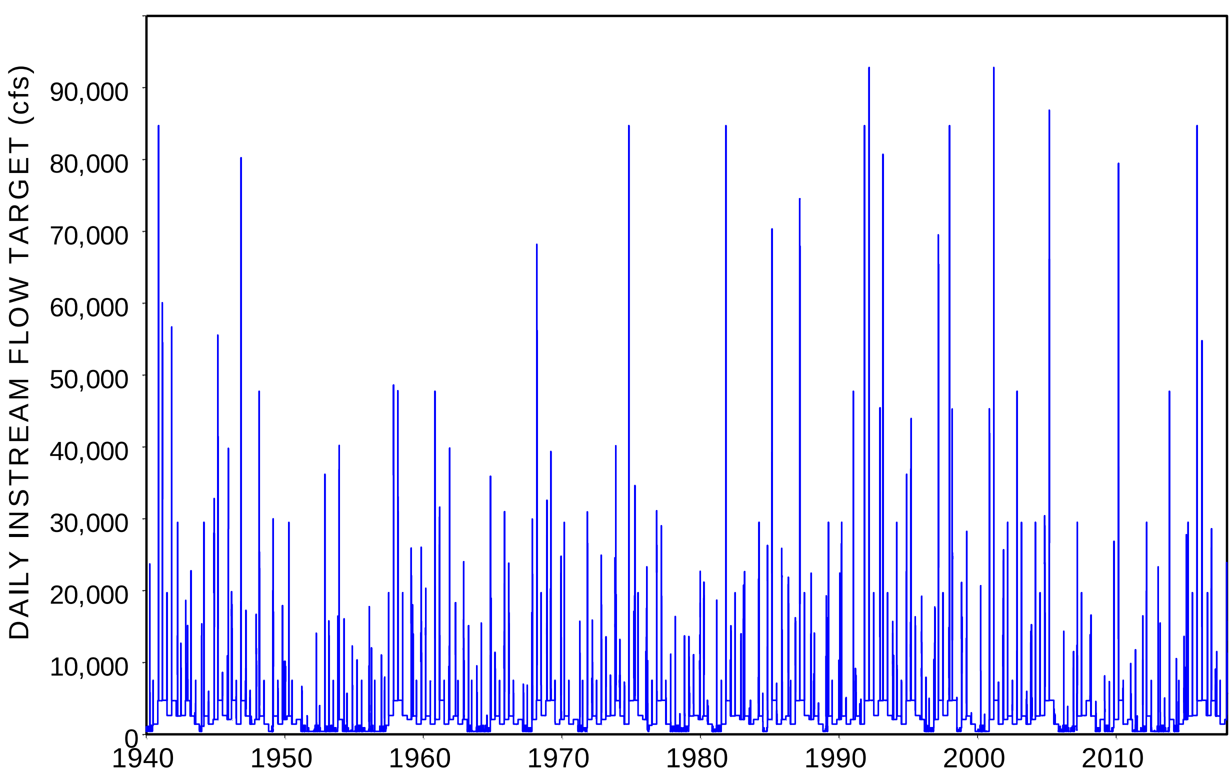

Figure 10.110 Daily Instream Flow Targets (cfs) for Brazos River at Rosharon (BRRI72)

Multiple Instream Flow Targets or Target Components at the Same Control Point

The table on page 47 of the WRAP *Users Manual* [2] lists 43 time series variables that may be included in *SIM* and *SIMD* simulation results output files. Five of these variables are forms of instream flow targets or shortages in meeting instream flow targets. These five instream flow targets and shortage quantities are listed in the first column of Table 10.10 below. The second column of Table 10.10 refers to the *OF* record labels listed on page 47 of the *Users Manual* [2] that are used to select variables for inclusion in the *SIM/SIMD* output DSS file. The labels in DSS pathname part C of the output records are listed in the third column. The corresponding *TABLES* monthly and daily time series input records are listed in the last two columns of Table 10.10. The DSS pathname part C labels in the third column are adopted in the following discussion for referring to the quantities listed in Table 10.10.

Table 10.10
Instream Flow Targets and Shortages in *SIM/SIMD* Simulation Results

Instream Flow Target or Shortage	*SIM/SIMD* *OR* Record	DSS Record Part C	*TABLES* Monthly	*TABLES* Daily
final target at control point	15. IFT	IFT-CP	2IFT	6IFT
shortage for final control point target	16. IFS	IFS-CP	2IFS	6IFS
combined target for IF water right	27. IFT	IFT-WR	2IFT	6IFT
shortage for IF water right	28. IFS	IFS-WR	2IFS	6IFS
individual target for IF water right	29. TIF	TIF-WR	2TIF	6TIF

With only one *IF* record instream flow water right located at a control point, the IFT-CP, IFT-WR, and TIF-WR targets are the same. IFT-CP, IFT-WR, and TIF-WR instream flow targets are different only in the case of two or more *IF* record rights located at the same control point. A IFT-CP target refers to the final target at the control point at the completion of the priority sequenced simulation computations. TIF-WR refers to the instream flow target computed for an individual *IF* record right without consideration of any other *IF* record rights located at the same control point. IFT-WR refers to the instream flow target for an *IF* record right after combining with the target for the preceding *IF* record right in the water rights priority sequence.

With two or more *IF* record rights at the same control point, the target for a junior right is combined with the target from the preceding senior right as specified by IFM(IF,2) in *IF* record field 7. The IF record IFM(IF,2) target combining options are listed in Table 10.11.

SB3 EFS standards are modeled as a set of *IF*, *HC*, *ES*, and *PF* records as explained in the *Daily and Users Manuals* [2, 4]. Pulse flow *PF* and subsistence/base flow *ES* records are normally combined as a single *IF* record instream flow water right at a control point. With pulse flow *PF* and subsistence/base flow *ES* records for the same *IF* record right, the instream flow targets are combined as specified in *PF* record field 14. The options for combining consecutive PF record targets for a single *IF* record right are also listed in Table 10.11. Alternatively, a SB3 EFS can be modeled as two separate *IF* record rights at the same control point with the ES records included with one *IF* record and the *PF* records included with a different IF record [4].

Table 10.11
Options for Combining Targets for Instream Flow Rights at the Same Control Point

IF record field 7	*PF* record field 14	Method for combining junior and senior targets.
1 (default)	1	The junior target replaces the senior target.
2	2 (default)	The largest target is adopted.
3	3	The smallest target is adopted.
−	4	The two targets are added together

The computation of a SB3 target consists of computing a subsistence and base flow target as specified by *ES* records and a pulse flow target as specified by *PF* records. The larger of the two targets is adopted. The two targets are typically computed as a single *IF* record water right target. A daily time single time series of targets consisting of the larger of the two targets in each day is recorded in the *SIMD* simulation results output files. The primary reason for separating subsistence and base flow (*ES* record) targets and pulse flow (*PF* record) targets into two *IF* record water rights is to generate separate targets in the output for information purposes. The actual simulation computations are not otherwise affected.

<u>Instream Flow Targets and Shortages at Four Selected Control Points</u>

The following four SB3 EFS sites are selected for purposes of further discussion as being representative of the 19 different SB3 EFS sites.

Control Point LRCA58 – Little River at Cameron
Control Point BRSE11 – Brazos River at Seymour
Control Point BRWA41 – Brazos River at Waco
Control Point BRRI70 – Brazos River at Richmond

Watershed areas and averages of stream flows and instream flow targets and shortages for the 1940-2017 hydrologic period-of-analysis at control points LRCR58, BRSE11, BRWA41, and BRRI70 for simulations D7 and M3 are tabulated in Table 10.12 and 10.13. Daily regulated flows at these four selected control points are plotted in Figures 10.69, 10.71, 10.73, and 10.75. Annual volumes of observed, naturalized, regulated, and unappropriated flows, and instream flow targets (IFT-CP) and shortages at these four sites are plotted in Figures 10.70, 10.72, 10.74, and 10.76.

Final total (IFT-CP) SB3 EFS daily instream flow targets in cfs for all 19 sites are plotted in Figures 10.92 through 10.113. The separated pulse flow and subsistence/base flow components (TIF-WR) of the SB3 EFS daily instream flow targets in cfs at control points LRCR58, BRSE11, BRWA41, and BRRI70 are plotted in Figures 10.111, 10.113, 10.115, and 10.117. The corresponding monthly means in cfs are plotted in Figures 10.112, 10.114, 10.116, and 10.118.

The 122 *IF* records contained in the DAT file of the September 2008 authorized use Brazos WAM are listed in Table 2.7 of Chapter 2. The recently added 19 *IF* records for SB3 EFS are replicated in Table 5.8 of Chapter 5. Other instream flow rights in addition to the SB3 EFS instream flow rights are located at control points LRCR58, BRWA41, and BRRI70 but not BRSE11.

