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

Ralph A. Wurbs
Texas A&M University
College Station, Texas

for the
Texas Commission on Environmental Quality
Austin, Texas

under

Contract 582-21-10039

March 2022

TABLE OF CONTENTS

Chapter 1 Introduction 1

Colorado Daily WAM and Modified Monthly WAM 1
Previous Versions of the Colorado WAM 2
Colorado River Basin and Adjoining Brazos-Colorado Coastal Basin 3
Scope and Organization of this Report 6
Colorado WAM Data Files 7

Chapter 2 Colorado Water Availability Model 9

Initial Monthly WAM Data Files 9
Model Components of the Latest and Earlier Versions of the WAM 10
Primary Control Points 10
Reservoirs 14
Water Rights 17
IF Record Instream Flow Water Rights 20
WAM Hydrology 22
Simulation Results 25
WAM Modifications 31
DSS Files of Simulation Input and Output Time Series Data 31
Artificial Control Points, Reservoirs, and Water Rights 33

Chapter 3 Conversion of Monthly Colorado WAM to Daily 39

Daily SIMD Simulation Input Dataset 40
Disaggregation of Monthly Naturalized Stream Flow to Daily 43
Daily Flow Pattern Hydrographs 44
Other Aspects of Monthly-to-Daily Disaggregation 50
River Flow Routing and Forecasting 50
Lag and Attenuation Routing Parameters 52
Routing and Forecasting Complexities and Approximations 55

Chapter 4 Reservoir Flood Control Operations 57

Flood Control Reservoir Operations in the Colorado River Basin 57
SIMD Capabilities for Simulating Reservoir Operations During Floods 64
Colorado WAM Simulation of Reservoir Flood Control Operations 66
Additions to the SIMD Input Dataset to Model Flood Control Operations 69

Chapter 5 Environmental Flow Standards 71

Environmental Flow Standards Established Pursuant to Senate Bill 3 Process 71
Other Instream Flow Requirements in the Colorado WAM 83
Modeling SB3 Environmental Flow Standards 84
Multiple Instream Flow Targets or Target Components at the Same Control Point 91
Monthly WAM with Instream Flow Targets from the Daily WAM 93

Chapter 6 Historical River System Hydrology 95

Monthly Precipitation and Reservoir Surface Evaporation Depths 95
Observed Flows at USGS Gages on the Colorado River 97
Naturalized Flows at Three Control Points on the Colorado River 99
Historical Observed Reservoir Storage Contents 103

Chapter 7 Daily Simulation Study 105

Organization of the Simulation Study 105
Statistical Analyses of Simulated River Flows and Reservoir Storage 111
Basic WAM Concepts Explored with Simulations MC, M1, and D1 117
Beginning-of-Simulation Storage Contents in Simulations D1 and D2 125
Routing in Simulations D3 and D4 128
Routing and Forecasting in Simulations D5 and D6 130
Reservoir Flood Control Operations in Simulation D7 134
Summary of Comparative Analyses of Alternative Simulations 139

Chapter 8 Modeling and Analysis of Environmental Flow Standards 141

Instream Flow Requirements in the Colorado WAM 141
Environmental Flow Standards Established Pursuant to the Senate Bill 3 Process 142
Comparison of Simulation Results for Alternative Variations of the WAM 144
Instream Flow Targets for SB3 Environmental Flow Standards 148
Daily and Monthly Regulated Flows from a Daily SIMD Simulation with C3D Dataset .. 165
Comparison of Annual Means of Flow Rate Quantities from
Simulations with WAM Versions MC, C3D, and C3M 169
SB3 Environmental Flow Standards in the Monthly WAM 171
Comparison of Simulation Results from Monthly C3M and Daily C3D
Versions of the WAM 173

Chapter 9 Summary and Conclusions 177

Daily WRAP/WAM Modeling System 177
Application of the Daily Colorado WAM to Model SB3 EFS 177
Modeling Options Adopted for the Daily Colorado WAM 179
Stream Flow and Reservoir Storage Variability and Stationarity 184
Data Files 187

References 189

CHAPTER 1
INTRODUCTION

The Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System consists of simulation input datasets for the generalized Water Rights Analysis Package (WRAP) modeling system for all of the river basins of Texas and related information. The TCEQ WAM System WRAP input dataset for a particular river basin is called a water availability model (WAM). The term "*Colorado WAM*" refers to the WRAP simulation input dataset for the Colorado River Basin and adjoining Brazos-Colorado Coastal Basin in the TCEQ WAM System and modified monthly or daily variations thereof.

The WAM System was originally implemented by the TCEQ and its partner agencies and contractors during 1997-2003 pursuant to water management legislation enacted by the Texas Legislature in 1997 as Senate Bill 1 (SB1). Capabilities provided by the WRAP/WAM system have been expanded over the years since their initial implementation. The WRAP/WAM modeling system is based on a monthly computational time step. Development of auxiliary daily modeling features was motivated by the need to improve capabilities for incorporating into the WAMs the environmental flow standards (EFS) established pursuant to the 2007 Senate Bill 3 (SB3).

WRAP software, manuals, other related publications, training courses, and a link to the TCEQ WAM website are available at the WRAP website (https://wrap.engr.tamu.edu/). The latest versions of the various components of the WRAP modeling system are documented by a set of manuals [1, 2, 3, 4, 5, 6]. [Numbers in brackets refer to the list of references at the end of this report.] New daily modeling capabilities are incorporated in the May 2019 version of WRAP and further improved in January 2021 modifications in the WRAP daily simulation model *SIMD* [7].

Colorado Daily WAM and Modified Monthly WAM

A strategy explored, adopted, and demonstrated with the Brazos, Trinity, and Neches WAMs documented in May 2019, December 2019, and June 2020 reports [8, 9, 10] consists of: (1) converting monthly WAMs to daily, (2) computing daily targets for environmental flow standards using the daily simulation model *SIMD*, and (3) incorporating monthly summations of the daily instream flow targets into the input datasets read by the monthly simulation model *SIM*. This general strategy is employed to develop the daily and modified monthly Colorado WAM datasets documented by this report. Environmental flow standards (EFS) were adopted by the TCEQ in 2012 employing the process created by the 2007 Senate Bill 3 (SB3). Daily SB3 EFS targets computed in a daily Colorado WAM simulation are summed to monthly and incorporated in the monthly WAM simulation input dataset. Modeling options adopted for the Brazos, Trinity, and Neches WAMs for dealing with various other complexities and issues likewise guide creation and application of the daily Colorado WAM.

Daily WAMs can also be employed directly, without summing daily SB3 EFS targets for input to monthly WAMs, for various other studies in which EFS and/or reservoir operations for flood control are important. Various issues of integrated multiple-objective water management can be investigated applying the daily WAM. Capabilities for satisfying the instream flow requirements reflected in the SB3 EFS can be assessed. Effects of the EFS on unappropriated flows available for municipal, industrial, and agricultural water use can be quantified.

Conversion of the latest edition of the monthly full authorization scenario version of the Colorado WAM to daily included the following tasks documented by this report.

1. Creation of the daily simulation *SIMD* input dataset began with the full authorization monthly *SIM* dataset from the TCEQ WAM System. This latest version of the Colorado WAM has a hydrologic period-of-analysis of 1940-2016, 2,457 control point *CP* records, *IN* records of naturalized flows at 45 control points, 484 actual permitted reservoirs, 42 artificial computational reservoirs, 120 instream flow *IF* records, and 2,167 water right *WR* records.

2. Daily flow pattern (*DF* record) hydrographs for 45 control points are added to the dataset. The 1940-2016 sequences of *DF* record daily flows are developed based on combining observed daily flows downloaded from the U.S. Geological Survey (USGS) National Water Information System (NWIS) website with WAM naturalized monthly flows.

3. Sets of *RT* record routing coefficients for the Colorado WAM compiled from past studies were reviewed. Simulation studies similar to those in the Brazos, Trinity, and Neches daily WAM reports were performed to analyze the effects of routing daily flow changes. The daily Colorado WAM was concluded to be valid either with or without adding optional routing and forecasting. Routing at 30 control points and forecasting with a three-day forecast period with incorporated in the final daily WAM adopted for modeling SB3 EFS.

4. O.C. Fisher, Twin Buttes, Hords Creek, and Travis Reservoirs have designated flood control pools. Operations of the flood control pools are simulated in *SIMD* using flood reservoir (*FR*) and flood flow (*FF*) records.

5. SB3 EFS for the Colorado and Lavaca Rivers and Matagorda and Lavaca Bays adopted by the TCEQ in August 2012 are documented as Subchapter D of Chapter 298 of the Texas Administrative Code [11]. The SB3 EFS for the 14 sites on the Colorado River and its tributaries were incorporated in the daily *SIMD* input dataset for the Colorado WAM employing capabilities provided by sets of instream flow *IF*, environmental standard *ES*, hydrologic condition *HC*, and pulse flow *PF* and *PO* records. Daily flow targets computed by *SIMD* for each day of a 1940-2016 simulation were summed to 1940-2016 monthly targets for incorporation as target series *TS* records incorporated in the monthly *SIM* input dataset.

6. The daily WRAP modeling system is complex with many optional features. Complexities, issues, and alternative modeling methods are investigated through simulation studies similar to those documented in the Brazos, Trinity, and Neches daily WAM reports [8, 9, 10].

Previous Versions of the Colorado WAM

Development of the original monthly Colorado WAM is documented by a 2001 report [12] prepared by the R. J. Brandes Company (contractor) and other consulting firms (subcontractors) for the Texas Natural Resources Conservation Commission, later renamed the Texas Commission on Environmental Quality. The TCEQ has periodically updated the Colorado WAM along with the WAMs for the other river basins of the state created pursuant to the 1997 SB1. The original Colorado WAM had a hydrologic period-of-analysis of January 1940 through December 1998. The latest version, last updated by the TCEQ in February 2020, has a hydrologic period-of-analysis of January 1940 through December 2016. The February 2020 TCEQ WAM also includes the 2020 updated Lower Colorado River Authority (LCRA) Water Management Plan (WMP) [13, 14].

The Colorado WAM served during 2012-2014 as one of several case studies for TCEQ sponsored research and development at TAMU of daily simulation and monthly hydrology extension capabilities of WRAP [15, 16, 17, 18, 19]. Daily modeling capabilities incorporated in the May 2019 and January 2021 versions of WRAP reflect major modifications and additions since earlier versions. The 2020 updated monthly Colorado WAM also reflects significant modifications since earlier versions. The initial developmental versions of daily WAMs are now obsolete.

Colorado River Basin and Adjoining Brazos-Colorado Coastal Basin

The Colorado River Basin extends from southeast New Mexico across Texas to Matagorda Bay as shown in Figure 1.1. The river basin has a total area of 45,570 square miles of which about 42,870 square miles are in Texas. About 11,830 square miles of the upper basin contributes essentially no inflow to the river system and thus is classified by the USGS as non-contributing. The headwaters in New Mexico and northwest Texas are at elevations of about 4,000 feet. The climate of the basin varies from arid in the northwest upper basin with an average annual precipitation of between 12 and 16 inches to humid subtropical in the southeast lower basin with average annual precipitation of about 44 inches. The major tributaries of the Colorado River are Beals Creek, Pecan Bayou, Concho River, San Saba River, Llano River, and Pedernales River, all entering the Colorado River upstream of the City of Austin.

The Brazos-Colorado Coastal Basin is located to the east of the Colorado River Basin between the Colorado and Brazos River Basins. The watershed area is about 1,860 square miles. The main streams are the San Bernard River and Caney Creek. There are no major reservoirs in this coastal basin. The Colorado WAM combines the coastal and major river basins of Figure 1.1.

Austin is the largest city in the Colorado River Basin, fourth largest city in Texas, and one of the fastest growing large cities in the nation. The population of Austin increased 28.0 percent from 790,000 people in 2010 to 1,012,000 people in 2020. The five-county Austin-Round Rock-San Marcos metropolitan area had a 2020 population of about 2,283,000. The Colorado River flows through Austin and serves as the primary water supply source for the city. Austin both holds its own water right permits and contracts with the Lower Colorado River Authority (LCRA) for water supplied under LCRA water right permits.

The LCRA and the Colorado River Municipal Water District (CRMWD) control most of the reservoir storage capacity in the lower and upper basins, respectively. Lake Buchanan is viewed as the divide between the Upper and Lower Colorado River.

LCRA created by the Texas Legislature in 1934 has no taxing authority and operates solely on utility revenues and fees generated from supplying electrical energy, water, and community services. LCRA supplies wholesale electrical power to 43 city-owned utilities and electric cooperatives that serve over a million people in Central Texas. LCRA owns and operates three gas-fired electric power plants, one coal-fired power plant, and six hydroelectric plants and also purchases electricity from three wind farms. LCRA manages more than 16,000 acres of recreational lands along the Colorado River and administers other programs supporting community and economic development. The agency operates the off-channel Lakes Bastrop and Fayette County (Cedar Creek) to provide cooling water for thermal-electric power plants as well as operating the six multiple-purpose Highland Lakes.