Table 10.12
Means for Daily Stream Flows and Daily SB3 EFS Targets and Shortages
at Four Sites for *SIMD* Simulation D7

	Control Point	LRCA58	BRSE11	BRWA41	BRRI70
1	Watershed Area (square miles)	7,100	5,996	20,065	35,454
2	Mean of 1940-2017 Observed Flow (cfs)	1,772	297.2	2,261	7,633
3	Mean of Daily Naturalized Flows (cfs)	1,841	304.7	2,569	8,061
4	Mean of Daily Regulated Flows (cfs)	1,442	285.3	1,757	6,381
5	Mean of Daily Unappropriated Flows (cfs)	777.0	36.56	748.4	3,652
	Mean of Daily Targets and Shortages (cfs) – Junior *IF* Record Water Right Controls				
6	Final Target at Control Point (IFT-CP)	410.3	30.24	511.3	2,374
7	Final Target for EFS Water Right (IFT-WR)	410.3	30.24	511.3	2,374
8	Individual Target for EFS Right (TIF-WR)	410.3	30.24	511.3	2,374
9	Shortages for IFT-CP targets (IFS-CP)	136.4	8.380	266.5	797.0
10	Shortages for IFT-WR targets (IFS-WR)	136.4	8.380	266.5	797.0
	Mean of Daily Instream Flow Targets (cfs) – Largest *IF* Record Water Right Controls				
11	Final Target at Control Point (IFT-CP)	538.1	30.24	602.2	2,920
12	Final Target for EFS Water Right (IFT-WR)	538.1	30.24	602.2	2,920
13	Individual Target for EFS Right (TIF-WR)	410.3	30.24	511.3	2,374
14	Shortages for IFT-CP targets (IFS-CP)	217.14	8.377	323.7	1,126
15	Shortages for IFT-WR targets (IFS-WR)	217.14	8.377	323.7	1,126
	Mean of High Pulse Component of Daily Targets and Shortages (cfs)				
16	Mean of Pulse Flow IFT-WR Targets	538.1	30.24	602.2	2,920
17	Mean of Pulse Flow TIF-WR Targets	172.8	10.69	234.2	676.0
18	Mean Pulse flow IFT-WR Target Shortages	217.14	8.377	323.7	1,126
	Mean of Subsistence and Base Flow Component of Daily Targets and Shortages (cfs)				
19	Mean of *ES* record IFT-WR Targets	391.9	19.87	383.7	2,368
20	Mean of *ES* record TIF-WR Targets	253.4	19.87	289.3	1,809
21	Mean *ES* record IFT-WR Target Shortages	137.4	3.451	158.1	774.0

Lines 6, 7, 8, 9, and 10 of Table 10.12 provide 1940-2017 means of the simulated daily *IF* record instream flow targets and shortages for the SB3 EFS at the four sites. Other more senior *IF* record water rights are located at three of the four control points. The SB3 EFS *IF* record rights employ the standard default IFM(IF,2) combining option (Table 10.11) with the target for the junior right replacing the target for the preceding more senior right in the priority sequenced simulation. Thus, the IFT-CP, IFT-WR, and TIF-WR targets (defined in Table 10.10) are all identically the same. Likewise, the IFS-CP and IFS-WR shortages are identically the same.

Table 10.13
Means for Monthly Stream Flows and SB3 EFS Targets and Shortages
at Four Sites for *SIM* Simulation M3

Control Point	LRCA58	BRSE11	BRWA41	BRRI70
Mean of Monthly Observed Flows (cfs)	1,772	297.2	2,261	7,633
Mean of Monthly Naturalized Flows (cfs)	1,844	303.8	2,570	8,073
Mean of Monthly Regulated Flows (cfs)	1,401	285.0	1,759	6,353
Mean of Monthly Unappropriated Flows (cfs)	1,011	117.7	1,176	3,984
Mean of Monthly IFT-CP Targets (cfs)	408.8	30.18	508.9	2,372
Mean of IFT-CP Target Shortages (cfs)	94.26	2.20	142.3	365.2

The daily *IF* record instream flow targets and shortages with means shown in lines 11, 12, 13, 14, and 15 of Table 10.12 are from a different simulation in which IFM(IF,2) option 2 defined in Table 10.10 is activated. With multiple *IF* record rights at the same control point, the largest target is adopted. Other *IF* record instream flow rights more senior than the SB3 EFS *IF* records are located at control points LRCR58, BRWA41, and BRRI70. These other *IF* record rights result in the final control point targets sometimes being larger and thus controlling over the SB3 EFS targets. Therefore, the IFT-CP and IFT-WR means in lines 11 and 12 are larger than the TIF-WR means in line 13. The SB3 EFS is the only instream flow right at control point BRSE11, and thus the IFT-CP, IFT-WR, and TIF-WR means in lines 11, 12, and 13 are the same.

A third simulation was performed with the SB3 EFS at each of the four control points separated into two *IF* record water rights, one *IF* record right for the subsistence/base (*ES* record) EFS component and a separate *IF* record right for the pulse flow (*PF* record) component. The average of the pulse flow targets (TIF-WR) is tabulated in line 17 of Table 10.12. The average of the subsistence/base flow targets (TIF-WR) is tabulated in line 20.

The separate daily subsistence/base and pulse flow components (TIF-WR) are plotted for comparison in Figures 10.111, 10.113, 10.115, and 10.117. The corresponding monthly means of the daily targets are plotted in Figures 10.112, 10.114, 10.116, and 10.118. The daily target volumes in acre-feet computed in the daily *SIMD* simulation are summed to monthly volumes in acre-feet within *SIMD*. Both daily and aggregated monthly quantities are included in the *SIMD* simulation results output files. The quantities are converted to cfs here to facilitate comparisons.

Tables 10.12 versus 10.13 and the plots of Figures 10.111, 10.113, 10.115, and 10.117 versus Figures 10.112, 10.114, 10.116, and 10.118 illustrate the effects of aggregating daily flows to monthly or vice versa disaggregating monthly flows to daily. The smoothing or averaging out of daily fluctuations in the aggregation to monthly is evident in the plots.

The monthly means of daily targets in Table 10.13 of 408.8 cfs, 30.18 cfs, 508.9 cfs and 2,372 cfs correspond to the TIF-WR, IFT-WR, or TIF-CP targets of 410.3 cfs, 30.24 cfs, 511.3 cfs, and 2,374 cfs in Table 10.12. The monthly targets are computed for each of the 936 individual months of 1940-2017 as the precise average or summation of daily quantities. However, the 1940-2017 means in Table 10.13 are computed by averaging 936 monthly means and thus are affected by the different number of days (28, 29, 30, or 31) in each month.

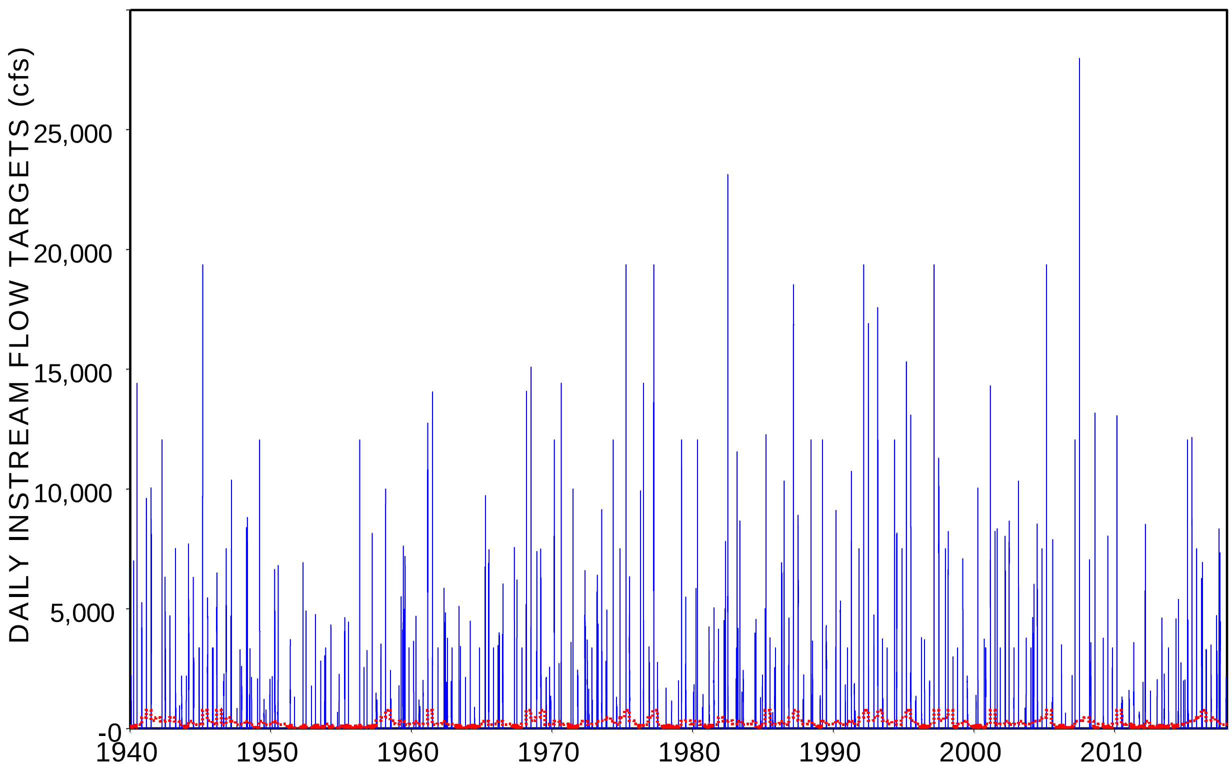

Figure 10.111 Daily Subsistence/Base Flow Targets (red dotted line) and Pulse Flow Targets (blue solid line) at Control Point LRCA58

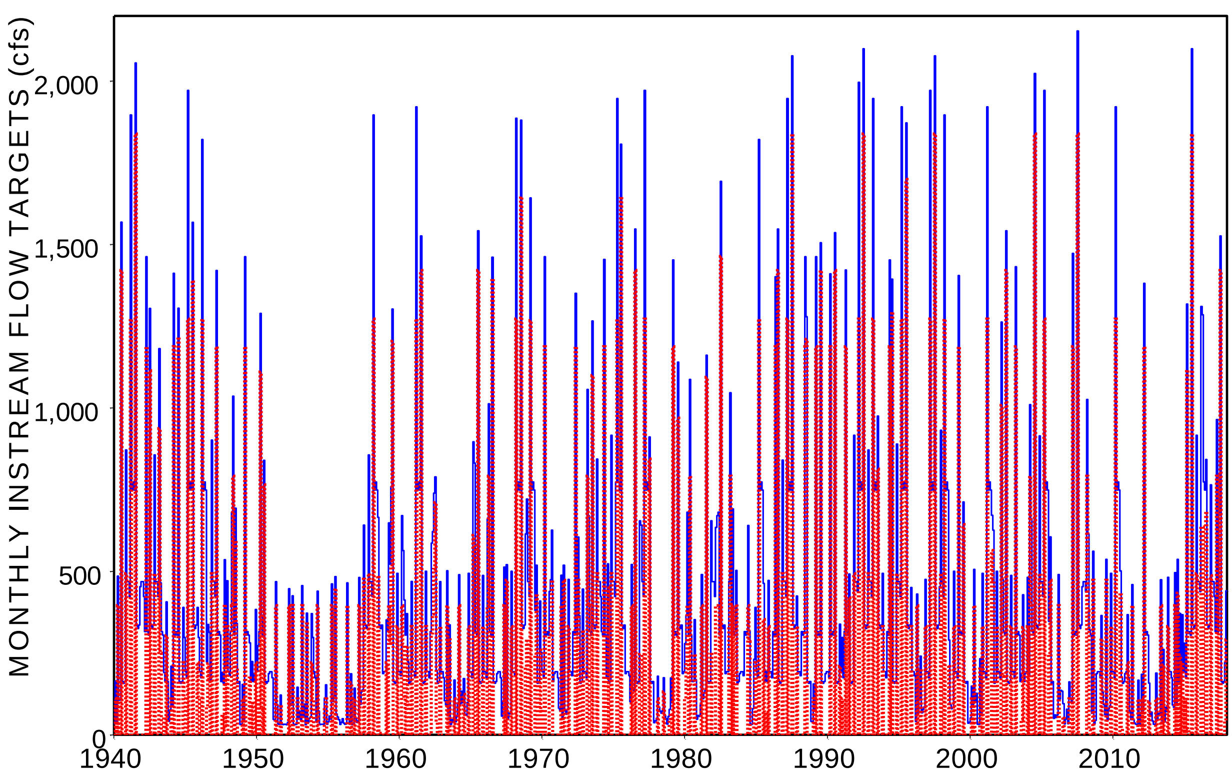

Figure 10.112 Monthly Subsistence/Base Flow Targets (red dotted line) and Pulse Flow Targets (blue solid line) at Control Point LRCA58

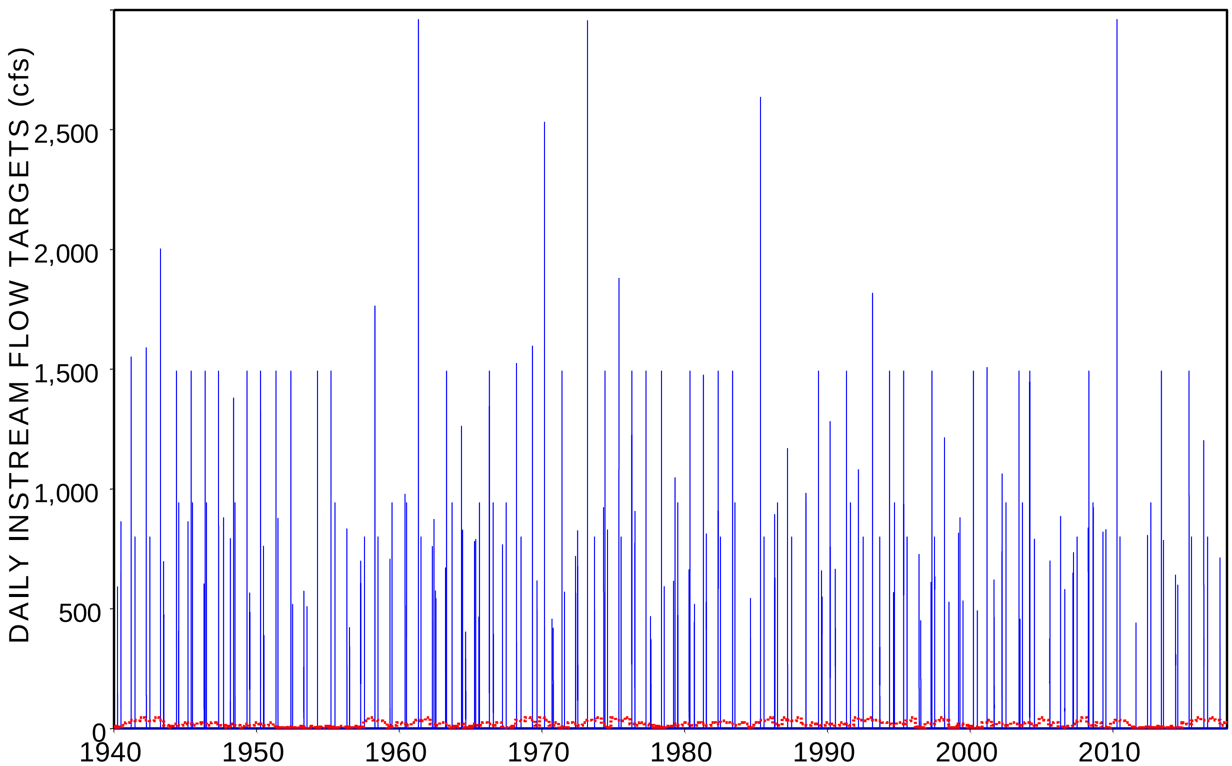

Figure 10.113 Daily Subsistence/Base Flow Targets (red dotted line) and Pulse Flow Targets (blue solid line) at Control Point BRSE11

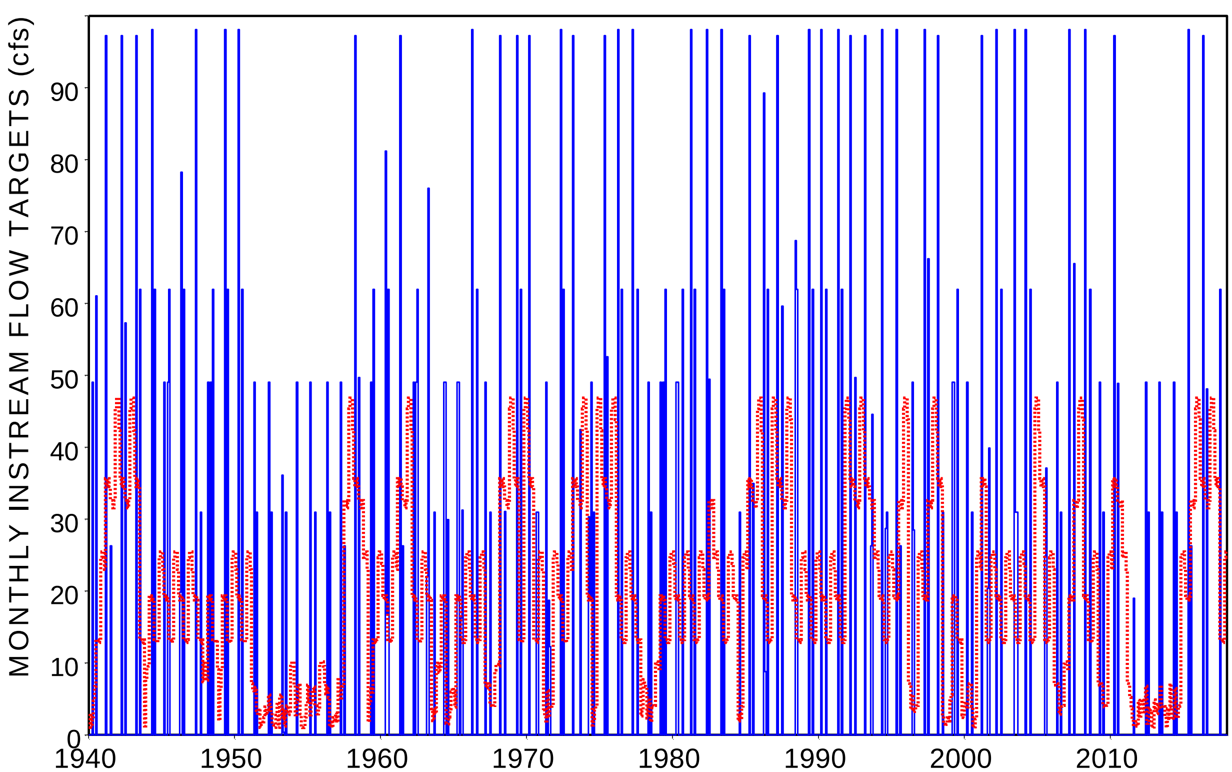

Figure 10.114 Monthly Subsistence/Base Flow Targets (red dotted line) and Pulse Flow Targets (blue solid line) at Control Point BRSE11

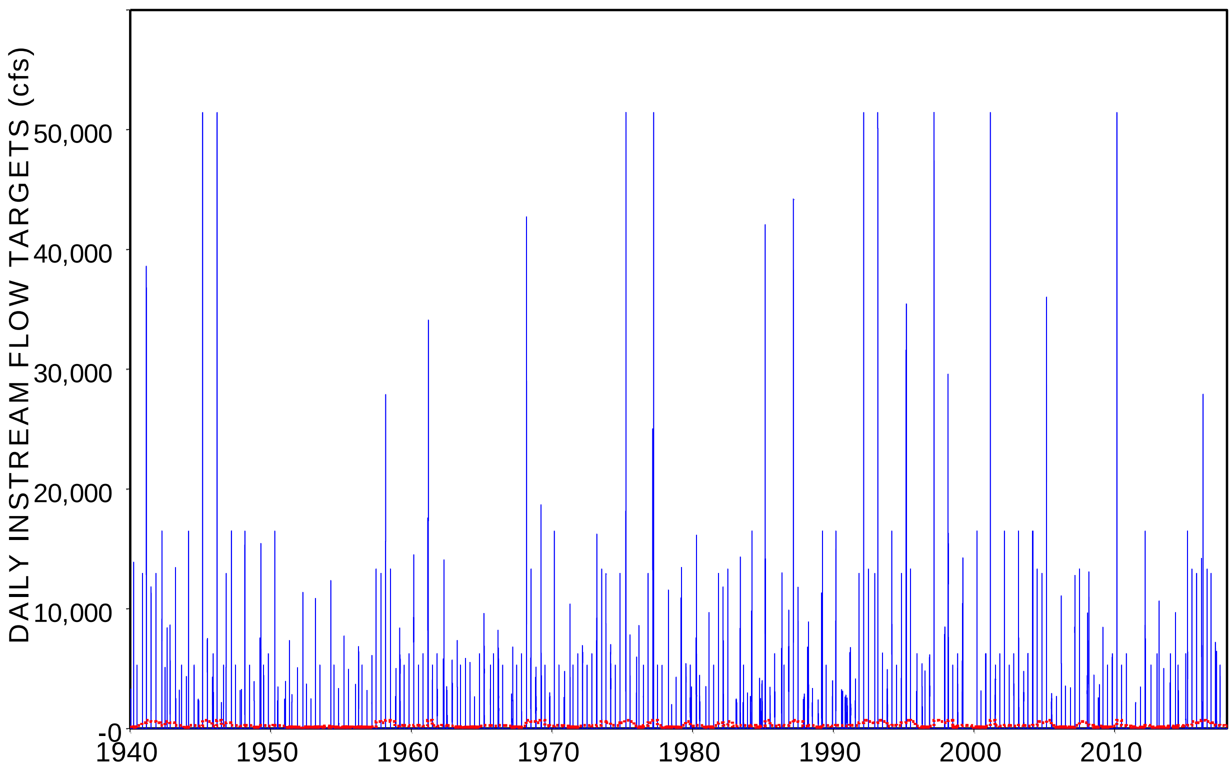

Figure 10.115 Daily Subsistence/Base Flow Targets (red dotted line) and Pulse Flow Targets (blue solid line) at Control Point BRWA41