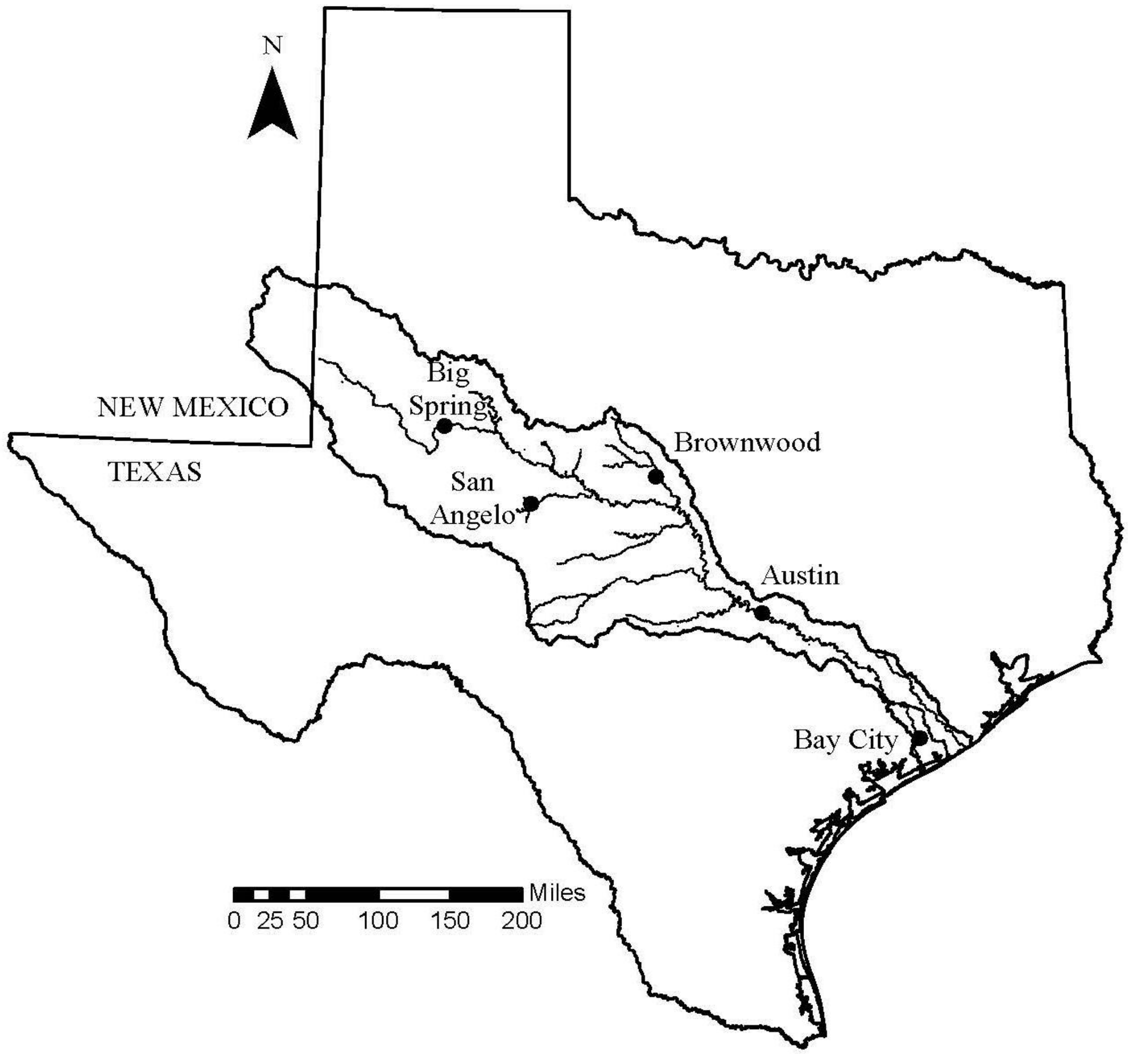

Figure 1.1 Colorado River Basin and Brazos-Colorado Coastal Basin

LCRA owns five and operates all six of the Highland Lake projects on the Colorado River. The lakes are listed in upstream-to-downstream order in Table 1.1. The authorized storage capacities in the third column are from the water right permits. The information in the last four columns is provided at the LCRA website. Capacities and water surface areas for Lakes Buchanan, LBJ, Marble Falls, and Travis reflect volumetric surveys performed during 2020-2021.

Tom Miller Dam is owned by the City of Austin and operated by LCRA. Lake Austin is located in the City of Austin. The five other lakes are owned by LCRA and located upstream of Austin. Hydroelectric power plants at each of the six dams are operated to use water supply releases for downstream diverters to help meet peak electric power demands. Releases for only hydroelectric energy generation occur only during energy-related emergencies. Lake Travis has a flood control pool. Lake LBJ provides cooling water for a LCRA thermal-electric power plant. Lakes Buchanan and Travis contain water supply storage used primarily to supply municipal and industrial users in Austin and vicinity and agricultural irrigation needs primarily for the Gulf Coast, Lakeside, Garwood, and Pierce Ranch irrigation operations near the Gulf Coast.

Table 1.1
Highland Lakes on the Colorado River Operated by LCRA

Dam	Lake	Permitted Capacity (acre-feet)	Actual Capacity (acre-feet)	Surface Area (acres)	Elevation at Top of Normal Pool (feet msl)	Elevation at Top of Dam (feet msl)
Buchanan	Buchanan	992,475	880,356	22,452	1,020	1,025.5
Inks	Inks	17,545	13,668	777	888	922
Wirtz	LBJ	138,500	131,618	6,432	825	838.5
Starke	Marble Falls	8,760	7,597	613	737	761.5
Mansfield	Travis	1,170,752	1,115,076	19,044	681	750
Tom Miller	Austin	21,000	24,644	1,830	492.8	517

The LCRA system is operated in accordance with a water management plan that governs water allocation during droughts when all LCRA customers cannot be fully supplied [13, 14]. Water is released from Lakes Buchanan and Travis whenever flows in the lower river are inadequate to meet downstream needs, including environmental instream river flows and freshwater inflows to Matagorda Bay. The water management plan divides supplies between *firm* (*uninterruptible*) and *interruptible* based on storage level triggers in Lakes Buchanan and Travis. Firm water is available even during a severe drought. During water shortages, interruptible water, which is used primarily for agricultural irrigation, is curtailed as necessary to protect firm water supply commitments for primarily municipal, industrial, and thermal-electric cooling uses.

The Colorado River Municipal Water District (CRMWD) is the largest reservoir owner, water right permit holder, and water supplier in the upper Colorado River Basin. The CRMWD was created by the Texas Legislature in 1949 for the purpose of providing water to its member cities of Odessa, Big Spring, and Snyder. The CRMWD also has water supply contracts with the cities of Midland, San Angelo, Stanton, Robert Lee, Grandfalls, Pyote, and Abilene and the Millersview-Doole Water Supply Corporation. CRMWD owns and operates J.B. Thomas, E.V. Spence, and O.H. Ivie Reservoirs, which have permitted water supply storage capacities of 204,000 acre-feet, 488,760 acre-feet, and 554,340 acre-feet. The CRMWD also operates four well fields used primarily to supplement surface water sources during the summer months.

The CRMWD owns nine other reservoirs that are used to prevent low-quality, high salinity water from flowing downstream. Water is permanently impounded or diverted for other uses. These nine salinity control impoundments are Sulphur Draw Reservoir, Red Lake Reservoir, Natural Dam Lake, Barber Reservoir, Mitchell County Reservoir, Red Draw Reservoir, Beals Creek Sump, Three Mile Lake, and Four Mile Lake.

The Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE) owns and operates Hords Creek Dam and Reservoir and O.C. Fisher Dam and Reservoir (formerly called San Angelo Dam and Reservoir) for flood control, water supply, and recreation. Hords Creek is by far the smallest Corps of Engineers reservoir in Texas. The Central Colorado River Authority has contracted for the water supply storage of Hords Creek Reservoir which is used to supply the City of Coleman. The Upper Colorado River Authority has contracted for the water supply storage of O.C. Fisher Reservoir. The USACE FWD is also responsible for operations of the flood control pools of two other reservoirs in the Colorado River Basin that were constructed by the U.S. Bureau of Reclamation and are now owned and operated by nonfederal project sponsors: Lake Travis owned by the LCRA and Twin Buttes Reservoir owned by the City of San Angelo.

As discussed in Chapter 2, the 484 reservoirs included in the full authorization scenario Colorado WAM last updated by the TCEQ in February 2020 include 31 reservoirs with permitted storage capacities exceeding 5,000 acre-feet. These 31 major reservoirs listed in Table 2.4 of Chapter 2 include 29 existing reservoirs and two other permitted but not yet constructed projects. One of the two proposed but not yet constructed projects may consist of storage in multiple LCRA off-channel reservoirs though modeled in the WAM as a single storage project. The 29 existing major reservoirs with capacities summing to 4,648,860 acre-feet account for 88.3 percent of the authorized storage capacity of 5,263,900 acre-feet of the 484 reservoirs included in the WAM.

The permitted storage capacity authorized by water right permits for the six Highland Lakes listed in Table 1.1 total 2,349,032 acre-feet, which is 50.5 percent of the authorized capacity of the existing 29 reservoirs with storage capacities exceeding 5,000 acre-feet and 44.6 percent of the total storage capacity of the 484 reservoirs in the authorized use scenario Colorado WAM.

Lakes J.B. Thomas, E.V. Spence, and O.H. Ivie Reservoirs owned and operated by the CRMWD have authorized storage capacities that total 1,247,100 acre-feet. These three reservoirs in the upper basin contain 26.8 percent of the permitted storage capacity of the 29 existing major reservoirs and 23.7 percent of the total permitted storage capacity of the 484 reservoirs included in the WAM. Thus, nine large reservoirs operated by the LCRA and CRMWD account for 77.3 percent of the permitted storage capacity of the 29 existing major reservoirs and 68.3 percent of the total permitted storage capacity of the 484 reservoirs included in the WAM. The LCRA and CRMWD also own and operate several smaller reservoirs in addition to these nine larger projects.

Scope and Organization of this Report

This report documents the development of a version of the Colorado WAM that employs a daily computational time step. The new daily WAM provides capabilities for simulating operation of reservoir flood control pools based on downstream flows and environmental flow standards (EFS) that have been established by the TCEQ and collaborating science and stakeholder committees through the 1997 Senate Bill 3 (SB3) process. The daily WAM consists of a set of *SIMD* input files that are listed and briefly described in the next section of the present Chapter 1.

This report focuses on a specific daily modeling application in which the monthly WAM is modified by adopting monthly SB3 EFS instream flow targets stored in the monthly *SIM* input dataset that were computed by summing daily targets generated in a daily *SIMD* simulation. *SIM* input data files for the monthly WAM are listed in the next section of the present Chapter 1.

The monthly Colorado WAM full authorization scenario dataset last updated by the TCEQ in February 2020 is described in Chapter 2 along with the following additional modifications. DSS files are employed for storing time series input data and simulation results. *SIM/SIMD* options are adopted that allow designating WAM components as artificial to clarify organization of simulation results without affecting the numerical values of time series quantities computed by the simulation.

The latest TCEQ updated version of the monthly WAM was expanded as described in Chapter 3 to develop a daily *SIMD* input dataset. Flood control operations of four multiple-purpose reservoirs containing flood control pools are added to the daily WAM as described in Chapter 4.

Environmental flow standards (EFS) established in 2012 [11] through the process created by the 2007 Senate Bill 3 (SB3) are described in Chapters 5 and 8. Incorporation of the SB3 EFS in both the daily and monthly versions of the WAM is a central focus of this report. The SB3 EFS are modeled in the daily WAM as instream flow *IF* record rights using the new environmental standard *ES*, hydrologic condition *HC*, and pulse flow *PF* and *PO* record features of *SIMD*. Daily SB3 EFS targets from a daily *SIMD* simulation are summed to monthly for inclusion as target series *TS* records in the time series DSS file read by *SIM* for a monthly simulation.

Simulation studies investigating various water management and modeling issues are presented in Chapters 7 and 8. Daily and monthly WAMs are applied to model SB3 EFS. Monthly-to-daily naturalized flow disaggregation, routing flow changes, flow forecasting, flood control operations, and other complexities of water management and modeling thereof are explored. Simulation results are presented. Study results and conclusions are summarized in Chapter 9.

Colorado WAM Data Files

The monthly WAM last updated by the TCEQ in February 2020 is discussed in Chapter 2. This latest WAM dataset consists of *SIM* input files with filenames C3.DAT, C3.DIS, C3.FLO, C3.EVA, C3.FAD, and C3.HIS. The "C" in the filenames denotes Colorado, and the "3" denotes the full authorization scenario (run 3). The contents of the files are discussed in Chapter 2.

Daily and modified monthly versions of the full authorization Colorado WAM developed as described in this report include the following DSS and DIS files common to monthly *SIM* and daily *SIMD* simulations and separate *SIM* and *SIMD* DAT files. A *SIMD* daily input DIF file provides routing parameters (*RT* records) and flow disaggregation specifications (*DC* records).

C3HYD.DSS − The hydrology DSS file contains 1940-1996 monthly series of *IN* record naturalized flows, *EV* record net reservoir surface evaporation less precipitation depths, *TS* record monthly SB3 EFS instream flow targets, *FA* record flow adjustments, a *HI* record monthly hydrologic index series, and 1940-2016 daily series of *DF* record daily flows.

C3.DIS.DIS − The flow distribution DIS file contains the flow distribution *FD* and watershed parameter *WP* records used to distribute monthly naturalized flows from 45 primary to over 2,000 secondary control points the same with the daily versus monthly versions of the WAM. The *FD* and *WP* records and DIS file are not changed in the work reported here.

C3D.DIF − The DIF file contains flow disaggregation specifications on *DC* records and lag and attenuation routing parameters on *RT* records. A daily *SIMD* simulation can be performed optionally with or without routing of flow changes using the *RT* records.

C3D.DAT − The daily version of the full authorization scenario (run 3) DAT file with filename C3D.DAT expands the monthly DAT file with filename C3.DAT.

C3M.DAT − The C3M version of the monthly full authorization scenario DAT file with SB3 EFS added replaces the monthly DAT file with filename C3.DAT.

The WAM simulation input files described on the preceding page and the two additional DSS files described below contain very large datasets. Data storage system (DSS) files are viewed, analyzed, and modified with *HEC-DSSVue*. The other files are in normal text format read with Microsoft WordPad, NotePad, Word, Excel or other editors. Program *TABLES* is used to organize and display the information in *SIM* and *SIMD* simulation input DAT and output OUT files.

With *HEC-DSSVue*, the DSS files become very conveniently managed appendices to this report. WRAP applications of Hydrologic Engineering Center (HEC) Data Storage System (DSS) files and the interface program *HEC-DSSVue* are explained in Chapter 6 of the *Users Manual* [2]. DSS files are read with *HEC-DSSVue*, which provides flexible comprehensive capabilities for organizing, managing, and analyzing time series data. *HEC-DSSVue* facilitates convenient graphical and tabular displays and statistical analyses of these time series datasets. The datasets can also be efficiently modified within *HEC-DSSVue*. For example, daily time series can be aggregated to monthly or annual. Monthly time series can be uniformly divided to daily or converted to annual. Quantities can be switched between flow rates in cubic feet per second (cfs) or other units and period volumes in acre-feet or other units.

The *SIM/SIMD* input file with filename C3HYD.DSS stores hydrology time series (*IN*, *EV*, *FA*, *HI*, *DF* records) and target time series (*TS* records) data as described on the preceding page 7. This DSS file can be called either the hydrology or the time series input file. The same single *SIM/SIMD* hydrology or time series input file with filename C3HYD.DSS is read by both *SIM* and *SIMD*. Model users can read this DSS file, like all DSS files, with *HEC-DSSVue*. The DSS pathname part A, B, C, D, E, and F labeling conventions adopted for the *IN*, *EV*, *FA*, *HI*, *DF* records are defined in Chapter 6 of the *WRAP Users Manual* [2].

This report is also accompanied by two additional DSS files with the following filenames that contain datasets developed as described in the chapters indicated in parenthesis. The format and contents of these two auxiliary files along with the WAM *SIM/SIMD* simulation input files are summarized in the last section of the last chapter (Chapter 9) of this report.

ColoradoAuxiliaryData.DSS	(Chapters 2, 3, 6, 7, 8)
ColoradoSimulationResults.DSS	(Chapter 8)

The file with filename ColoradoAuxiliaryData.DSS contains selected datasets compiled in the work reported in Chapters 2, 3, 6, 7, and 8. Most of the datasets in this DSS file are represented by the tables of statistical frequency metrics and the time series plots presented in these chapters. Pathname labeling conventions for *SIM* and *SIMD* simulation results, though intuitive perhaps without need for explanation, are explained in Chapter 6 of the *Users Manual* [2].

The file with filename ColoradoSimulationResults.DSS records simulation results from the daily and monthly versions of the WAM with *SIM* and *SIMD* input files with filename roots C3D and C3M. These simulations are presented in Chapter 8. *SIMD* and *SIM* write time series of simulation results to an output DSS file with filename C3D.DSS or C3M.DSS, respectively. Selected DSS records from multiple simulations are copied to the single consolidation file with filename ColoradoSimulationResults.DSS that companies this report and serves similarly as a set of report appendices. The format and content of this DSS files and the other files noted above are discussed further in the last section of Chapter 9.

CHAPTER 2
COLORADO WATER AVAILABILITY MODEL

The term *Colorado WAM* refers to the monthly WRAP simulation model *SIM* input dataset for the Colorado River Basin and adjoining Brazos-Colorado Coastal Basin from the TCEQ WAM System and modified variations thereof. The Colorado WAM includes both monthly *SIM* and daily *SIMD* datasets. The original Colorado WAM was completed by the R. J. Brandes Company (contractor) and other consulting firms (subcontractors) for the TNRCC (TCEQ) in 2001 [12]. The TCEQ has periodically updated the monthly WAM as existing water rights are amended or new water rights added. The TCEQ has also updated (extended) the hydrologic period-of-analysis.

Chapter 2 describes the monthly WAM for the full authorization scenario that was last updated by the TCEQ in February 2020. The daily WAM described in this report was created from this latest version of the monthly WAM available from the TCEQ. Latter sections of Chapter 2 describe modifications to the monthly WAM in conjunction with the present work that affect model results only in regard to organization and format. Additions and modifications to the monthly WAM to create a daily WAM are covered in Chapters 3, 4, 5, 7, and 8.

Initial Monthly WAM Data Files

The monthly WAM last updated by the TCEQ in February 2020 consists of the following *SIM* input files. The letter C in the filenames denotes Colorado, and the integer 3 denotes the full authorization scenario (run 3) also called the authorized use scenario. The filename extensions denote the type of *SIM* input data contained in the file. The DAT file was last updated by the TCEQ in February 2020 to reflect the updated LCRA Water Management Plan approved by the TCEQ in February 2020 [13]. The hydrology data in the FLO, EVA, and FAD files were last updated by the TCEQ in 2018 to extend the hydrology through 2016. The TCEQ had previously extended the hydrologic period-of-analysis from 1940-1998 to 1940-2013.

C3.DAT –The DAT file contains the many types of *SIM* simulation input records that are not contained in the following five other *SIM* simulation input files.

C3.DIS – The flow distribution (DIS) file contains 2,240 flow distribution (*FD*) records and 2,285 watershed parameter (*WP*) records employed in the *SIM* simulation to distribute monthly naturalized stream flows from primary to secondary control points.

C3.FLO – The FLO file contains 3,465 *IN* records with 1940-2016 monthly naturalized stream flow volumes at 45 primary control points.

C3.EVA – The EVA file contains 3,696 *EV* records with 48 sequences of 1940-2016 monthly net reservoir evaporation minus precipitation depths assigned control point identifiers.

C3.FAD – The flow adjustment (FAD) file contains 1,001 flow adjustment (*FA*) records with 1940-2016 monthly adjustments at 13 control points. The quantities on the *FA* records are used to adjust the *IN* record naturalized stream flows for the effects of spring flows.

C3.HIS – The hydrologic index series (HIS) file contains 77 hydrologic index (*HI*) records for a 1940-2016 monthly index at control point G50000 at USGS gage 08148500 on the North Llano River near Junction referenced by target options (*TO*) records in the DAT file used to model environmental flow requirements for water right FKNJSVD1.

Model Components of the Latest and Earlier Versions of the WAM

The WRAP simulation model *SIM* prints a listing in its message file of the number of various system components. The *SIM* counts in the last column of Table 2.1 are from the latest TCEQ updated (February 2020) WAM adopted for the work documented by this report. Counts for a previous August 2007 version of the WAM are included in Table 2.1 for comparison. The Colorado WAM files for the authorized use scenario (run 3) and current use scenario (run 8) have the filename roots C3 and C8, respectively. The *SIM* message file counts in Table 2.1 are totals that include the artificial control points, reservoirs, and water rights discussed later in this chapter.

Table 2.1
Number of Model Components in Colorado WAM Datasets

Latest Update of Datasets Water Use Scenario Filename Root	Aug 2007 Authorized C3	Aug 2007 Current C8	Feb 2020 Authorized C3
total number of control points	2,395	2,396	2,457
number of primary control points	45	45	45
control points with evaporation-precip rates	48	47	48
number of reservoirs as counted by *SIM*	511	510	526
number of *WR* record water rights	1,922	1,928	2,167
number of instream flow *IF* record rights	86	93	120
number of system water rights	132	134	446
number of drought index *DI* records	6	7	21
number of *FD* records in DIS file	2,206	2,206	2,240

The hydrologic period-of-analysis is January 1940 through December 2016 for the February 2020 updated WAM and January 1940 through December 1998 for both the original 2001 and August 2007 WAM. The 2020 update employs the dual simulation option. The 2007 and earlier versions did not include the dual simulation option which had not yet been added to *SIM*. Negative incremental ADJINC option 5 is activated in *JD* record field 9 in both the 2007 and 2020 versions of the Colorado WAM. Computational adjustments were performed during development of the naturalized flows to remove the majority of negative incrementals in the flow data.

Primary Control Points

The Colorado WAM has 45 primary control points, as shown in Table 2.2 and Figures 2.1 and 2.2, for which 1940-2016 monthly naturalized flows are provided as *IN* records in in the FLO file. The 45 primary control points are the sites of USGS stream gaging stations. Three of the gages are at dams and measure reservoir releases. Forty-three of the primary control points are in the Colorado River Basin. Control point L2000 is on Big Boggy Creek which flows into the Gulf Intracoastal Waterway west of the Colorado River. Control point L1000 is on the San Bernard River in the Brazos-Colorado Coastal Basin to the east of the Colorado River Basin.

Primary control points are locations at which naturalized flows are provided in a *SIM* input dataset. Naturalized flows at all other sites, called *secondary* control points, are computed within the simulation based on the naturalized flows at primary control points and watershed parameters provided on DIS file *FD* and *WP* records and/or DAT file *CP* records. Naturalized flows are synthesized during execution of *SIM* for over 2,200 secondary control points based on information provided in the DAT and DIS files. In most cases, naturalized flows are distributed to secondary control points using the drainage area ratio method, in some cases in combination with channel loss factors, as specified by flow source options 6 and 7 in control point *CP* record field 6.

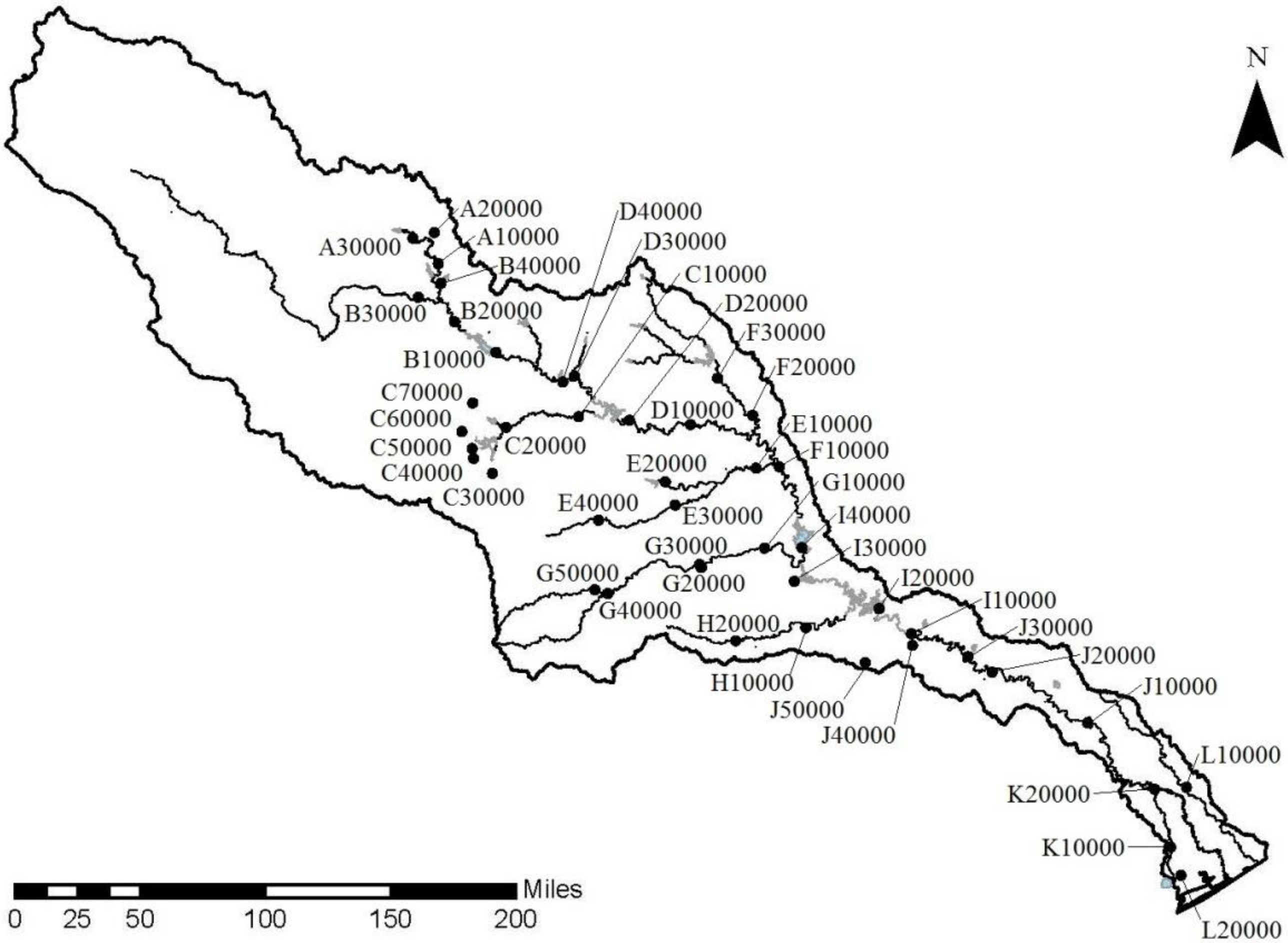

Figure 2.1 Map of Primary Control Points in the Colorado WAM

The Colorado River Basin and adjoining coastal basin are divided into the sub-basins shown in Figure 2.3 for purposes of organizing WAM control point identifiers. The two most upstream sub-basins are designated with the letters A and B. The letter identifiers continue downstream to the basin outlet. The two most downstream sub-basins of the Colorado River are designated with letters K and M. The two coastal sub-basins designated as N and L are separate watersheds that are not hydrologically connected to the Colorado River.

Within each sub-basin, the control point at the outlet is assigned the sub-basin letter and followed by a 5-digit integer number. The control point at the outlet of sub-basin A has control point identifier A10000. Primary control point identifiers are incremented by 10000 upstream of the sub-basin outlet. For example, the primary control point upstream of the outlet of sub-basin A has control point identifier A20000. Secondary control points between primary control points follow a similar convention but are incremented by less than 10000. The artificial control points listed later in Table 2.8 are not included in this control point labeling scheme.