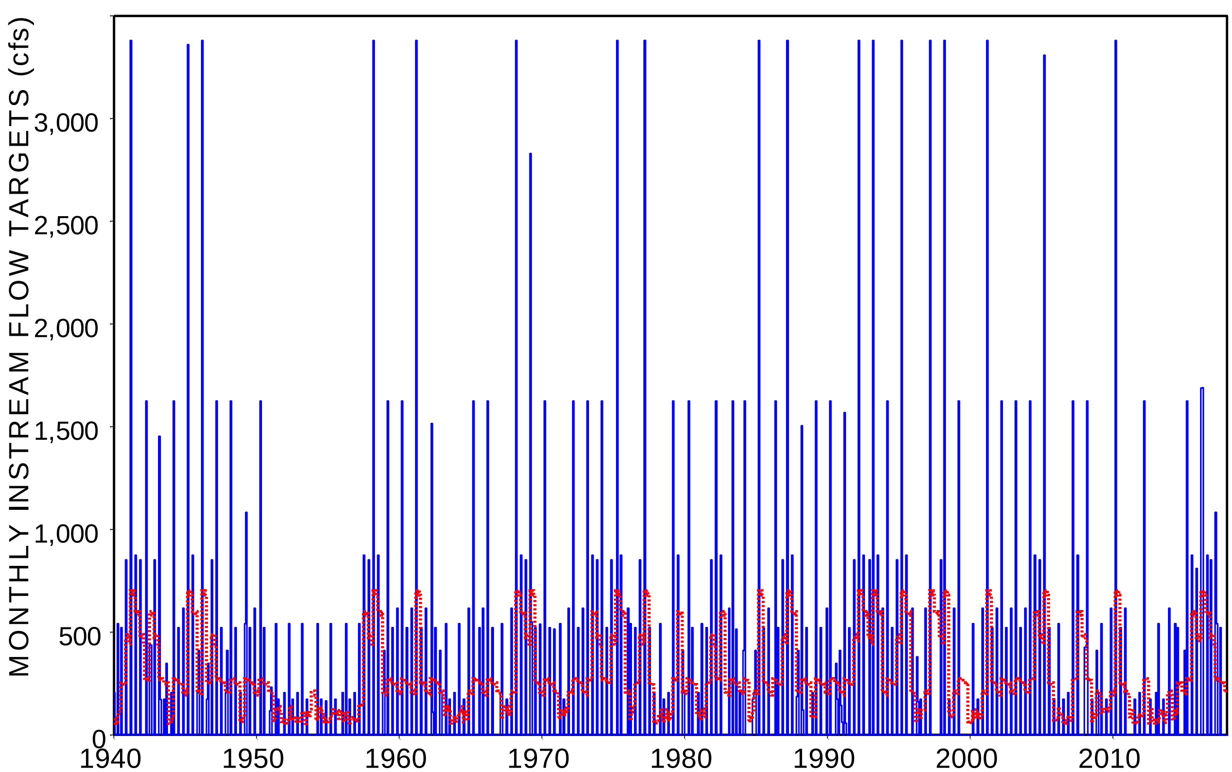

Figure 10.116 Monthly Subsistence/Base Flow Targets (red dotted line) and Pulse Flow Targets (blue solid line) at Control Point BRWA41

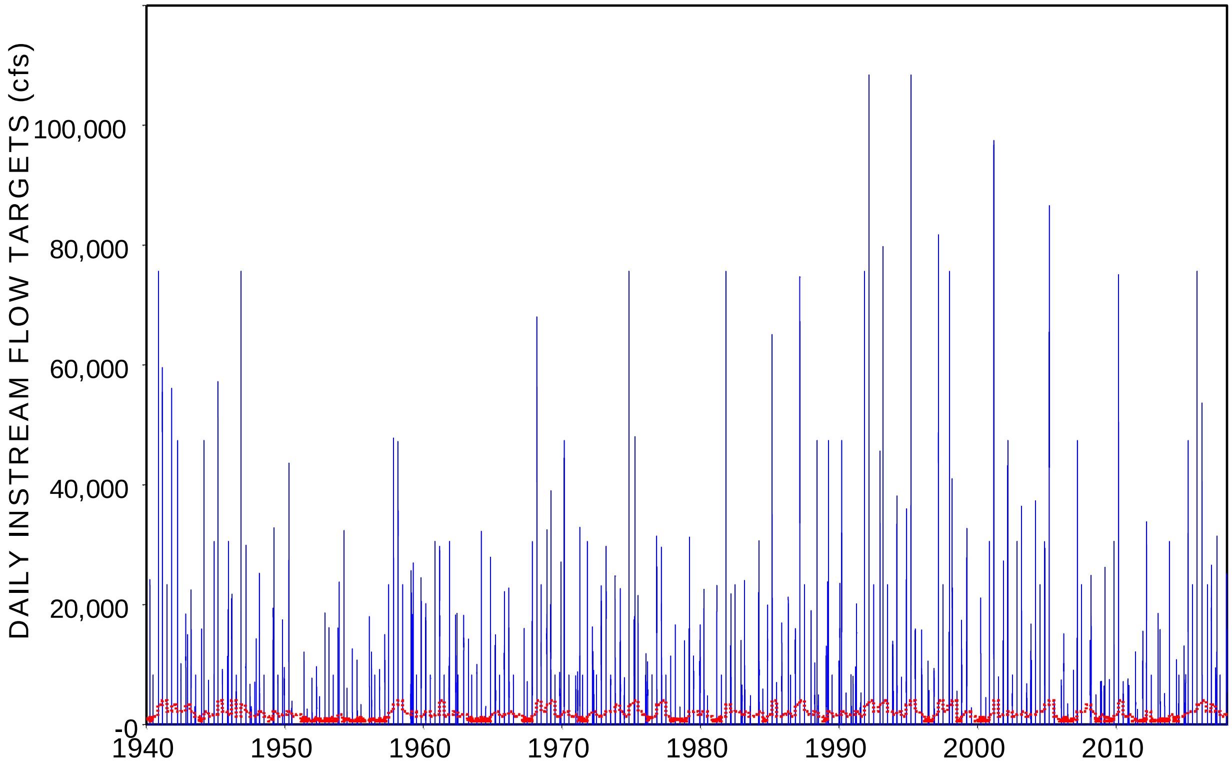

Figure 10.117 Daily Subsistence/Base Flow Targets (red dotted line) and Pulse Flow Targets (blue solid line) at Control Point BRRI70

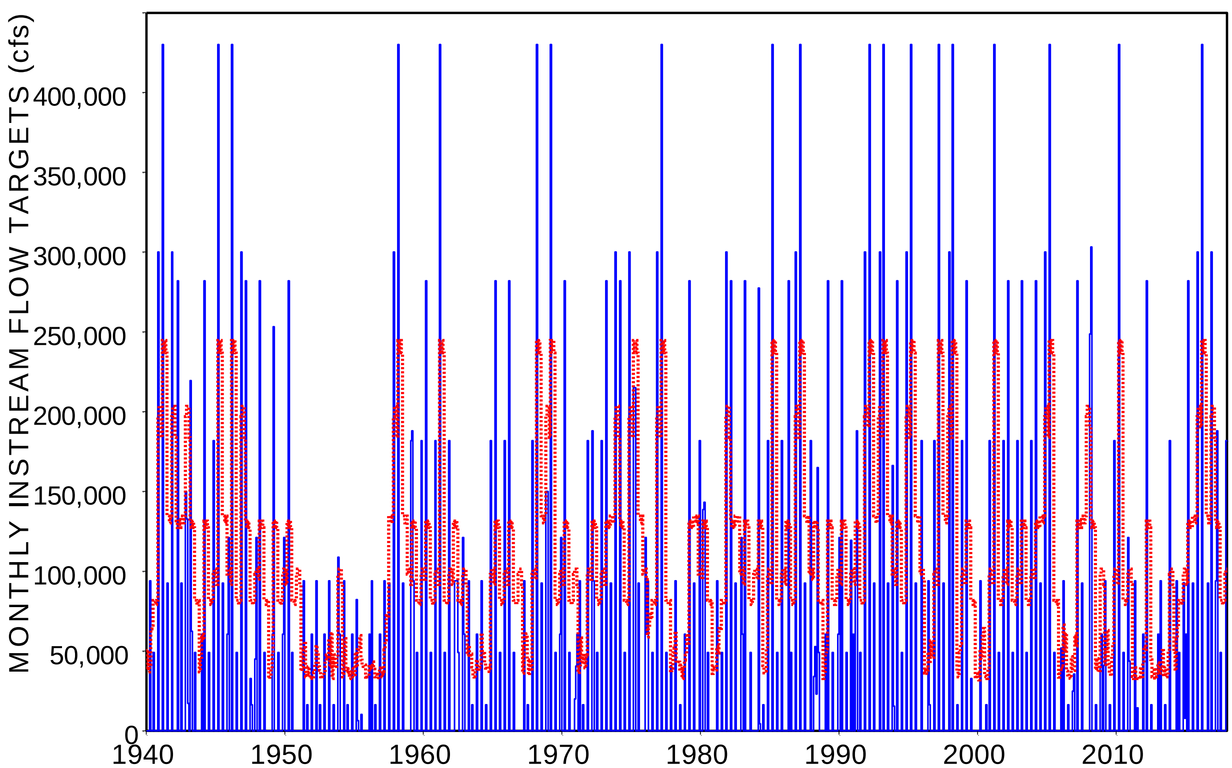

Figure 10.118 Monthly Subsistence/Base Flow Targets (red dotted line) and Pulse Flow Targets (blue solid line) at Control Point BRRI70

Shortages in Meeting the SB3 EFS Instream Flow Targets

Daily instream flow targets for the SB3 EFS are computed in the *SIMD* simulation for each day as the maximum of the computed subsistence and base flow target and pulse flow target. Subsistence and base flow targets are set as minimum flow limits defined on environmental flow *ES* records. Shortages in meeting subsistence and base flow targets are deficits between the targeted minimum flow limits and regulated stream flow at the end of the water right priority sequence simulation for the day. The high pulse flow components of the SB3 EFS controlled by pulse flow *PF* records replicate regulated flows computed within the water rights priority sequence, which differs from the final regulated flow at the completion of the priority sequence. Thus, shortages can also occur in meeting pulse flow targets.