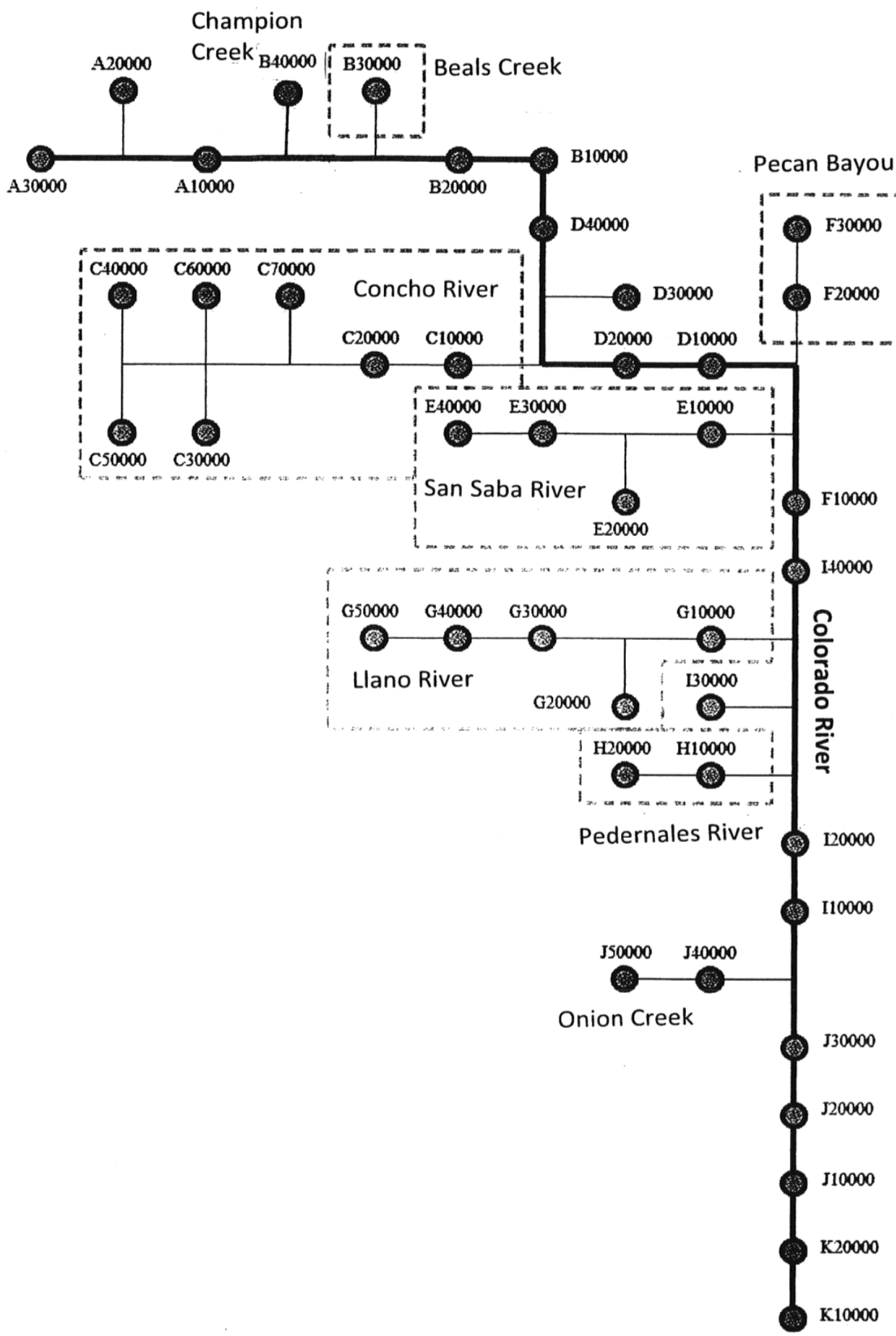

Figure 2.2 Schematic of Primary Control Points in the Colorado WAM

Table 2.2
Primary Control Points in the Colorado WAM

WAM CP ID	USGS Gage No.	Location	Watershed Area (sq. miles)	USGS Gage Period-of-Record
A30000	08119500	Colorado River near Ira	1,074	1947-1989
A20000	08120500	Deep Creek near Dunn	193	1953-present
A10000	08121000	Colorado River at Colorado City	1,575	1923-present
B40000	08123600	Champion Creek Reservoir	176	reservoir releases
B30000	08123800	Beals Creek near Westbrook	1,974	1958-present
B20000	08123850	Colorado River above Silver	4,560	1967-present
B10000	08124000	Colorado River at Robert Lee	5,046	1923-present
C70000	08134000	North Concho R near Carlsbad	1,202	1924-present
C60000	08128400	Middle Concho R nr Tankersley	1,613	1961-present
C50000	08129300	Spring Creek above Tankersley	340	1960-1995
C40000	08130500	Dove Creek at Knickerbocker	164	1960-2009
C30000	08128000	South Concho R at Christoval	258	1930-present
C20000	08136000	Concho River at San Angelo	4,139	1915-present
C10000	08136500	Concho River at Paint Rock	5,185	1915-present
D40000	08126380	Colorado River near Ballinger	6,090	1907-present
D30000	08127000	Elm Creek at Ballinger	464	1932-present
D20000	08136700	Colorado River near Stacy	12,548	1968-present
D10000	08138000	Colorado River at Winchell	13,788	1923-2011
E40000	08144500	San Saba River at Menard	1,137	1915-present
E30000	08144600	San Saba River near Brady	1,636	1979-present
E20000	08145000	Brady Creek at Brady	589	1939-present
E10000	08146000	San Saba River at San Saba	3,048	1915-present
F30000	08143500	Pecan Bayou at Brownwood	1,654	1923-1983
F20000	08143600	Pecan Bayou near Mullin	2,074	1967-present
F10000	08147000	Colorado River near San Saba	19,830	1915-present
G50000	08148500	North Llano River near Junction	897	1915-present
G40000	08150000	Llano River near Junction	1,859	1915-present
G30000	08150700	Llano River near Mason	3,251	1968-present
G20000	08150800	Beaver Creek near Mason	215	1963-present
G10000	08151500	Llano River at Llano	4,201	1939-present
H20000	08152900	Pedernales R nr Fredericksburg	370	1979-present
H10000	08153500	Pedernales R near Johnson City	901	1939-present
I40000	08148000	Lake Buchanan near Burnet	20,521	reservoir releases
I30000	08152000	Sandy Creek near Kingsland	346	1966-present
I20000	08154500	Lake Travis near Austin	27,357	reservoir releases
I10000	08158000	Colorado River at Austin	27,611	1898-present
J50000	08158700	Onion Creek near Driftwood	124	1979-present
J40000	08159000	Onion Creek at U.S. Hwy 183	324	1924-present
J30000	08159200	Colorado River at Bastrop	28,580	1960-present
J20000	08159500	Colorado River at Smithville	29,062	1930-present
J10000	08161000	Colorado River at Columbus	30,244	1916-present
K20000	08162000	Colorado River at Wharton	30,601	1938-present
K10000	08162500	Colorado River near Bay City	30,862	1948-present
L20000	08117900	Big Boggy Creek nr Wadsworth	14	1970-1977
L10000	08117500	San Bernard River near Boling	725	1954-present

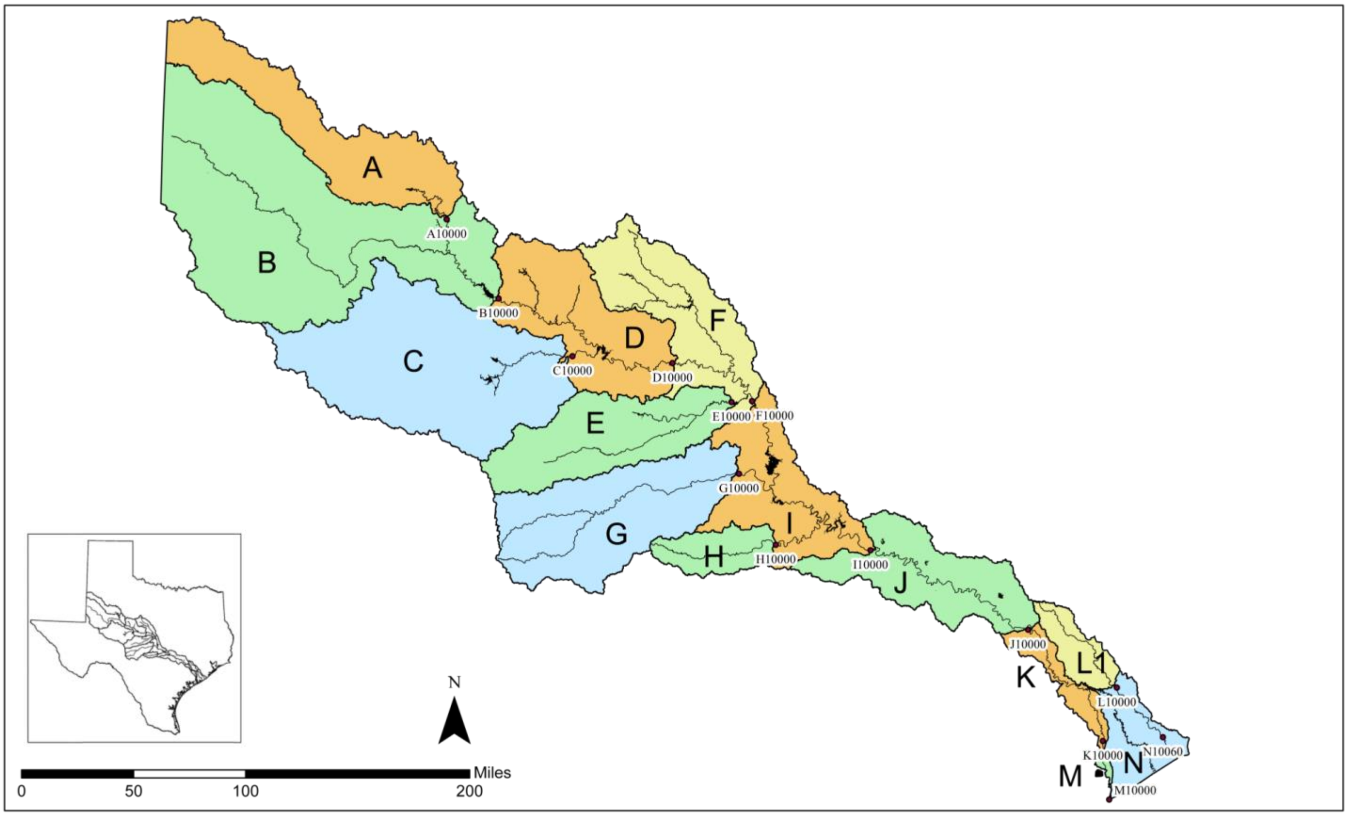

Figure 2.3 Colorado WAM Sub-Basins for Labeling Control Points

Reservoirs

The 31 major reservoirs in the full authorization scenario version of the Colorado WAM that have authorized storage capacities of 5,000 acre-feet or greater are listed in Table 2.3. All of these major reservoirs are located in the Colorado River Basin. There are no reservoirs with 5,000 acre-feet or greater authorized storage capacity in the Brazos-Colorado Coastal Basin. The numbers in the first column of Table 2.3 are labels for the reservoirs in the map of Figure 2.4. Lake Buchanan is viewed as the divide between the Upper and Lower Colorado River.

The last five reservoirs or proposed projects listed in Table 2.3 are not included on the map of Figure 2.4. Baylor Creek Reservoir and the 500,000 acre-feet of storage capacity authorized by LCRA permit 5731 have not yet been constructed. The 500,000 acre-feet of storage capacity authorized by LCRA water right permit 5731 may be divided into multiple off-channel reservoirs yet to be constructed that would store high flows of the Colorado River. However, the proposed LCRA owned storage capacity of 500,000 acre-feet authorized by permit 5731 is modeled in the WAM as a single reservoir with reservoir identifier FLDFLW located at control point 573141. The Phillips Petroleum reservoir also represents storage facilities at multiple sites.

The Colorado River Municipal Water District (CRMWD) controls the majority of the reservoir storage capacity in the upper basin. Lakes O. H. Ivie, E. V. Spence, and J. B. Thomas owned and operated by the CRMWD contain 26.8 percent of the total permitted storage capacity of the 29 existing major reservoirs.

Table 2.3
Major Reservoirs in the Colorado WAM

Map ID	Reservoir	Reservoir Identifier	Control Point	Initial Impoundment	Permitted Capacity
					(acre-feet)
1	Lake Travis	TRAVIS	I20000	1940	1,170,752
2	Lake Buchanan	BUCHAN	I40000	1937	992,475
3	O.H. Ivie Reservoir	OHIVIE	D20050	1990	554,340
4	E.V. Spence Reservoir	SPENCE	B10050	1968	488,760
5	Lake J.B. Thomas	THOMAS	A30060	1952	204,000
6	STP Main Cooling Pond	STHTEX	M10024	1979	202,988
7	Twin Buttes Reservoir	TWINBU	C20240	1962	186,200
8	Lake LBJ	LAKLBJ	I21280	1951	138,500
9	Lake Brownwood	BROWNW	F30130	1933	135,963
10	O.C. Fisher Lake	OCFISH	C20040	1952	119,200
11	Fayette County (Cedar Cr)	CEDARC	J10121	1977	71,400
12	Champion Creek Reservoir	CHAMPI	B40000	1959	42,500
13	Lake Coleman	COLEMA	F30420	1966	40,000
14	Oak Creek Reservoir	OAKCRK	D40620	1953	39,360
15	Walter E. Long Lake	DECKER	J30330	1967	33,940
16	Lake Colorado City	COLOCI	B20020	1949	29,934
17	Brady Creek Reservoir	BRADYC	E20090	1963	30,000
18	Lake Austin	LKAUST	I10340	1939	21,000
19	Inks Lake	ROYINK	I20820	1938	17,545
20	Lake Bastrop	BASTRO	J30030	1964	16,590
21	Lake Nasworthy	NASWOR	C20240	1930	12,500
22	Lake Marble Falls	MARBLE	I20590	1957	8,760
23	Hords Creek Lake	HORDSC	F30370	1948	7,959
24	Lake Winters	ELMCRK	D30450	1983	8,374
25	Ballinger Municipal Lake	BALLIN	D40040	1978	6,050
26	Clyde Lake	LCLYDE	F31130	1970	5,748
-	Eagle Lake	EAGLAK	FK20050	1900	9,600
-	Mitchell County Reservoir	1008EV	B30010	1991	38,304
-	Phillips Petroleum	PRES	PHILL	-	16,118
-	Baylor Creek	BAYLOR	J10150	proposed	46,600
-	LCRA Permit 5731	FLDFLW	573141	proposed	500,000

The Lower Colorado River Authority (LCRA) controls most of reservoir storage in the lower basin. Lakes Travis, Buchanan, LBJ, Austin, Inks, and Marble Falls (Table 1.1) on the Colorado River and LCRA off-channel Lakes Fayette and Bastrop contain 52.4 percent of the total permitted storage capacity of the existing 29 major reservoirs in Table 2.3 and 45.9 percent of the total permitted storage capacity contained in the 484 reservoirs included in the Colorado WAM. As discussed later in the last section of this chapter, the 526 reservoirs in the Colorado WAM includes 42 artificial "computational" reservoirs which account of most the storage capacity in the simulation computations in addition to the 484 actual reservoirs.

Six of the ten existing reservoirs in Table 2.3 with storage capacities exceeding 100,000 acre-feet are owned by the LCRA or CRMWD. The other four of these ten largest reservoirs are as follows.

- The South Texas Project (STP) includes a cooling water lake for a nuclear power plant main with an authorized storage capacity of 202,988 acre-feet.
- Twin Buttes Reservoir with an authorized storage of 186,200 acre-feet was constructed by the Bureau of Reclamation and is owned by the City of San Angelo.
- The 135,963 acre-feet Lake Brownwood is owned by the City of Brownwood.
- O.C. Fisher Reservoir with an authorized conservation storage capacity of 119,200 acre-feet is owned and operated by the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD). The Upper Colorado River Authority has contracted with the federal government for the water supply storage.

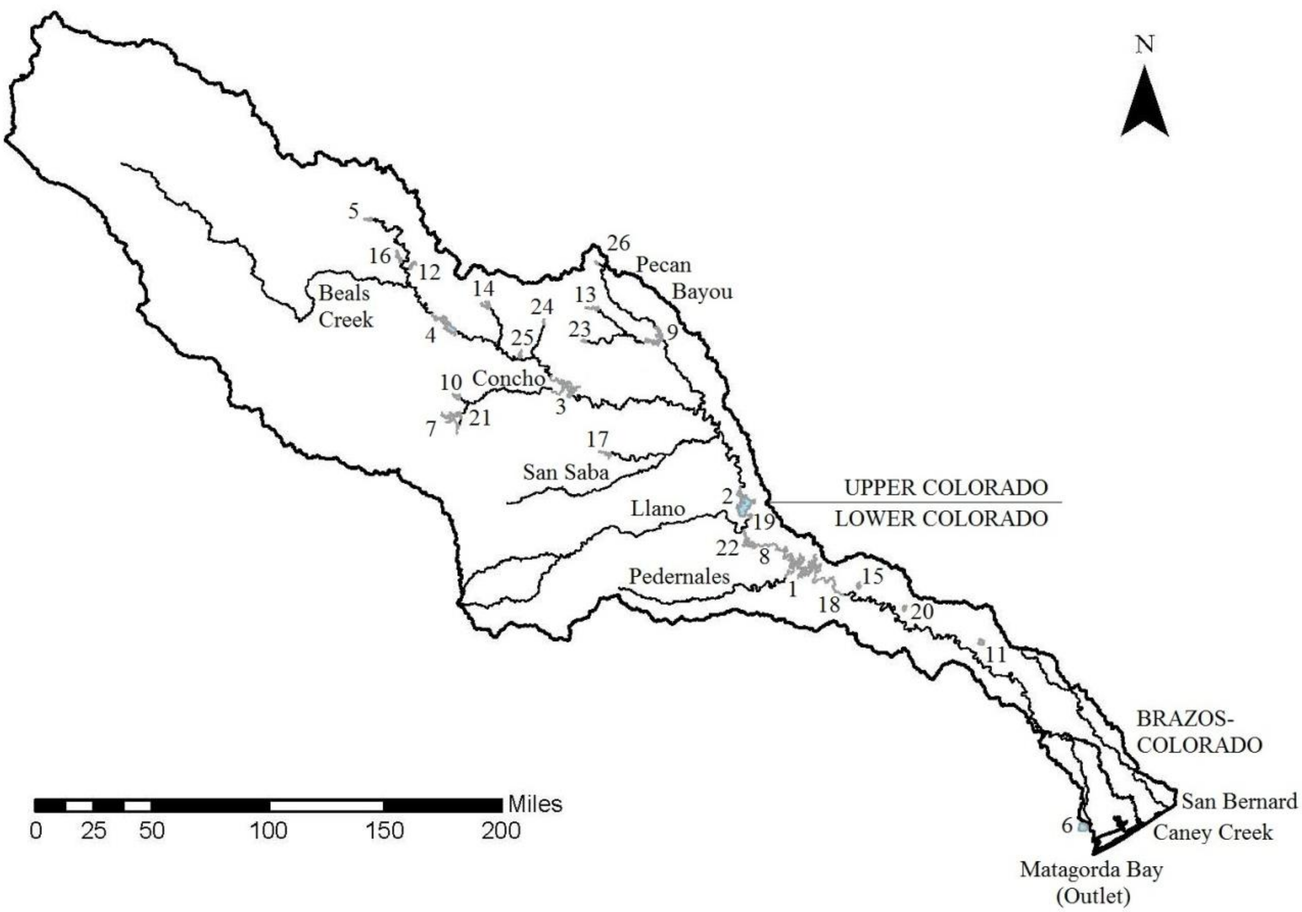

Figure 2.4 Major Tributaries and Largest Reservoirs

The full authorization scenario Colorado WAM includes 484 actual reservoirs that have authorized storage capacities that sum to 5,263,900 acre-feet. The 31 major reservoirs listed in Table 2.3 contain authorized storage capacities that total 5,195,460 acre-feet, which is 98.7 percent of the total authorized capacity of the 484 reservoirs. As previous noted, the proposed but not yet constructed storage capacity assigned WAM reservoir FLDFLW listed last in Table 2.3 may be divided among multiple future reservoirs though modeled as only one of the 484 reservoirs.