The priorities for the *FR* record flood control operations are set junior to the SB3 EFS *IF* record water rights. However, FCDEP option 2 is activated in *FR* record field 6 which means that storing flood waters is not constrained by water availability at downstream control points. Thus, flood control operations can result in shortages in meeting SB3 EFS targets. Eight of the 19 SB3 EFS sites are located downstream of reservoirs operated for flood control. These 8 SB3 EFS sites are at USGS gaging stations also used in the flood control operations. Five of these 8 sites have multiple periods with SB3 EFS targets that are significantly larger than the maximum allowable flood flow limits tabulated in Tables 4.2, 4.3, and 4.4 and other tables in Chapter 4.

Shortages in meeting instream flow targets depend upon regulated flows. Within-month daily variations in the simulated regulated flows are averaged-out in a monthly simulation. Daily shortages in meeting D7 daily instream flow targets are computed by *SIMD* based on D7 daily regulated flows. Monthly shortages for M3 monthly instream flow targets are computed by *SIM* based on monthly regulated flows. Although SB3 EFS monthly instream flow targets are the same in the *SIM* monthly simulation M3 as the daily *SIMD* simulation D7, shortages in meeting the targets differ greatly between simulations D7 and M3. The total shortages in meeting the SB3 EFS instream flow targets are smaller in the monthly *SIM* simulation than in the daily *SIMD* simulation.

An alternative version of this strategy introduced in Chapter 5 and applied in Chapter 10 is to sum the daily targets less shortages in each month of the daily *SIMD* simulation for use as SB3 IFS targets in the monthly *SIM* simulation. This alternative approach would better reflect limitations to capabilities for meeting the SB3 EFS. The proposed strategy adopted in the D7 and M3 simulations provides a more conservative protection of SB3 EFS side-asides in the WAM.

With the strategy reflected in simulation M3 employing the final DAT file Brazos3M.DAT, after SB3 EFS targets are established with the daily WAM, routine modeling applications can employ the monthly WAM. SB3 EFS set-asides are incorporated in the monthly WAM appropriately reducing the quantities of stream flow available for further appropriation by additional junior appropriators. This strategy is appropriate for evaluating water right permit applications and various types of planning studies.

The daily WAM can also be employed directly in many other types of studies with input data varied in alternative simulations to explore various water management strategies and issues. The daily WAM should be used if assessments of capabilities for meeting the SB3 EFS, reflected by simulated levels of shortages, is of interest.

CHAPTER 11
SUMMARY AND CONCLUSIONS

This report and accompanying data files and the simulation study documented by this report serve the following purposes.

1. A daily version of the Brazos WAM was developed that may be employed for various types of studies in the future. The study documented by this report focused on using the daily WAM to develop Senate Bill 3 (SB3) environmental flow standard (EFS) instream flow targets for the monthly WAM.
2. The original 1940-1997 hydrologic period-of-analysis for the monthly Brazos WAM was extended to cover 1940-2017 for both the daily and monthly versions of the WAM.
3. Both the conversion of a monthly WAM to daily and the update of the hydrologic period-of-analysis employs an array of recently developed input data compilation and computational methodologies. The Brazos WAM case study facilitated testing, evaluating, comparing, and improving these new modeling capabilities.
4. The case study also supported testing and debugging of the *SIMD* and *SIM* computer programs. Several problems in the July 2018 developmental version of the programs were detected and corrected during the Brazos WAM simulation studies, contributing to the May 2019 WRAP.
5. This report and accompanying data files provide an illustrative example for model-users interested in better understanding WRAP/WAM modeling capabilities and the tasks, data, and choices required in employing the various features of the modeling system.
6. In addition to *SIM/SIMD* input and output files, other relevant datasets were compiled as DSS files that may be used in future WAM updates and various other types of studies.

Expanded Brazos WAM

The expanded Brazos WAM for the authorized use scenario (run 3) allowing *SIM* and *SIMD* simulations with either daily or monthly computational time steps includes the following input files which accompany this report.

Brazos3M.DAT and Brazos3D.DAT
BrazosHYD.DSS
Brazos.DIS
Brazos.DIF

The monthly DAT file with filename Brazos3M.DAT contains 19 *IF* record instream flow rights that model SB3 EFS with target series *TS* records derived from daily WAM simulation results using the DAT file with the filename Brazos3D.DAT. A single hydrology input DSS file with the filename BrazosHYD.DSS and the same flow distribution file Brazos.DIS are read by both the monthly *SIM* and daily *SIMD*. The daily input file Brazos.DIF is relevant only for a daily *SIMD* simulation. Simulations D7 and M3 defined in Tables 10.2 and 10.3 of Chapter 10 were performed with these input datasets. The other alternative simulations were performed with variations thereof.

Twelve different types of *SIM* and *SIMD* input files and 13 different types of *SIM* and *SIMD* output files are described in the *Reference* and *Users Manuals* [1, 2]. Only DAT, DSS, DIS, and DIF simulation input files and OUT, SUB, and DSS simulation output files are used in the simulations discussed in Chapter 10 of this report. The *SIM/SIMD* OUT and SUB files were used with *TABLES* primarily for frequency analyses. The DSS input and output files are accessed with *HEC-DSSVue* primarily to prepare plots and compute frequency analysis statistics.

The *SIM* and *SIMD* simulations discussed in Chapter 10 create Brazos WAM DSS output files with the filenames Brazos3M.DSS and Brazos3M.DSS. The set of DSS files that accompany this report includes a file with filename BrazosSimulationResults.DSS that contains results from simulations D7 and M3 of Chapter 10. Output control records and DSS pathnames for this output file are illustrated by Tables 9.6 and 9.7 of Chapter 9.

Auxiliary Data Storage System (DSS) Datasets

In addition to the *SIM/SIMD* input and output files, this report is also accompanied by the following four DSS files which are introduced in Chapter 1 and explained in Chapters 5, 6, 7, and 8. The organization, format, and content of these files are summarized in Chapter 9.

BrazosPHDI.DSS
BrazosDailyFlows.DSS
BrazosMonthlyFlows.DSS
BrazosEvapPrecip.DSS

The datasets stored in these DSS files can be explored with HEC-DSSVue to develop a better understanding of Brazos WAM hydrology and/or used in future updates of the WAM hydrology. The datasets can also support other research or planning studies involving comparative analyses of stream flow characteristics and investigations of river system hydrology independently of the WRAP/WAM *SIM* and *SIMD* simulation models.

The Hydrologic Engineering Center Data Storage System (HEC-DSS) and HEC-DSSVue interface provide comprehensive capabilities for managing, organizing, searching, tabulating, and plotting large time series datasets and performing statistical analyses and mathematical operations.

SIM and *SIMD* Hydrology

The *SIM/SIMD* input file with filename BrazosHYD.DSS contains monthly naturalized flow *IN* records for 77 control points (Chapter 7), evaporation-precipitation *EV* records assigned 67 control point identifiers (Chapter 8), daily flow *DF* records for 58 control points (Chapter 6), hydrologic index *HI* records for the lower, middle, and upper Brazos River Basin (Chapter 5), and target series *TS* records for 19 SB3 environmental flow standard instream flow rights (Chapter 5).

The original monthly Brazos WAM has a hydrologic period-of-analysis of January 1940 through December 1997. The 1998-2017 hydrology extension was compiled from available data that were developed differently than the original 1940-1997 hydrology as explained in Chapters 6, 7, and 8 of this report. The January 1998 through December 2017 extension can be easily switched on or off in simulation studies. With the hydrology input data covering 1940-2017, a simulation for 1940-2017, 1940-1997, or any other sub-period between 1940 and 2017 can be performed by setting *YRST* and *NYRS* on the *JD* record in the DAT file.

Monthly Naturalized Flows at 77 Primary Control Points on *IN* Records

Monthly naturalized flows at over 3,700 secondary control points are synthesized during the *SIM* or *SIMD* simulation based on the flows at 77 primary control points and information provided on *CP* records in the DAT file and *FD* and *WP* records in the flow distribution file. Flow distribution option 6 based on drainage area ratios and channel loss factors is employed for synthesizing monthly naturalized flows at most secondary control points in the Brazos WAM.

The 77 primary control points for which naturalized flows are provided in the hydrology input file are listed in Table 2.8. The original 1940-1997 sequences of monthly naturalized flows at 72 of the 77 primary control points were developed by adjusting actual observed flows recorded at USGS gaging stations. Gaps in the records at many of the 72 gages were synthesized by regression analyses using flows at other gages. Naturalized flows at two of the primary control points were developed by adjusting gaged releases from reservoirs. The other three primary control points represent the Gulf of Mexico outlets for the Brazos River and two coastal basin streams.

Gage records for 1998-2017 are available at 50 of the 77 primary control points. Gages have been discontinued with no recorded flows for 1998-2017 at 22 of the gage sites.

The 1940-1997 monthly naturalized flows in the TCEQ WAM are adopted without modification in the expanded WAM. The following two other sets of naturalized flows were compiled and are included in the DSS files noted in the preceding section of this chapter.

1. 1998-2015 flows at 73 control points were developed by Freese and Nichols for the Brazos River Authority in conjunction with submission to the TCEQ of a system operations permit application and water management plan. All 73 primary control points in the Brazos River Basin are included, but the four control points in the San Jacinto-Brazos coastal basin are not.
2. 1998-2017 sequences of naturalized flows at all 77 primary control points were synthesized with the calibrated WRAP program *HYD* hydrologic model as described in Chapter 7.

The naturalized monthly flows adopted for the *SIM/SIMD* input file BrazosHYD.DSS consists of the following data sequences selected and combined as discussed in Chapter 7.

1. The 1940-1997 sequences at 77 control points from the TCEQ WAM.
2. The 1998-2015 sequences at 73 control points developed by Freese and Nichols for the Brazos River Authority in conjunction with the system operations permit application and water management plan.
3. 2016-2017 sequences at the 73 control points in the Brazos River Basin and 1998-2017 sequences at 4 control points in the coastal basin consisting of a combination of observed flows at USGS gages and flows synthesized with the *HYD* hydrologic model.

Sixty-Seven Net Evaporation-Precipitation Rate Sequences on *EV* Records

The original Brazos WAM evaporation EVA input file contains 67 sets of *EV* records with January 1940 through December 1997 sequences of monthly net reservoir surface evaporation-precipitation depths. The Freese and Nichols WAM update for the BRA system operations permit and associated water management plan included extending the original 1940-1997 evaporation-precipitation rates through December 2015 using the same basic methods used in compiling the original WAM dataset during 2000-2001. The work also included minor revisions to earlier data. The TCEQ/FN/BRA monthly evaporation-precipitation rates as well as monthly naturalized flows are adopted for the daily Brazos WAM for the period 1940-2015.

The WRAP program *HYD* was applied as described in Chapter 8 to develop an alternative set of 67 sequences of 1998-2017 monthly *EV* record evaporation-precipitation rates. The final adopted *EV* records consist of 1940-2015 quantities from the TCEQ/FN/BRA dataset combined with 2016-2017 quantities from the *HYD* generated dataset. The *EV* records were converted from EVA file format to DSS file format for incorporation in the input file BrazosHYD.DSS.

The parameter EPADJ in *JD* record field 10 is -1 in all versions of the Brazos WAM. This input parameter activates a methodology within *SIM* and *SIMD* for correcting the net evaporation less precipitation depths from the *EV* records for runoff from land area covered by reservoirs. This methodology is explained in Chapter 3 of the *Reference Manual* [1].

<u>Daily Pattern Hydrographs at 58 Control Points on *DF* Records</u>

The monthly naturalized flows at the over 3,800 primary and secondary control points are disaggregated to daily in a *SIMD* simulation based on the *DF* record daily flow pattern hydrographs input for 58 control points. The monthly naturalized flow volumes in acre-feet/month are allocated to daily volumes in acre-feet/day for each day of each month while maintaining the same monthly volumes. The flows at 58 control points are automatically repeated at the numerous other control points using an algorithm activated in *SIMD*.

Initial 1940-2017 pattern hydrographs of daily mean flow rates in cfs at the 58 control points were developed as described in Chapter 6 and stored as *DF* records in a DSS file. Some of the 1940-2017 sequences reflect combinations of flows from different data sources and/or different stream locations. Daily flow volumes in acre-feet/day at the 58 sites were computed with *SIMD* by combining monthly naturalized flow volumes with the initial daily flow pattern hydrographs in cfs from the first step described above. These final *DF* record daily flows represent 1940-2017 daily naturalized flow volumes, rather than just flow patterns, and have units of acre-feet/day.

The compilation of daily flows for the *DF* record pattern hydrographs is documented by Chapter 6. Unregulated daily flows for January 1940 through December 1997 from an USACE modeling system are adopted for 37 control points (16 primary and 21 secondary). Observed flows from USGS gages are adopted for January 1998 through December 2017 for these 16 gaged and 21 ungaged sites. Only relative, not absolute, magnitudes of daily flows within each month are relevant in the initial pattern hydrographs. Thus, months of daily flows from two or more different sources or sites were combined to develop complete 1940-2017 sequences at all relevant sites.

The preceding paragraph covers 37 of the 58 control points with *DF* records. Observed daily flows for 1940-2017 recorded at USGS gaging stations were adopted for the other 21 control points. The 21 WAM control points are located at USGS gage sites. However, gage records for eleven of the 21 gages have gaps with missing data. The gaps were filled in with flows recorded at other gages. Gage selections are tabulated and explained in Chapter 6.

SB3 EFS Hydrologic Indices for Three Regions on *HI* Records

The Senate Bill 3 (SB3) environmental flow standards (EFS) for the Brazos River system are unique in that the Palmer hydrologic drought index (PHDI) was adopted by the Expert Science Team [24], Stakeholder Committee [25], and TCEQ [23] for defining hydrologic conditions. Hydrologic conditions for the SB3 EFS for the other river systems with SB3 EFS established to date are defined based on preceding reservoir storage levels or preceding 12-month stream flow.

Hydrologic conditions for the 19 SB3 EFS *IF* record instream flow rights are defined in the daily Brazos WAM by hydrologic indices recorded on three hydrologic index *HI* records in the hydrology input DSS file representing three regions (watersheds) of the Brazos River Basin: Upper Basin above Possum Kingdom Dam, Lower Basin below Whitney Dam, and Middle Basin between Possum Kingdom Dam and Whitney Dam. Each *HI* record contains a monthly 1940-2017 sequence of numbers that are either 1, 2, or 3 signifying dry (1), average (2), or wet (3) conditions in the lower, middle, and upper Brazos River Basin. The hydrologic conditions are defined based on whether the PHDI falls within the lowest PHDI quartile (dry), middle two quartiles (average), or highest quartile (wet).

The PHDI frequency statistics were originally developed by the Expert Science Team [24] from area-weighted 1895-2010 values of the monthly PHDI. The statistics were recomputed in the present study with 1895-2017 values for the PHDI. The original (1895-2010) and updated (1895-2017) frequency statistics are compared in Table 5.5. The differences are small.

The area-weighted PHDI were recomputed in this study for the three regions along with an extension through 2017. The 1895-2010 PHDI quartile based criteria originally developed by the Expert Science Team [24] and published by the TCEQ in the Texas Water Code [23] were applied in assigning the PHDI-based hydrologic index classification of 1 (dry), 2 (average), or 3 (wet) on the hydrologic index *HI* records for each month of 1940-2017 for each of the three regions.

Daily Modeling System

The daily *SIMD* simulation model includes all the modeling capabilities of the monthly *SIM* simulation model, adjusted if and as necessary for a daily computational time step. *SIMD* includes additional disaggregation, routing, and forecasting features needed and/or relevant for dealing with complexities in a daily model that do not occur in a monthly simulation. The daily computational time step provides opportunities not possible with a monthly time step to add reservoir flood control operations and high pulse flow components of environmental flow standards to the model.

The *SIMD* simulation model is the central component of the daily modeling system. *TABLES* and *HEC-DSSVue* provide a variety of capabilities for managing, organizing, and analyzing either *SIM* or *SIMD* input datasets and simulation results. Methods for calibrating flow routing parameters are implemented in the WRAP program *DAY*. The concepts and methodologies employed in the WRAP modeling system are documented by the *Reference Manual* and auxiliary *Daily Manual.* The logistics of preparing input records shared by *SIM* and *SIMD* and additional *SIMD*-only records are explained in Chapters 3 and 4, respectively, of the *Users Manual*. Instructions for using *TABLES* and *HEC-DSSVue* with either daily or monthly input or output datasets are found in Chapters 5 and 6 of the *Users Manual*. The daily WRAP programs *DAY* and *DAYH* are documented in Appendices A and B of the *Daily Manual*.

Either *SIMD* or *SIM* can be employed to perform a monthly simulation with an input dataset prepared for a monthly simulation that contains no input records that are applicable only to *SIMD*. The monthly *SIM* can also be employed to perform a monthly simulation with an input dataset prepared for a daily simulation that contains input records that are applicable only to *SIMD*. *SIM* simply skips over daily-only *SIMD* records. However, a monthly *SIMD* simulation terminates with an error message if a daily-only *SIMD* input record is found in the DAT file.

Modeling Options Adopted for the Daily Brazos WAM

This report, including the following discussion, deals specifically with the Brazos WAM. However, the options adopted, lessons learned, and experience base acquired in this case study are also relevant to the future development of daily WAMs for other river basins.

SIMD capabilities listed in Table 11.1 are a series of optional modeling features that can be added singly or in combination to convert a monthly WAM to daily. Much of the complexity of both *SIM* and *SIMD* is due to the models containing multiple optional alternative methods for performing the same tasks. A choice of optional methodology leads to another list of choices of options for implementing that selected methodology. Several *SIMD* modeling tasks are listed in the first column of Table 11.2. Multiple alternative approaches are provided in *SIMD* for performing each of these tasks. Methods adopted for the daily Brazos WAM are listed in the second column of Table 11.2. The third column of Table 11.2 lists other options that are not chosen for use with the final daily Brazos WAM.