Water Rights

The original 2001 Colorado WAM contained 1,287 water rights, including 1,226 water rights in the Colorado River Basin and 61 water rights in the Brazos-Colorado Coastal Basin [12]. The water rights included authorized diversions totaling 3.3 million acre-feet per year, with approximately 66% used for municipal purposes, 25% used for irrigation, 8% used for industrial purposes, and 1% used for mining, recreation, and other purposes. The water right permits include no authorized release amounts specifically for hydroelectric energy generation. Hydropower is generated only from spills or reservoir releases for other purposes. Several water rights in the Colorado WAM include authorization to divert and/or impound water only when stream flows at specified locations exceed prescribed levels. These restrictions are designed to protect senior water rights and/or environmental flow needs. The CRMWD and LCRA are the largest water right holders in the upper and lower basins, respectively.

Model water rights are categorized as either water right *WR* record water rights or instream flow *IF* record water rights. Table 2.1 indicates that the August 2007 update to the authorized use and current use versions of the Colorado WAM contain 1,922 and 1,928 *WR* records, respectively, and 86 and 93 *IF* records, respectively. The February 2020 updated authorized use scenario WAM contains 2,167 *WR* and 120 *IF* records. This includes the artificial water rights discussed later.

The term "*water right*" or "*model water right*" is used in WRAP/WAM modeling to refer to a water right *WR* record or instream flow *IF* record and set of auxiliary supporting records. In some cases a water right permit is represented as a single "*model water right*". In other cases, multiple *WR* records are used to model a particular water right permit. Thus, the Colorado WAM, like other WAMs, includes many more *WR* records and associated sets of auxiliary records than the number of water right permits that are simulated by the WAM.

WR Record Water Rights in the Colorado WAM

Totals of authorized annual diversion amounts from *WR* record field 3 are included in Table 2.9 on page 34. The 2,167 *WR* records have priority numbers ranging from zero to 99999999. The most senior actual water right permit specified priority date is December 31, 1864, represented by a *WR* record priority number of 18641231 (Table 2.9). The 1,730 "*non-artificial*" *WR* record rights include 1,595 type 1; 63 type 2; 19 type 3; and 53 type 8 rights as defined by *WR* record field 6. Although hydroelectric power plants are actually operated by the LCRA at each of the six Highland Lakes, there are no hydroelectric power rights in the Colorado WAM that are modeled as hydroelectric power rights (types 5 and 6 in *WR* record field 6). The 437 artificial rights (Table 2.9) include 143 type 1; one type 2; 74 type 3; and 219 type 8 as defined by *WR* record field 6.

Colorado River Municipal Water District (CRMWD) Water Rights

The CRMWD holds the water rights listed in Table 2.4, which include impoundment of water in 12 reservoirs. O. H. Ivie, E. V. Spence, and J. B. Thomas Reservoirs on the Colorado River store water for municipal, industrial, and mining purposes. The other nine smaller reservoirs located on tributaries of the Colorado River are designed to reduce the volume of poor quality (high salinity) water entering the Colorado River. The CRMWD also partially owns and manages the City of Big Springs water right for water supply from Moss Lake and Powell Lake.

Table 2.4
CRMWD Water Rights [12]

Water Right Number	Priority Date mm/dd/year	Stream	Reservoir	Storage Capacity (acre-feet)	Authorized Diversion (ac-ft/year)
61401002	08/05/1946	Colorado River	J. B. Thomas	204,000	30,000
	08/05/1946	Bull Creek	–	–	–
61401008	08/17/1964	Colorado River	E. V. Spence	488,760	41,571
	03/06/1984	Beals Creek	Beals Creek Sump	3.4	–
	08/17/1964	Off-Channel	Barber Lake	2,500	
	03/06/1984	Red Draw	Red Draw	8,538	8,427
	02/14/1990	Colorado/Beals	Mitchell County	27,266	14,692
11403676	02/21/1978	Colorado River	O. H. Ivie	554,340	113,000
61401012	07/23/1973	Beals Creek	–	–	2,200
	07/23/1973	Beals Creek	Three Mile Lake	–	2,000
	07/23/1973	Beals Creek	Four Mile Lake	–	
11405457	04/01/1993	Sulphur Sprs Draw	Sulphur Draw	7,997	2,500
	04/01/1993	Off-Channel	Red Lake	9,150	
11405480	03/21/1994	Sulphur Sprs Draw	Natural Dam Lake	54,560	2,500

The water right for J. B. Thomas Reservoir authorizes the diversion of 30,000 acre-feet/year for municipal, industrial, recreational, and mining purposes, with no specific allocations to these different types of use. The water right for E. V. Spence Reservoir authorizes the diversion of 41,573 acre-feet/year, with 38,573 acre-feet/year for municipal use, 2,000 acre-feet/year for industrial use, and 1,000 acre-feet/year for mining purposes. The Spence Reservoir water right also authorizes diversion of up to 14,692 acre-feet/year of poor quality water from the Colorado River and Beals Creek for storage in the salinity control reservoirs. The water right for O. H. Ivie Reservoir authorizes the diversion of 113,000 acre-feet/year for municipal and industrial use.

The nine salinity control reservoirs are Sulphur Draw Reservoir, Red Lake Reservoir, Natural Dam Lake, Barber Reservoir, Mitchell County Reservoir, Red Draw Reservoir, Beals Creek Sump, Three Mile Lake, and Four Mile Lake. These reservoirs are designed to prevent runoff from salinity-source watersheds from entering the Colorado River and major tributaries.

Lower Colorado River Authority (LCRA) Water Rights

In addition to the Highland Lakes, which are the focus of the following discussion, LCRA also holds water rights for other existing reservoirs and additional other water supply projects that have been permitted but have not yet been constructed. As indicated by the last entry in Table 2.3, LCRA water right permit 5731 with a priority date of February 28, 2001 authorizes up to 500,000 acre-feet of off-channel storage, which may be developed at multiple reservoir sites, with use of up to 327,591 acre-feet/year from this storage. A maximum diversion rate of 10,000 cfs cumulative for all reservoir sites is specified. No reservoirs have been constructed to date under permit 5731. However, the 500,000 acre-feet storage capacity and 327,591 acre-feet/year diversion target are included in the full authorization version of the WAM.

The six Highland Lakes on the Colorado River are listed in Table 1.1 and discussed in Chapter 1. Tom Miller Dam is owned by the City of Austin and operated by LCRA. The LCRA owns and operates the other five Highland Lakes projects. Austin both holds its own water right permits and contracts with the LCRA for water supplied under LCRA water right permits.

A 1988 adjudication order adjudicated LCRA water rights and other water rights in the lower Colorado River Basin. The 1988 adjudication order requires that LCRA develop and periodically update a reservoir operations plan which is subject to review and approval by the TCEQ [13]. The original LCRA Water Management Plan (WMP) was approved by the TCEQ in 1989. Revisions were approved in 1991, 1992, 1999, 2010, 2015, and 2020 [13]. The WMP plan is incorporated in the LCRA water rights and the Colorado WAM.

Modeling the LCRA water management plan (WMP) adds significant complexity to the Colorado WAM. Most of the artificial water rights, reservoirs, and control points discussed later in the last section of this chapter were inserted in the *SIM* input DAT file in conjunction with model water accounting schemes devised to simulate various components of the WMP.

The WMP governs LCRA operation of the Highland Lakes to meet the needs of water users throughout the lower Colorado River Basin. The WMP prescribes rules for allocating water during supply shortages. During severe drought, the WMP requires the curtailment of releases from Lakes Buchanan and Travis for downstream agricultural irrigation to protect capabilities for supplying municipal and industrial water needs. The plan also prescribes operating rules that help protect the environmental flow needs of the lower Colorado River and Matagorda Bay. The WMP specifies operational trigger levels based on the combined storage in Lakes Buchanan and Travis. LCRA and its customers take curtailment actions if storage contents are below specified trigger levels. Reliabilities for firm water supply users are protected by curtailment of interruptible supplies whenever the storage contents of Lakes Buchanan and Travis drop below specified trigger levels.

The combined firm yield of Lakes Buchanan and Travis, as established by the 2020 WMP, is 418,848 acre-feet per year replacing the value of 434,154 calculated in the 2015 WMP. As long as water demands from firm water customers are less than this firm yield, LCRA may consider supplying water for irrigated agriculture on an interruptible basis. To manage water supplies for both firm and interruptible demands, the WMP imposes triggers based on the combined storage contents of Lakes Buchanan and Travis.

Under the WMP, if a drought is occurring that is characterized by specified metrics that result in it being declared by the LCRA Board of Directors as being potentially worse than the drought-of-record, interruptible customers would be fully and immediately curtailed. No stored water would be made available for agricultural irrigation or other interruptible uses until lake levels recover or the flows into the lakes increase substantially. Under these conditions LCRA will also implement a pro rata curtailment of its firm water customers. Without a declaration that a drought potentially worse than the drought-of-record is underway, LCRA is obligated by the WMP to supply at least some water to the four major irrigation operations.

The 2020 WMP includes the following key provisions [13, 14].

- The amount of interruptible stored water available for diversion in the lower basin for agricultural operations for a given season is based on the declared curtailment condition, current storage in the Highland Lakes, inflows to the lakes, and a look-ahead test to determine whether storage could fall below specified levels. Three curtailment conditions are defined: normal, less severe, and extraordinary drought.
- Limits are placed on releases from interruptible stored water from Mansfield Dam and Lake Travis for each of two defined agricultural seasons.
- The combined storage in Lakes Buchanan and Travis is maintained above 600,000 acre-feet through a repeat of the worst drought on record.
- Dedicated releases of water for the environmental health of the Colorado River is provided based on three levels of instream flow criteria that decrease incrementally as combined storage levels in Lakes Buchanan and Travis drop.
- Dedicated releases of water for the environmental health of Matagorda Bay is provided based on five levels of criteria that decrease incrementally as combined storage levels drop in along with necessary curtailment of interruptible stored water for agriculture.

IF Record Instream Flow Water Rights

Instream flow requirements defined by the 120 *IF* records in the full authorization scenario Colorado WAM last updated by TCEQ in February 2020 are listed in Table 2.5. The 120 *IF* records represent instream flow requirements at fewer than 120 locations. Sets of multiple *IF* records are employed in combination to model instream flow requirements at single locations. Table 2.5 is a 2SRT record tabulation created by the WRAP program *TABLES* based on reading the *IF* records from the *SIM* input DAT file. The *IF* record water rights are listed in priority order, with priorities ranging from 19041231 to 20100804 (December 31, 1904 to August 4, 2010).

Environmental flow standards (EFS) established pursuant to the 1997 Senate Bill 3 (SB3) with priority dates of March 1, 2011 are added later to the daily Colorado WAM as described in Chapters 5 and 8. The relationship between the 120 previously existing *IF* records and the new SB3 EFS are discussed in Chapters 5 and 8. The existing *IF* record water rights in the monthly Colorado WAM are not altered in the conversion to a daily WAM other than uniformly distributing the monthly instream flow targets to the 28, 29, 30, or 31 days in each month. The new SB3 EFS described in Chapter 5 are additional *IF* record water rights added to the daily WAM.

Table 2.5
Instream Flow *IF* Record Water Rights in February 2020 Update of Colorado WAM

Water Right	Control Point	Annual Target (ac-ft/yr)	Monthly Distrib	Priority
IF1783_1	E40000	5270	IF1783	19041231
IF1783_2	E40000	0	IF1783	19041231
IF2511_1	F10000	31336	IF2511	19071231
IF2511_2	F10000	0	IF2511	19071231
NJBSFIN	NJBASE	0		19131231
IF5437_1	M10020	217200		19740610
IF1829	E30200	5712.4		19741125
IFCEDAR	J10121	362		19750203
IFBAYLOR	J10150	362		19750203
IFCEDBAYLOR	J10140	144793		19750203

ONJBSFIN	NJBASE	0		19131231
IF1288_4	C30000	6587	1288IB	19140604
IF1288_5	C30000	0	1288IB	19140604
IF1261	C40110	4998.3		19140623
IF5471A	J10140	144793		19140627
IF5471B	J10140	0		19140627
	C20000	1616.3	IF1298	19140730
	C20000	0		19140730
	DRTCND	4		19260324
	DRTCND	0		19260324
HAB-A-SUB	AUSSUB	36198	I1HT-S	19260327
HLS-ASUB	AUSSUB	36198	I1HT-S	19260327
HAB-B-AVG	BASAVG	382480	J3HT-A	19260327
HAB-B-DRY	BASDRY	229585	J3HT-D	19260327
HAB-B-SUB	BASSUB	137994	J3HT-S	19260327
HLS-BSUB	BASSUB	137994	J3HT-S	19260327
HAB-C-AVG	COLAVG	646935	J1HT-A	19260327
HAB-C-DRY	COLDRY	402085	J1HT-D	19260327
HAB-C-SUB	COLSUB	232012	J1HT-S	19260327
HLS-CSUB	COLSUB	232012	J1HT-S	19260327
HAB-W-AVG	WHAAVG	663475	K2HT-A	19260327
HAB-W-DRY	WHADRY	407692	K2HT-D	19260327
HAB-W-SUB	WHASUB	168129	K2HT-S	19260327
HLS-WSUB	WHASUB	0		19260327
THRESH-INF	M1-1DS	0		19260327
HLS-BTCO	M1-1DS	0		19260327
OP60-INF	M10000	0		19260327
IF3676_1	D20050	3808	IF3676	19260328
IF3676_2	D20050	0	IF3676	19260328
IF5715_1	F10000	96732	IF5715	19260328
IF5715_2	F10000	0	IF5715	19260328
IFBOOT1	H10800	145	OTH	19260328
IFBOOT2	H10800	0	OTH	19260328
IF3421_1	L10000	43185	IF3421	19280913
IF3421_2	L10000	0	IF3421	19280913
	C20000	1616.3	IF1298	19311008
	C20000	0		19311008
	G30285	63737.6	OTH	19351231
	G30285	0	IRR-G	19351231
IFMENSUB	MENSUB	14182	SUBMEN	19461231
IFMENBAS	MENBAS	35683	BASMEN	19461231
IFMENSUBOFF	MENSUB	0	SUBMEN	19461231
IFMENBASOFF	MENBAS	0	BASMEN	19461231
IF1460_1	H10000	21659	1460IF	19481231
IF1460_2	H10000	0	1460IF	19481231
IF3956_1	D10300	3620		19531231
IF3956_2	D10300	0		19531231
IF1564_1	G50470	3213.2		19531231
IF1564_2	G50470	0		19531231
138702_1	F10000	31339	SS-SEV	19560227
138702_2	F10000	0	SS-SEV	19560227
IF1288_1	C30000	7093	1288IF	19620118
IF1288_2	C30000	0	1288IF	19620118
IF1282_1	C206DS	1687.9	SAWYER	19641231
IF1282_2	C206DS	0	SAWYER	19641231
IF1489	G50500	1448		19750908
IF1572	G40950	6426.4		19760202
IF1639	G10310	35702.5		19760329
IF3325	D20190	7240		19760726
IF1800	E40130	1428.1		19761025
IF3522	J10530	137560		19770620
IF3429	N30090	8688		19770627
IF3427	N30140	7946		19771107
IF3432	N30030	7240		19771212
IF3676_3	D20050	3808	IF3676	19780221
IF3428	N30130	8688		19781106
IF3418	L10550	10136		19790507
IF3419	L10550	10136		19790507
IF3420	L10420	65160		19790910
IF3417	L10650	14480		19800714
IF3814	L10230	7964		19810324
IF3816	L10330	1193		19810530
IF3846	N30190	4344		19811109
IF3847	L10500	9412		19820419
IF3435	N30270	796		19820426
IF3926	L10380	3258		19820907
IF3967	N30050	7602		19821220
IF3955	N10150	47784		19830110
IF3957	L20020	362		19830110
IF4162	L10400	43440		19840918
IF4177	L10020	61540		19840925
IF3810	N10120	65160		19841127
IF4229	L10040	1448		19850319
IF4284	L10520	9412		19850730
IF5067	L10350	3620		19860604
IF5086	J50190	724		19860815
IF1570_1	G40090	14280		19861014
IF5111	F11080	905	IF5111	19861124
IF5156	L10690	0		19870915
IF3956_3	D10300	3620		19900214
IF5273	J50050	362		19900404
IF3438	N30210	724		19900621
IF5324	L10450	46336		19901025
IF5338	L10130	12308		19901219
IF5446	N20010	1448		19930129
IF5459	L10150	5792		19930421
IF5432	J10003	235351	SUCKER	19931020
IF1564_3	G50470	3213.2		19950206
IF5623	L10000	44942	5623IF	19991105
IF5715_3	F10000	96732	IF5715	20001030
HAB-AVG-WHA	K10090	655697	K2HT-A	20010228
EFMBHE	M1-1DS	0		20010228
IF5702	L10115	9820	IFWBER	20011101
IF5721	L10117	9820	IFWBER	20011116
IF1460_3	H10000	21659	1460IF	20050921
IFBOOT3	H10800	145	OTH	20051108
	C20000	1616.3	IF1298	20060706
IF1288_3	C30000	7093	1288IF	20090722
	G30285	63737.6	OTH	20090730
IF1288_6	C30000	6587	1288IB	20100804

The 120 *IF* records in the monthly Colorado WAM last updated by TCEQ in February 2020 protect downstream senior water rights and environmental instream flow needs. As noted in the preceding section, several of the *IF* record water rights model minimum flow requirements at four gages on the Colorado River below Lake Travis and bay and estuary freshwater inflows to

Matagorda Bay described in the LCRA Water Management Plan [13]. Many of the *IF* record rights model instream flow requirements associated with particular water right permits for water supply diversions and storage at scattered locations throughout the river basin.

Instream flow requirements are modeled with the 120 *IF* records in Table 2.5 using various combinations of options. In many cases, instream flow requirements are modeled using only input parameters entered on the *IF* record. In other cases, instream flow requirements are modeled by combining *IF* record specifications with additional options activated using monthly use coefficient *UC*, reservoir storage *WS*, target options *TO*, flow switch *FS*, and/or drought index *DI/IS/IP/IM* records. *WR* record type 8 water rights are also used in combination with *TO* records to develop instream flow targets for *IF* record water rights. A *WR* record with the water right type 8 option selected does nothing but compute a target, though various options can the employed to compute that target. *IF* records may employ *TO* records that reference *WR* record water right type 8 targets.

The May 2019 and later versions of the WRAP simulation models *SIM* and *SIMD* include environmental standard *ES*, hydrologic condition *HC*, pulse flow *PF*, and pulse flow options *PO* records that are designed for modeling environmental instream flow requirements formulated in the format adopted by the 2007 SB3 process. Both *SIM* and *SIMD* include *ES* and *HC* records. *PF* and *PO* records are applicable only in a daily *SIMD* simulation. The SB3 EFS are modeled with *IF*, *ES*, *HC*, *PF*, and *PO* records as explained in Chapter 5.

WAM Hydrology

The original 1940-1998 hydrologic period-of-analysis of the Colorado WAM was updated by the TCEQ to extend through 2013 and then more recently updated again to extend through 2016. Hydrology is represented by 1940-2012 sequences of naturalized stream flow volumes in acre-feet and net reservoir surface evaporation minus adjusted precipitation depths in feet.

Monthly Naturalized Stream Flow

Monthly naturalized flows at the 45 primary control points listed in Table 2.2 with locations shown in Figures 2.1 and 2.2 are stored on *IN* records in the *SIM* input FLO file. Naturalized flows are synthesized during execution of *SIM* for the over 2,200 secondary control points based on information provided on DIS file *FD* and *WP* records and/or DAT file *CP* records. Naturalized flows are distributed to most secondary control points using the drainage area ratio method, which is combined with channel loss factors for some of the control points.

The next computations in the *SIM* simulation, after the distribution of monthly naturalized flows from primary (gaged) to secondary (ungaged) control points, is the addition to the monthly naturalized flows of adjustments from *FA* records [1, 2]. *SIMD* monthly-to-daily disaggregation computations occur after the *FA* record flow adjustments have been added [1, 4]. Thus, the monthly flow adjustments on the *FA* records are treated as components of the monthly naturalized flows that are disaggregated to daily in a daily *SIMD* simulation.

The flow adjustment FAD file of the Colorado WAM contains flow adjustment *FA* records with 1940-2016 monthly flow volumes at 13 control points that are used to adjust the *IN* record naturalized stream flows for the effects of spring flows. In general, the flow *FA* records can contain any quantities to be added within the simulation to the naturalized flows. However, the optional *FA* record flow adjustment feature was originally designed for modeling effects of springs flows on stream flows and has been used primarily, if not completely, for that purpose. FAD files are included in the WAM datasets for only a few of the river basins in the TCEQ WAM System.

The spring flows in the FAD file of the Colorado WAM were excluded from the monthly naturalized flows recorded on *IN* records during the original development of the naturalized flows [12]. The spring flows are added back to the naturalized stream flows at the beginning of the *SIM* simulation. The primary effect of separating the *FA* record spring flow component of naturalized flows from the remainder of the flows entered on the *IN* records appears to be reflected in the distribution of flows from primary to secondary control points within the *SIM* simulation. The spring flows do not affect naturalized flows at upstream control points.

<u>Net Monthly Reservoir Evaporation-Precipitation Depths</u>

Evaporation from a reservoir and precipitation falling directly on the reservoir water surface are combined as a net evaporation minus adjusted precipitation. Net evaporation less precipitation volumes are computed within the *SIM* simulation by multiplying the reservoir water surface area by net evaporation-precipitation rates provided on *EV* records in feet.

Precipitation depths are adjusted for reservoir site runoff that is reflected in the naturalized stream flows. Without a reservoir, the runoff from the land area of the non-existent reservoir contributes to stream flow. However, only a portion of the precipitation falling at the reservoir site contributes to stream flow. The remainder is lost through infiltration and other hydrologic abstractions. With the reservoir in place, all of the precipitation falling on the water surface is inflow to the reservoir.

SIM includes an option activated by parameter EPADJ on the *JD* record and EWA(cp) on the *CP* record designed to account for the fact that a portion of the precipitation falling on the reservoir water surface is also reflected in the naturalized stream flows. Adjustment computations are performed during the *SIM* simulation based on the simulated reservoir water surface areas. However, this *SIM* option is not employed in the Colorado WAM. Rather, the net evaporation-precipitation rates on the *EV* records are adjusted during preparation of the *SIM* input EVA file. The adjustment of precipitation falling on the reservoir surface for *"runoff from reservoir area in absence of reservoir"* was determined by multiplying a regional monthly runoff coefficient by precipitation [12]. The regional monthly runoff coefficients were computed for various regions of the basin by relating historical monthly streamflow to corresponding historical monthly rainfall.

The Texas Water Development Board (TWDB) maintains datasets of monthly precipitation depths and reservoir surface evaporation depths for each of 92 one degree latitude by one degree longitude quadrangles that cover the state of Texas. The 18 quadrangles that encompass the Colorado River Basin and Brazos-Colorado Coastal Basin are delineated in Figure 2.5. The database of monthly precipitation and evaporation depths is accessible through the TWDB website.

The EVA file for the Colorado WAM contains forty-eight 1940-2016 sequences of monthly reservoir surface evaporation minus precipitation depths in feet. The 48 time series of monthly net evaporation-precipitation depths are labeled with control point identifiers shown in

Figure 2.5. Each of the reservoirs in the WAM is connected to one of the 48 evaporation-precipitation data sets through these identifiers. Eighteen identifiers in Figure 2.5 reference the 18 TWDB-defined quadrangles that encompass the Colorado River Basin and Brazos-Colorado Coastal Basin. These 18 sequences of evaporation-precipitation depths are each shared by multiple reservoirs. The other 30 control point identifiers refer to 30 large reservoirs for which the evaporation-precipitation depths recorded on *EV* records were computed using weighted values for multiple quadrangles. The integer identifiers assigned to each quadrangle by the TWDB are also included in Figure 2.5.

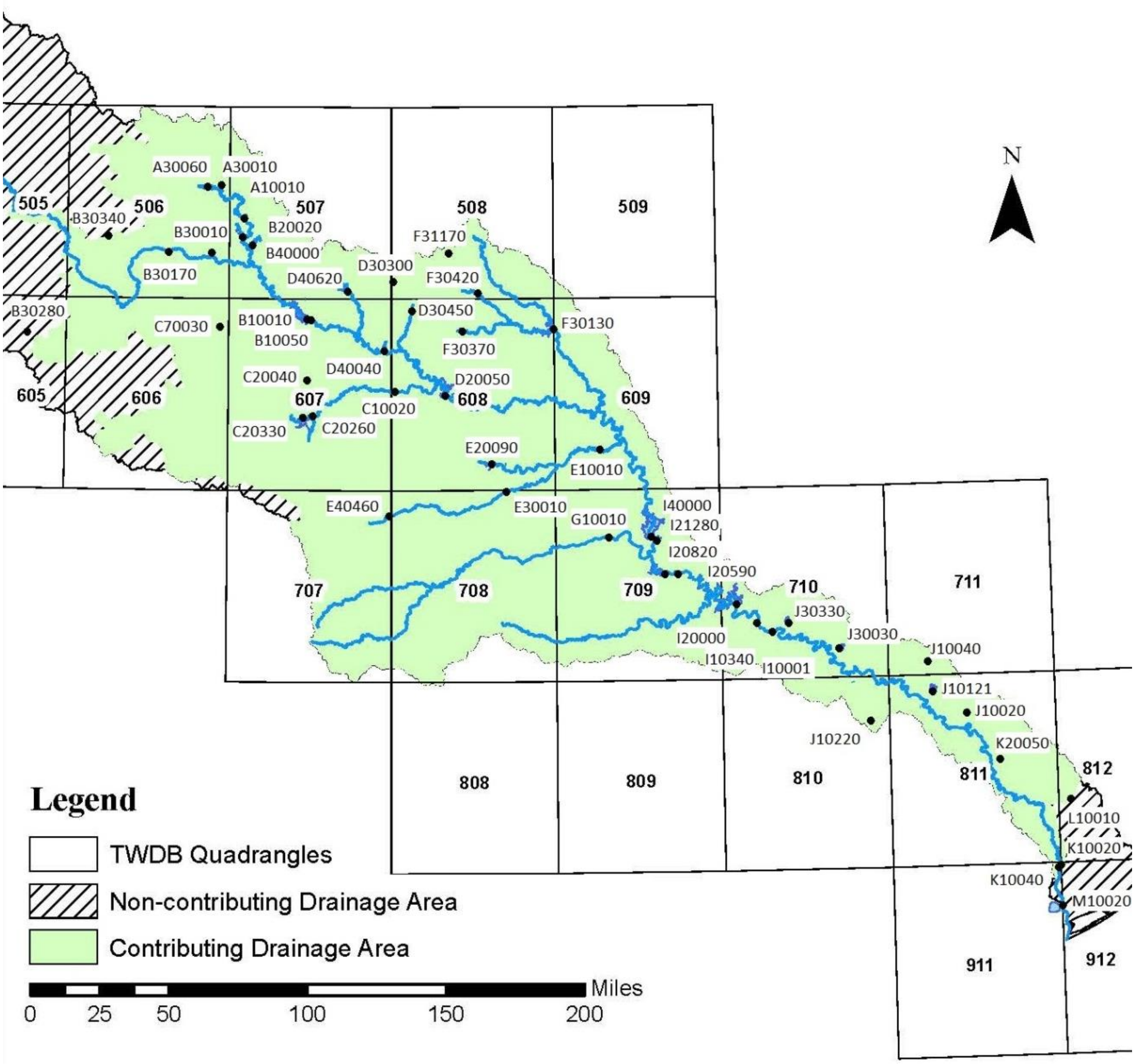

Figure 2.5 Reservoir Net Evaporation-Precipitation Identifiers and TWDB Database Quadrangles

Simulation Results

Figures 2.6, 2.7, 2.8, 2.9, and 2.10 and Tables 2.6 and 2.7 are derived from the results of a simulation with the full authorization scenario Colorado WAM last updated by the TCEQ in February 2020. Simulation results reflect the premises, computational methods, and input datasets that comprise the WAM. This includes the hypothetical scenario of all water right permit holders storing and diverting the full amounts of water authorized by their permits during a repetition of 1940-2016 natural river system hydrology. The selected simulation results presented here illustrate the general overall hydrologic characteristics of the river/reservoir system. The monthly simulation is performed with *SIM*. Selected simulation results are plotted using *HEC-DSSVue* . Frequency metrics are tabulated with WRAP program *TABLES*.