Table 11.1
Daily WRAP Modeling System

Simulation of River/Reservoir Water Management/Use System with *SIMD*

- All *SIM* monthly simulation capabilities are replicated in *SIMD*.
- Additional *SIMD* capabilities that are not available in *SIM*.
    1. Monthly-to-Daily Disaggregation of Naturalized Stream Flows
    2. Monthly-to-Daily Disaggregation of Other Quantities
    3. Routing Flow Changes Caused by Water Rights
    4. Stream Flow Forecasting for Assessing Water Availability
    5. Additional Negative Incremental Flow Option and other Adjustments
    6. Simulation of Reservoir Operations for Flood Control
    7. Tracking High Pulse Flow Events for Environmental Flow Standards

Management/Analysis of *SIMD* Input Datasets with *TABLES* and *HEC-DSSVue*

Management/Analysis of *SIMD* Simulation Results with *TABLES* and *HEC-DSSVue*

Calibration of Routing Parameters Using Program *DAY*

Table 11.2
SIMD Simulation Options Adopted for Brazos WAM and Recommended for Other WAMs

Modeling Function	Final Adopted Methods	Other Alternatives Not Adopted
time series input file	DSS file	FLO, EVA, FAD, TSF, HIS files
flow disaggregation	default DFMETH option 4	DFMETH options 1, 2, 3
target disaggregation	uniform	*JU* and *DW* record DND or ND
other water right options	only monthly options adopted	*DW* and *DO* record daily options
routing flow changes	lag and attenuation	Muskingum routing
routing parameter calibration	*DAY* statistical method	*DAYH* optimization options
negative incremental flows	NEGINC option 4	NEGINC options 1, 2, 3, 5, 6, 7, 8
next month placement	beginning priority sequence	within priority sequence
flow forecasting	no forecasting	wide range of forecast periods

Daily Versus Monthly Simulation Models

Computer simulation models are simplified approximations of real-world systems designed to provide meaningful information for relevant types of modeling and analysis applications. Actual real-world stream flow and other variables simulated in water availability modeling fluctuate continuous over time. Simulation model computations dealing with continuously varying variables are necessarily performed based on fixed computational time intervals. The monthly *SIM* completely ignores within-month variability. Both *SIMD* and *SIM* completely ignore within-day hourly or continuous instantaneous variability which can be relevant for certain modeling applications and situations, such as simulating flood events resulting from intense rainfall on relatively small watersheds.

The effects of computational time step choice on simulation results vary with different water management modeling situations and applications. Flood control reservoir operations, high pulse environmental flow requirements, and the interactions between environmental flow requirements and flood control operations are key aspects of water management that can be modeled much more accurately with a daily WAM than with a monthly WAM. Daily models are required for modeling both the high flow pulse components of environmental flow standards and reservoir operations during floods due to the extreme variability characteristic of stream flow.

Either monthly WAMs or daily WAMs may provide more accurate assessments of water supply availability/reliability depending on the situation. The accuracy of modeling water supply capabilities may or may not be improved by converting from a monthly to a daily WAM. A monthly WAM may be more accurate than a daily WAM in accessing water availability for water supply due to: the complexities of streamflow translation and attenuation modeled by routing and forecasting; disaggregation and associated limitations on available stream flow and water use data; and other aspects of daily modeling. Daily modeling requires major additional input data compilation efforts and is significantly driven by data availability.

The Texas WAM System is appropriately and effectively constructed based on a monthly computational time step. The month is the optimum time interval for the WAM System. However, environmental flow standards can be modeled much more accurately using a daily interval. In general, all components of environmental flow regimes can be modeled more accurately with a daily than with a monthly model. However, improved accuracy in tracking high pulse flows is represents a particularly significant advantage of daily modeling.

Stream Flow Variability

The great variability of stream flow is the primary factor responsible for the differences between the monthly versus daily simulations. The plots of observed, naturalized, and simulated stream flow found throughout this report illustrate the continuous variability and occasional extreme fluctuations that are characteristic of river flows throughout the Brazos River Basin and throughout Texas. Modeling within-month stream flow variability is the most significant aspect of the daily simulation model. Developing daily pattern stream flow hydrographs is the most important aspect of converting from a monthly to daily WAM.

In a daily simulation, refilling reservoir storage and meeting water supply demands in each day depends on the volume of stream flow available in that day. A monthly simulation averages stream flow availability over the month, generally resulting in more stream flow being available for filling reservoir storage and supplying diversion targets, while correspondingly reducing the unappropriated flows leaving the river system at the outlet. Instream flow targets and shortages are significantly affected by stream flow variability. Environmental high flow pulse standards are completely defined by stream flow variability.

The *DF* record daily flow pattern hydrographs compiled for 58 control points and employed to disaggregate monthly naturalized flows to daily at the over 3,800 control points in the Brazos WAM are described in Chapter 6. Only relative, not absolute, magnitudes of daily flows within each month are relevant for the daily flow pattern hydrographs. The *DF* record daily flows are a combination of unregulated flows from a U.S. Army Corps of Engineers Fort Worth District reservoir system operations model and observed flows recorded at USGS gaging stations. In some cases, flows recorded at another gage are used to fill in missing flow records at a particular site.

The flow pattern hydrographs are considered to provide a valid, reasonably accurate representation of stream flow variability at most of the over 3,800 individual control points. Since flows at numerous sites are represented by flows developed for only 58 sites, the *DF* record flows do not capture the lag and attenuation effects of the river reaches between the many control points for which the flows are repeated.

Routing of Flow Changes

Streamflow depletions for diversions and refilling reservoir storage, reservoir releases, and return flows result in stream flow changes that propagate through river reaches to downstream control points. An option allowing return flows to be returned in the next month is commonly employed in monthly WAMs to allow senior rights access to upstream junior return flows. Otherwise, a monthly *SIM* simulation has no routing. Flow changes are assumed to propagate to the river system outlet within the current month. This is an approximation since, in reality, the effects of diversions and refilling reservoir storage late in a particular month may still be propagating downstream during the first week or two of the next month.

The daily *SIMD* routing computations consist of lag and attenuation adjustments to the flow changes that occur as each of the water rights is considered in the priority-based simulation computations. Without routing, streamflow changes propagate to the outlet in the same day that they originate, with no lag, in a daily *SIMD* simulation analogously to a *SIM* monthly simulation.

The lag and attenuation routing method and calibration of routing parameters are described in Chapters 3 and 4 of the *Daily Manual* [4]. The routing parameters are stored on *RT* records in the daily input DIF file and are described in Chapter 4 of the *Users Manual* [2]. The routing computations are performed at the control points specified on the *RT* records but conceptually represent changes occurring gradually along river reaches.

Calibrating routing parameters and performing routing computations in the *SIMD* simulation for the river reaches between all control points is not feasible. Routing parameters are determined for only selected river reaches defined by stream flow gages. The routing computations are performed for only a sub-reach of each of the selected reaches. The daily Brazos WAM with over 3,800 control points includes routing parameters at 67 control points.

Development of the normal flow and high flow lag and attenuation parameters at 67 control points is described in Chapter 3. Routing parameter calibration is based on statistical analyses of flow changes detected in observed flows between USGS gages. Observed actual lag and attenuation characteristics of flow changes in actual gaged river reaches were found to exhibit great apparently random variability that is difficult to describe or explain. Calibrated values for the lag and attenuation parameters for the *SIMD* routing algorithm also exhibit great unexplained variability and associated uncertainty.

The *SIMD* routing algorithm simulates lag and attenuation of flow changes in free flowing stream reaches, not reservoirs. However, surcharge storage in reservoirs either with or without flood control pools can be modeled in the flood control routines using *FV/FQ* record reservoir storage volume versus outflow tables. However, *FV/FQ* records are used in the daily Brazos WAM only for modeling gated flood control pools of the USACE reservoirs.

The routing algorithm incorporated in the *SIMD* simulation is a very simplistic model of a very complex phenomena. However, adding greater complexity to the model would likely not improve the accuracy of the model. Likewise, further improvements to the recently developed new parameter calibration methodology would likely not further improve the accuracy of the model.

Routing is very approximate with inherent simplifications, uncertainties, inaccuracies, and variabilities. However, in general, this may not be a major concern because simulation results tend to not be overly sensitive to routing strategies and the values of routing parameters. The simulation study presented in Chapter 10 demonstrates the relative lack of sensitivity of simulation results to whether or not routing is employed at all. In many typically situations, reasonable simulation results can be obtained without routing and, with routing, results vary only minimally with significant changes to routing parameter values.

The daily Brazos WAM is a valid simulation model without any routing at all. However, routing with the calibrated parameters described in Chapter 3 are included in the WAM. Routing is considered to improve model validity even though not being essential to model validity.

Forecasting of Future Stream Flows

The simulation study presented in Chapter 10 explores and supports the following findings which are discussed further in this final summary and conclusions chapter.

1. Routing is very approximate, does not dramatically affect simulation results, but probably contributes positively to model validity.
2. Forecasting greatly impacts simulation results and adversely affects WAM accuracy and validity. Forecasting is not employed in the final Brazos WAM that accompanies this report but can easily be switched on and off in future studies.
3. Interactions between negative incremental flow adjustments, routing, forecasting, and other flow adjustments are complex. Negative incremental flow adjustment options in particular significantly affect stream flow availability in the water rights priority simulation. Flow forecasting significantly magnifies these effects by considering all days of the forecast period.

The monthly *SIM* and daily *SIMD* simulation algorithms for determining the amount of stream flow available to each water right are based on the minimum of the flows at the control point of the water right and all downstream control points. The reason for considering all downstream control points is to assure that a water right does not appropriate stream flow that has already been appropriated by other more senior water rights. With forecasting in a daily *SIMD* simulation, water availability depends on flows at downstream control points in future days as well as in the current day. The amount of streamflow available for refilling reservoir storage and supplying diversion targets for a water right at a particular control point in a particular day is set as the minimum available flow at that control point and many downstream control points in that day and, with forecasting, during the multiple days of the forecast period. Stream flow variability, routing inaccuracies, and other complexities may result in water availability being over-constrained by the consideration of many downstream control points and additional future days.

The *SIMD* forecasting algorithm is applicable only in a daily, not monthly, simulation. Also, forecasting is relevant only if routing is employed. Forecasting and accompanying reverse routing, as explained in Chapter 3 of the *Daily Manual* [4], are designed specifically to deal with the effects of water right actions in a particular day on downstream stream flows in future days, as reflected in routing computations. Due to routing (lag and attenuation), stream flow depletions, return flows, and reservoir releases in the current day can affect both (1) stream flow availability for downstream senior water rights in future days and (2) flood flow capabilities for releases from flood control pools. Forecasting serves the two purposes of: (1) protecting senior water rights in future days from the lag effects associated with stream flow depletions of junior water rights located upstream in the current day and (2) facilitating reservoir flood control operations by preventing current day releases from flood control pools that contribute to flooding in future days.