Annual and monthly stream flow volumes at control point K10000 near the outlet of the Colorado River Basin are plotted in Figures 2.6, 2.7, and 2.8. Control point K10000 is the site of USGS gage 08162500 on the Colorado River near Bay City, which has a watershed drainage area of 30,862 square miles (Table 2.2). Annual naturalized, regulated, and unappropriated flow volumes in acre-feet/year are compared in Figure 2.6. Water rights reduce the 1940-2016 annual naturalized flows to the annual regulated and unappropriated flows plotted in Figure 2.6. Figures 2.7 and 2.8 are plots of January 1940 through December 2016 WAM monthly naturalized and regulated flow volumes in acre-feet/month, respectively. These time series plots illustrate the great variability of stream flow in the Colorado River Basin that is characteristic of rivers and streams throughout Texas.

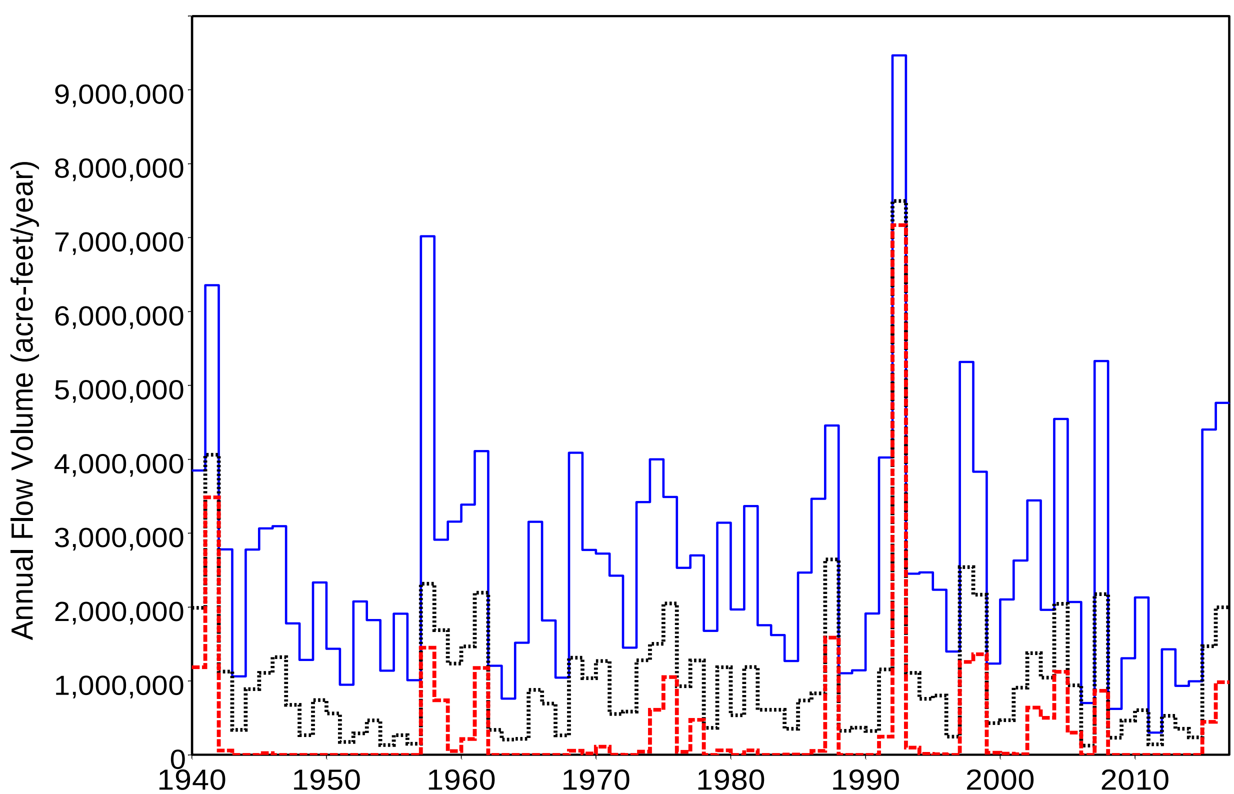

Figure 2.6 Annual Naturalized (blue solid line), Regulated (black dotted line), and Unappropriated (red dashed line) Flows at Control Point K10000

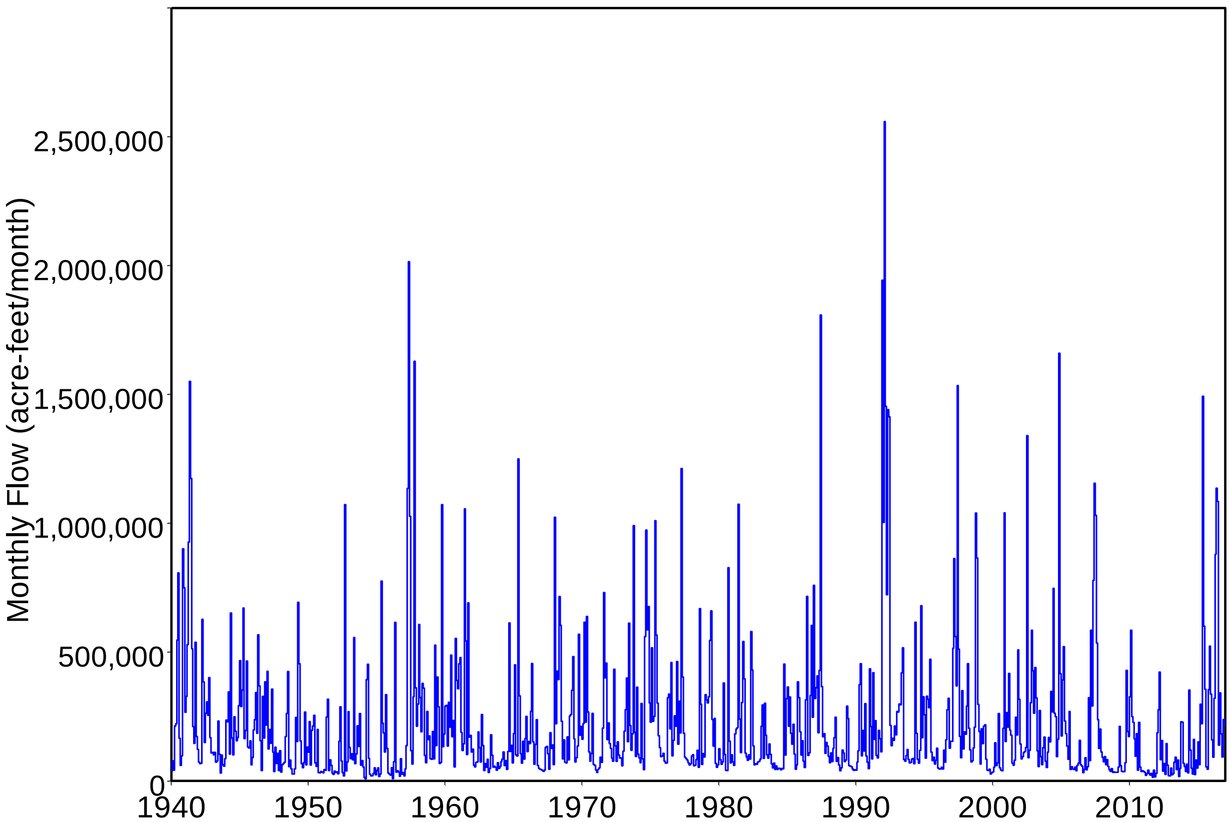

Figure 2.7 Monthly Naturalized Flows at Control Point K10000 near the Basin Outlet

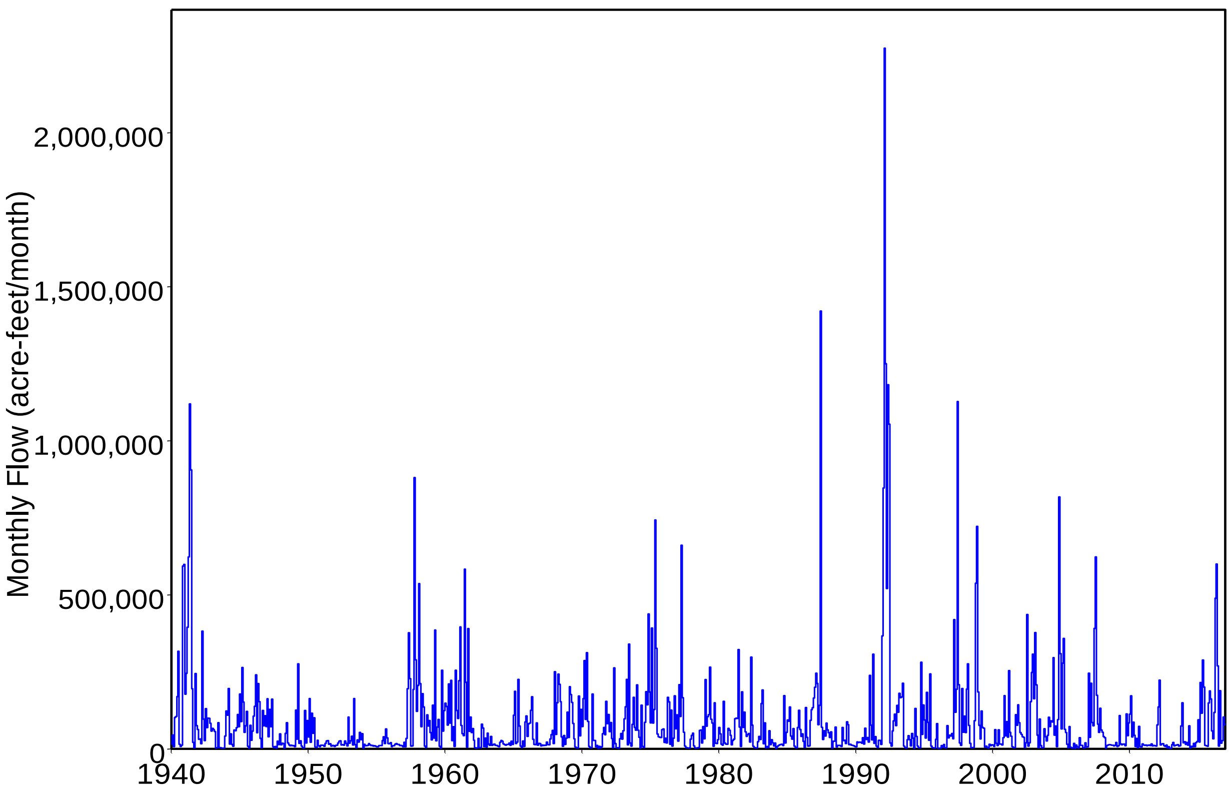

Figure 2.8 Monthly Regulated Flows at Control Point K10000 near the Basin Outlet

Frequency metrics for monthly naturalized, regulated, and unappropriated flow volumes in acre-feet/month near the basin outlet (control point K10000) are tabulated in Table 2.6. Figure 2.7 and Table 2.6 show the simulated effects of water resources development, management, and use on statistical frequency metrics of inflows to Matagorda Bay for the full authorization scenario.

Table 2.6
Statistical Frequency Metrics in acre-feet/month for
Naturalized, Regulated, and Unappropriated Flow of the Colorado River
at Control Point K10000 near the Basin Outlet

Stream Flow	Naturalized	Regulated	Unappropriated
Mean (ac-ft/month)	224,177	86,359	29,963
Standard Deviation	275,789	162,531	145,901
Minimum	8,382	2,119	0
99.50%	16,595	2,389	0
99%	19,558	2,546	0
98%	24,654	2,749	0
95%	32,402	3,149	0
90%	41,487	4,874	0
85%	48,862	8,097	0
80%	59,464	10,087	0
75%	67,463	11,584	0
70%	74,050	13,452	0
60%	95,953	19,397	0
50%	128,183	33,924	0
40%	172,176	53,469	0
30%	229,353	77,953	0
25%	268,382	95,546	0
20%	321,012	123,310	0
15%	390,706	161,911	0
10%	515,719	207,093	26,201
5%	729,396	305,648	172,537
2%	1,135,382	596,171	462,434
1%	1,483,226	872,710	816,617
0.50%	1,715,755	1,148,535	1,138,474
Maximum	2,558,081	2,274,219	2,274,219

Tables 2.6 and 2.7 consist of Wrap program *TABLES* 2FRE frequency tabulations for monthly naturalized, regulated, and unappropriated flow volumes in acre-feet/month at control points K10000 and L10000, respectively. Control point L10000 is the site of USGS gage 08117500 on the San Bernard River near Boling, which has a watershed drainage area of 725 square miles (Table 2.2). Tables 2.6 and 2.7 contain the mean, standard deviation, and flow quantities that are equaled or exceed during specified percentages of the 924 months of the 1940-2016 hydrologic period-of-analysis.

Table 2.7
Statistical Frequency Metrics in acre-feet/month for
Naturalized, Regulated, and Unappropriated Flow of the San Bernard River
at the USGS Gage near Boling Represented by Control Point L10000

Stream Flow	Naturalized	Regulated	Unappropriated
Mean (ac-ft/month)	22,388	86,359	29,963
Standard Deviation	41,675	162,531	145,901
Minimum	0	2,119	0
99.50%	0	2,389	0
99%	0	2,546	0
98%	0	2,749	0
95%	0	3,149	0
90%	0	4,874	0
85%	0	8,097	0
80%	0	10,087	0
75%	0	11,584	0
70%	0	13,452	0
60%	1,712	19,397	0
50%	5,282	33,924	0
40%	9,619	53,469	0
30%	17,363	77,953	0
25%	24,340	95,546	0
20%	34,807	123,310	0
15%	46,927	161,911	0
10%	67,663	207,093	26,201
5%	114,064	305,648	172,537
2%	166,010	596,171	462,434
1%	219,094	872,710	816,617
0.50%	246,712	1,148,535	1,138,474
Maximum	338,158	2,274,219	2,274,219

The Colorado WAM includes the Brazos-Colorado Coastal Basin as well as the Colorado River Basin. The coastal basin is much smaller. The 31 major reservoirs with authorized storage capacity of 5,000 acre-feet or greater listed in Table 2.3 are all located in the Colorado River Basin. There are no reservoirs with authorized storage capacity of 5,000 acre-feet or greater located in the coastal basin. The San Bernard River and Caney Creek are the main streams of the 1,860 square-mile coastal basin.

Reservoir storage contents provides both a meaningful measure of water supply capabilities and a drought severity index. Reservoir storage contents is adopted here as a general summarizing metric describing water availability. The WRAP/WAM simulated end-of-month storage volumes plotted in Figures 2.9 and 2.10 represent reservoir storage contents that would hypothetically occur if all water right permit holders appropriated the full amounts of water authorized by their water right permits. The storage contents at the beginning of January 1940 is set equal to capacity for each reservoir. The effects of changing the January 1940 beginning storage to the December 2016 ending storage is shown in Figures 7.7, 7.8, and 7.9 of Chapter 7 to generally propagate in the simulation to the mid-1940s, ending without affecting the 1950s and later drought draw-downs.