A monthly simulation inherently assumes that the effects of water right diversions and refilling reservoir storage on stream flow propagate to the outlet of the river system within the month. Routing and forecasting are relevant in a daily simulation. The effects of reservoir refilling and releases and water supply diversions and return flows during the current day may affect downstream river flows over a number of future days. With routing activated, forecasting serves to protect downstream senior water rights and prevent excessive reservoir flood control pool releases that contribute to exceeding maximum non-damaging flow limits at downstream gages.

The default automatically computed forecast period for the daily Brazos WAM is 93 days, which is computed within *SIMD* as twice the longest flow path measured in lag time plus one day. This option is conceptually based on preventing any impact of actions of junior water rights today on senior water rights in future days. The alternative simulations presented in Chapter 10 also include alternative forecast periods of 15 days and 30 days.

Forecasting greatly increases computer execution times. Run times for the simulations presented in Chapter 10 vary from 12 seconds for the monthly WAM, to 8 minutes and 22 seconds for the daily WAM with no forecasting, or over six hours for a daily *SIMD* simulation with a 30 day forecast period. The 1940-2017 period-of-analysis consists of 936 months or 28,490 days. For a daily simulation with forecasting, the simulation is repeated for each day of forecast period as the simulation progresses through each of the 28,490 simulation days.

Forecasting of future stream flow is highly uncertain in actual real-time water management, with inaccuracies increasing with the length into the future of the forecast period. The selection of a *SIMD* forecast period is largely arbitrary. Routing parameters are inherently highly uncertain and inaccurate. Routing inaccuracies contribute to forecasting inaccuracies. Tradeoffs between dealing with modeling issues inherent in negative incremental flow adjustments, routing, forecasting, and other *SIMD* options may vary between WAMs and between different WAM applications.

Other Modeling Features that Interact with Routing and Forecasting

As previously noted, forecasting is not employed in the final proposed daily Brazos WAM. Negative incremental flows during the forecast simulation is a consideration in the determination to not activate forecasting. Deactivating forecasting prevents over-constraining of stream flow availability by negative incremental flows as well as by various other flow conditions.

Negative incremental naturalized stream flows are a significant issue in monthly *SIM* simulations and have a much greater effect in a daily *SIMD* simulation. Negative incremental flows refer to time periods (days or months) during which the naturalized flow at the downstream end of a river reach are smaller than the flow at the upstream end. The several alternative negative incremental flow adjustment options including the recommended standard options for monthly and daily simulations are explained in Chapter 3 of the *Reference Manual* and Chapter 3 of the *Daily Manual*. Option 4 is generally the best ADJINC option but is not applicable to the future days in the forecast simulation. ADJINC option 7 is employed with forecasting to deal with the future forecast simulation days.

Most of the array of options for determining monthly water supply diversion targets can be replicated daily in a daily *SIMD* simulation. *SIMD* also has other options for non-uniformly distributing water supply diversion targets over the days of the month. The simulation studies presented in this report adopted the *SIMD* default of uniformly distributing monthly water supply diversion targets over the days of the month.

The selection parameters WRMETH and WRFCST in *JU* record fields 4 and 5 control the choice of next-day placement of routed flow changes. The simulations presented in this report employ the default option of placing the routed flows at the beginning of the water right priority sequence in the next day of the simulation, rather than within the priority sequence.

Reservoir Flood Control Operations

Flood control operations of the nine U.S. Army Corps of Engineers (USACE) Fort Worth District multiple-purpose reservoirs in the Brazos River Basin and *SIMD* simulation thereof are described in Chapter 4. The daily *SIMD* is necessary for WRAP modeling of reservoir flood control operations. In a monthly *SIM* simulation, outflow equals inflow with no flow attenuation (storage) whenever the reservoir is full to the top of conservation storage capacity. *SIMD* includes comprehensive capabilities for modeling the operations of single reservoirs or multiple-reservoir systems with releases controlled by a combination of dam outlet capacities and specified allowable non-damaging flow levels at any number of gaging stations located at downstream sites. Flood control operations greatly affect reservoir storage contents and downstream river flows during high flow periods but generally only minimally during non-flood periods.

The nine USACE reservoirs are operated to control flood flows at multiple downstream control points. The actual operating rules described in Chapter 4 consist of structured criteria with specified maximum flow limits at the downstream gages. However, the operating rules allow considerable flexibility for operator judgment in the continuous gate operation decisions during and after a flood regarding selecting between reservoirs for flood control pool storage and releases. Also, forecasting of flood flows over the next several days or weeks and estimation of flow travel time from the dams to downstream gages are not precise. Likewise, although *SIMD* provides a flexible array of options for simulating flood control operating rules, different reasonable representations of actual operations can yield different simulation results.

Multiple-Purpose Reservoir/River System Operations

Integration of Senate Bill 3 (SB3) environmental flow standards (EFS) in comprehensive water resources management is a key motivation for developing the daily WRAP modeling system. Future applications of the daily Brazos WAM could include more detailed investigations of the interactions between SB3 EFS and other aspects of multiple-purpose reservoir system operations and water management. Multiple-purpose reservoir system operations that enhance environmental flows while minimizing impacts on other water management purposes could be investigated in the future in simulation studies employing the Brazos WAM and future WAMs for other river basins.

No water right permits have been issued for flood control operations of the nine USACE reservoirs and hydroelectric power operations at Whitney Reservoir. Flood control and hydropower operations are not included in the monthly TCEQ WAM. Hydropower operations are not included in the current version of the daily Brazos WAM described in this report but could be added in the future. Conservation operations of Whitney Reservoir, the largest reservoir in the basin, are primarily for hydropower. Flood control operations can affect high flow pulse components of environmental flow standards and vice versa. Recreation considerations also affect reservoir operations. However, more detailed studies are required for an in depth understanding of these interactions. The daily WAM provides flexible capabilities for such future studies.

The expanded Brazos WAM documented in this report includes only the authorized use scenario DAT file, which does not include return flows from water supply diversions. The authorized use scenario WAMs do not include return flow unless specifically included in water right permits. The current use scenario WAMs do include estimates of return flows.

Senate Bill 3 Environmental Flow Standards

The work documented in this report is motivated by the need to improve capabilities for incorporating Senate Bill 3 (SB3) environmental flow standards (EFS) in the TCEQ WAM System. A strategy is demonstrated in which daily *IF* record instream flow targets for SB3 EFS are computed and summed to monthly quantities within the daily *SIMD* simulation for input to the monthly *SIM* simulation model. The monthly *SIM* simulation model is applied with the SB3 EFS modeled as *IF* record water rights with targets defined as target series *TS* records.

Alternative simulations performed in the simulation study presented in Chapter 10 are defined in Tables 10.2 and 10.3. Monthly instream flow targets for the SB3 EFS at 19 sites in the Brazos River Basin are computed in daily simulation D7 and converted to *TS* records which are copied to the hydrology input file BrazosHYD.DSS. *IF* records incorporated in the DAT file for simulation M3 access the *TS* record targets in the DSS input file. The conversion of *SIMD* simulation results to *SIM* input data is accomplished quickly and easily within HEC-DSSVue.

The SB3 EFS at 19 sites are described in Chapter 5. The 19 sets of instream flow *IF*, hydrologic condition *HC*, environmental standard *ES*, and pulse flow *PF* records that model the SB3 EFS in the daily *SIMD* input DAT file are replicated as Table 5.8. These input records control the computation of daily instream flow targets which are included in the *SIMD* daily simulation results. The daily targets in acre-feet/day are also summed to monthly targets in acre-feet/month by *SIMD* and included in the *SIMD* monthly simulation results. The monthly targets are transported within HEC-DSSVue from the *SIMD* DSS output file to the file BrazosHYD.DSS as *TS* records with pathnames shown in Table 5.9. The 19 sets of *IF* and *TS* records replicated in Table 5.10 are inserted in the monthly *SIM* DAT file to access the targets on the *TS* records in the DSS input file.

The choice between subsistence and base flow targets in each day of the *SIMD* simulation is affected by within-month stream flow variability. The determination of high pulse flow targets is totally controlled by within-month stream flow variability. Shortages in meeting instream flow targets are also greatly affected by within month stream flow variability.

The strategy outlined above precisely replicates monthly totals of daily SB3 EFS instream flow targets in the monthly WAM. However, shortages in meeting the targets differ significantly between the monthly and daily simulations as discussed in Chapter 10. Shortages in each month are differences between the regulated stream flow at the completion of the water rights priority sequence computations and the instream flow target in months in which the target exceeds the regulated flow. Shortages for the subsistence and base flow components of the SB3 EFS are differences between simulated regulated flows and the SB3 EFS regulated flow targets. Pulse flow targets replicate regulated flows within the water rights priority sequence which can differ from the regulated flows at the completion of the priority sequence from which shortages are computed.

A key consideration highlighted in the preceding paragraph is whether the particular WAM application requires primarily accurate estimates of SB3 EFS instream flow targets accompanied by only approximate estimates of shortages in meeting the targets or if accurate estimates of shortages are also important. The strategy outlined above focuses on developing accurate estimates of instream flow targets. A modified version of the strategy would be to aggregate daily targets minus daily shortages (rather than just daily targets) from the daily *SIMD* simulation results for transport to the monthly WAM for use as monthly instream flow targets. Such data manipulations can be quickly and easily accomplished. This alternative approach could perhaps provide a more accurate representation of actual capabilities for satisfying the SB3 EFS but would provide less conservative protection of the SB3 EFS in the WAM.

Different strategies for employing the expanded WAM will be useful for different types of applications. With the strategy proposed and applied in this report, after SB3 EFS targets are established with the daily WAM, routine modeling applications employ the monthly WAM. SB3 EFS set-asides are incorporated in the monthly WAM appropriately reducing the quantities of stream flow available for further appropriation by junior appropriators. This strategy is relevant for evaluating water right permit applications and various types of planning studies. However, as noted in the two preceding paragraphs, shortages or capabilities for satisfying the instream flow requirements are not accurately modeled due to the basic within-month flow variability issue.

The daily WAM can be employed directly in many other types of studies with input data varied in alternative daily *SIMD* simulations to explore various water management strategies and issues. The daily model can facilitate environmental flow studies in which assessments of capabilities (or risk of shortages) for meeting environmental flow standards are important. Daily simulation modeling capabilities also support studies in which flood control operations are a significant concern.

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