The summation of end-of-month storage in acre-feet of the 484 reservoirs included in the WAM is plotted in Figure 2.9. The 484 reservoirs have a total authorized storage capacity of 5,263,900 acre-feet. The maximum total storage contents after January 1940 is 5,124,498 acre-feet in June 1941. The minimum of the summation of end-of-month storage contents of the 484 reservoirs during the 1940-2016 simulation is 428,257 acre-feet (8.1% of capacity) in December 2014. Storage of individual reservoirs tend to exhibit greater variability than the summation of storage contents of 484 reservoirs due to differences in the timing of drawdowns and refilling.

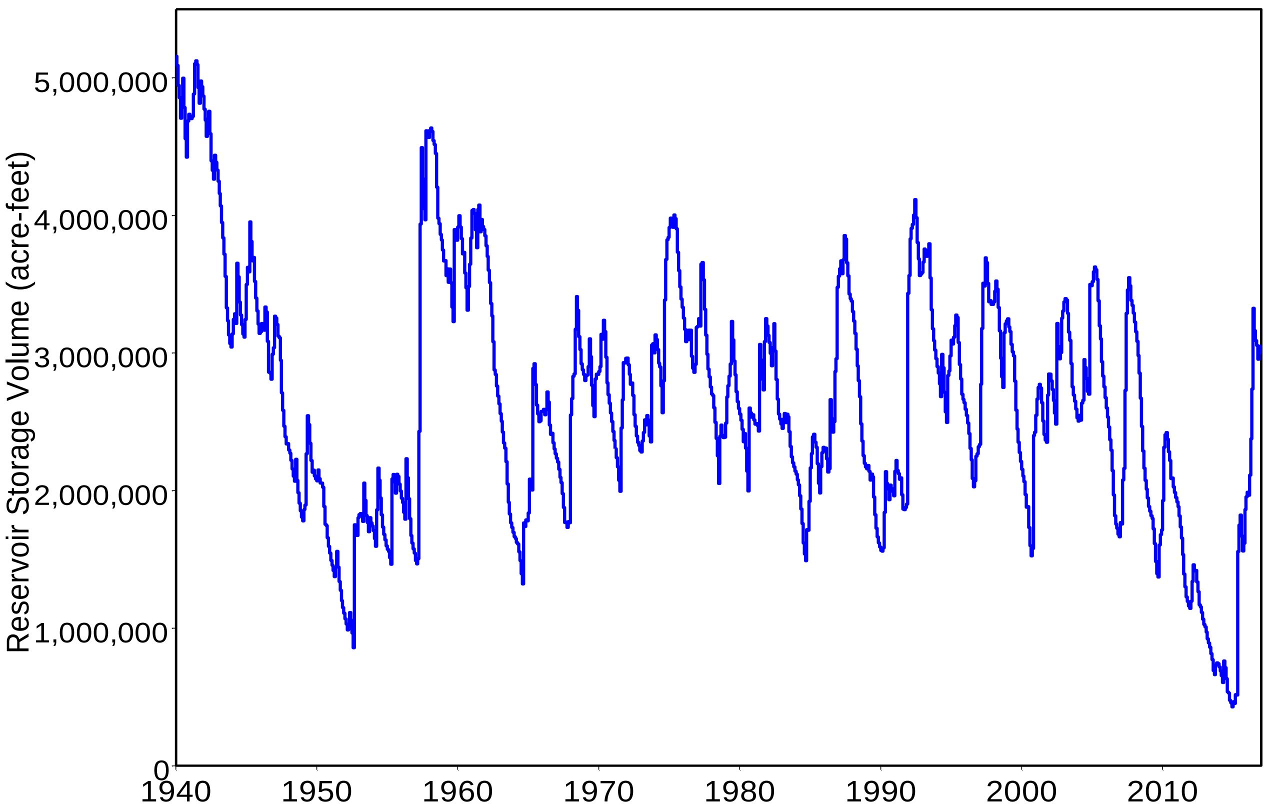

Figure 2.9 Total Simulated End-of-Month Storage Contents of 484 Reservoirs

The total simulated storage contents of the six Highland Lakes and the three large CRMWD reservoirs (Ivie, Spence, Thomas, Table 2.3) located in the upper basin are plotted in Figure 2.10. The six Highland Lakes operated by the LCRA contain 44.6% of the authorized storage capacity of the 484 authorized storage facilities. O.H. Ivie, E.V. Spence, and J.B. Thomas Reservoirs contain 23.7% of the authorized storage capacity of the 484 authorized storage facilities.

The six Highland Lakes have a total authorized storage capacity of 2,349,032 acre-feet (Tables 1.1 and 2.3). All six of the reservoirs are full to capacity often in the simulation reflected in Figure 2.10. The minimum total simulated storage contents of the six reservoirs is 184,809 acre-feet (7.9 percent of capacity) occurring in February 2015. The last time during the 1940-2016 simulation that the six reservoirs are all full to their authorized capacities totaling 2,349,032 acre-feet is the end of June 2007.

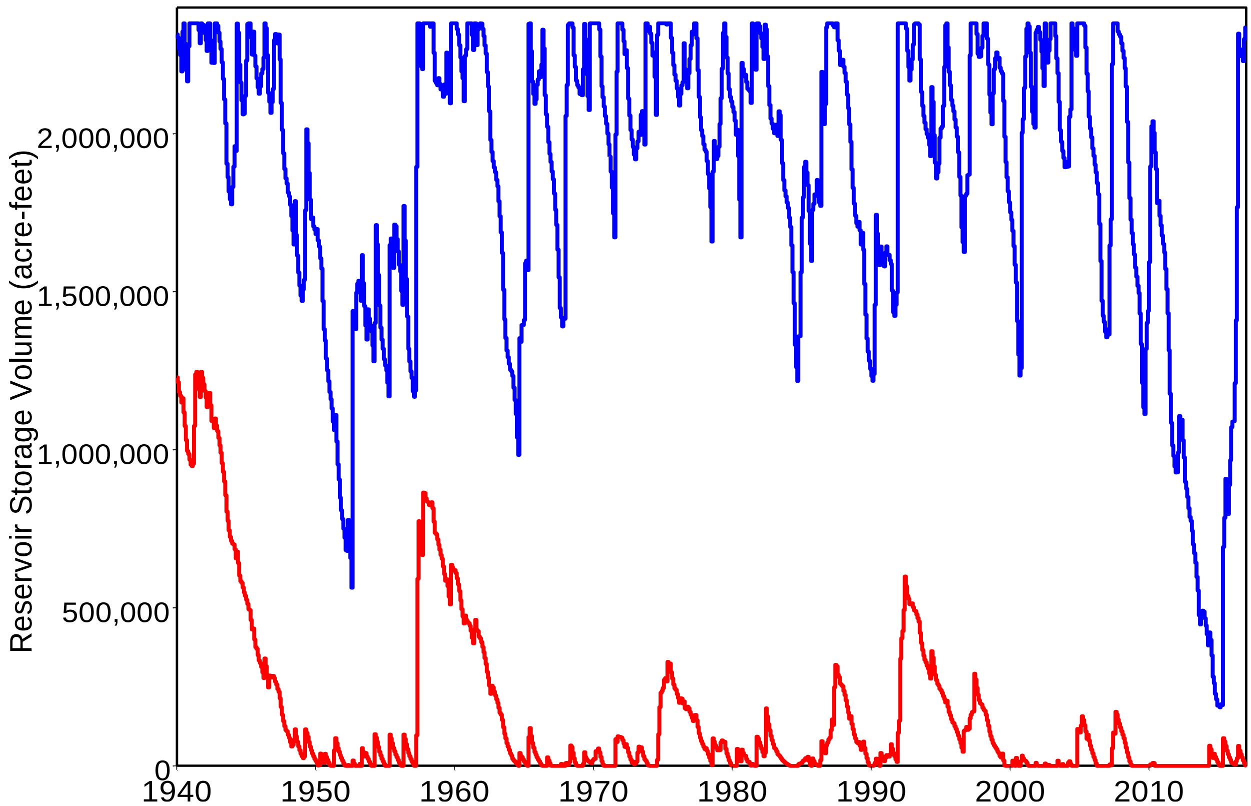

Figure 2.10 Total Storage Contents of Six Highland Lakes Operated by LCRA (blue line) and Three Reservoirs Operated by CRMWD (red line)

O.H. Ivie, E.V. Spence, and J.B. Thomas Reservoirs contain authorized storage capacities that total 1,247,100 acre-feet (Table 2.3). Figure 2.10 shows that these three CRMWD reservoirs located in the upper Colorado River Basin are empty or near empty during much of the 1940-2016 hydrologic period-of-analysis simulation.

Figures 2.6, 2.7, 2.8, 2.9, and 2.10 and Tables 2.6 and 2.7 are derived from the results of a simulation with the full authorization Colorado WAM last updated by the TCEQ in February 2020. Simulation results reflect the premises, computational methods, and input datasets that comprise the WAM. This includes the hypothetical scenario of all water right permit holders storing and diverting the full amounts of water authorized by their permits during a repetition of 1940-2016 natural river system hydrology and the assumption that reservoirs begin the simulation full.

The selected simulation results presented here provides general overview insight regarding hydrologic characteristics and water availability in the Colorado River Basin. The time series plots and frequency metrics demonstrate the extreme variability of stream flow. Reservoir storage dampens stream flow variability. Reservoir outflow equals inflow in the *SIM* simulation in months during which a reservoir is completed full to authorized storage capacity. Reservoirs pass inflows for downstream water rights. Otherwise, with storage below capacity, inflows are stored. Figures 2.9 and 2.10 shown that reservoirs are significantly below capacity during many of the 924 months of the 1940-2016 simulation. Flow variability and the effects of reservoir storage on flow variability are key consideration in converting the monthly WAM to daily in Chapters 3, 4, and 5.

WAM Modifications

The primary purpose of Chapter 2 is to describe the monthly Colorado WAM last updated by the TCEQ in February 2020. The modifications required to develop the daily WAM are covered in later chapters. However, these last three sections of Chapter 2 also describe initial organizational modifications of the dataset. The discussion of WAM modifications is organized as follows.

- The following sections of Chapter 2 describe the following modifications to the organization and format of the monthly *SIM* input dataset during late 2021 that do not affect the actual values of the quantities computed by the simulation. The modifications consist of addition of the records replicated in Table 2.8 to the initial DAT file and creation on a new DSS input file.
    1. The files C3.FLO, C3.EVA, C3.FAD, and C3.HIS are converted to a single hydrology time series C3HYD.DSS file referenced by the *JO*, *FA*, and *HI* records in Table 2.8.
    2. The ARTIF option on the *CO* and *WO* records in Table 2.8 is activated to label artificial (dummy) reservoirs, control points, and water rights as being artificial.
- Chapter 3 describes the conversion of the monthly WAM to daily. Chapters 4 and 5 describe addition of reservoir flood control operations and SB3 EFS.
    1. Chapter 3 covers monthly-to-daily flow disaggregation, forecasting, routing, and related input data requirements, simulation options, and issues.
    2. Chapter 4 focuses on adding USACE flood control operations of four reservoirs. Chapter 5 focuses on modeling environmental flow standards (EFS) established by the TCEQ and its collaborators pursuant to the 1997 Senate Bill 3 (SB3).
- The simulations presented in Chapters 7 and 8 include use of the daily WAM to compute monthly SB3 EFS instream flow targets for incorporation into the monthly WAM as well as comparative investigations of various water management and modeling methods and issues.

DSS Files of Simulation Input and Output Time Series Data

The advantages of using DSS files to store time series input and simulation results and the capabilities of *HEC-DSSVue* for organizing and analyzing data in DSS files are discussed in "*Chapter 6 HEC-DSS Data Storage System and HEC-DSSVue*" of the WRAP *Users Manual* [2]. *HEC-DSS* and *HEC-DSSVue* are fully integrated into recent editions of the WRAP modeling system. The WRAP programs read and create DSS files. The *HEC-DSSVue* interface has been adopted as a major component of the set of WRAP programs.

The Colorado WAM last updated by the TCEQ in February 2020 consists of *SIM* input files with filename extensions DAT, DIS, FLO, EVA, FAD, and HIS. These files are in regular text format read by various computer software as text files. The FLO, EVA, FAD, and HIS files contain 1940-2016 time series of monthly quantities that are combined into a single DSS file of *IN*, *EV*, *FA*, and *HI* records in conjunction with the work reported here. *DF* records of daily flows are added to the DSS file later as explained in Chapter 3. *TS* records of monthly SB3 EFS targets are added to the DSS file as explained in Chapter 4. The new input DSS file has the filename C3HYD.DSS and can be called the *hydrology DSS file*, *time series input file*, or *hydrology time series file*. This single DSS *SIM/SIMD* simulation input file is read by both *SIM* and *SIMD*.

Simulation results consist of hydrologic period-of-analysis time series of many different variables. *SIM* and *SIMD* have multiple options for recording simulation results in output files, including the option of recording the simulation results in a DSS file. The options selected on the file options *OF* record in Table 2.8 write both daily and aggregated monthly quantities from a daily *SIMD* simulation in a DSS file with filename C3.DSS. The term "HYD" is automatically appended to filename root (C3HYD.DSS) of the DSS input file to distinguish it from the DSS output file (C3.DSS). *OF* record options control selection of monthly *SIM* simulation results or daily and/or monthly *SIMD* simulation results in the DSS output file.

Table 2.8
Records Added to the DAT File for the Modifications Described in Chapter 2

```
**       1         2         3         4         5         6         7         8         9         10
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!
**
JO     6       0   1   0   1                                           2
OF     0   0   2   0   0                                      C3
**
FA        C30130  C40130  C50570  E10300  E10301  E10590  E10610  E10680  E10690  E40260  E40530  I10320
FA        I10330
HI        G50000
**
CO ARTIF  MENFK1  MENFK2  INKSTO  LBJSTO  FURSTO  MARSTO  AUSSTO     OFI
CO ARTIF  GARWRF  GULFRF  LAKERF  PIERRE  IRRTF1  IRRTF2  IRRTF3  IRRTF4  COASUB
CO ARTIF   FAKE1   FAKE2   FAKE3   FAKE4   FAKE5   FAKE6   FAKE7   FAKE8   FAKE9  FAKE10  FAKE11  FAKE12
CO ARTIF  FAKE13   TRACK  FAKE20  FAKE21  FAKE22  FAKE23  FAKE24  FAKE25  FAKE26  FAKE27  FAKE28  FAKE34
CO ARTIF  STPLIM  A-ZERO
CO ARTIF  IVIEFF  BRWNFF  FFOP60
CO ARTIF  SW-LIM  SWGLIM  FAK102  FAK103  SYSCNT  CUMINF  DRT-US  50S-TI  FAK104  FAK105  FAK106  33PCFL
CO ARTIF  50PCFL  FIXEDQ  EXTDRT  LS-DRT  HTI-00  HTI-01  HTI-02  DRTCND
CO ARTIF  STOMAR  STOJUL  AGNHEP  AGLHEP  EXDH14  LSDH14
CO ARTIF  LSDH15  ANY-CO  ANY-PT  ANYNOR  ANYLSD  EXTMAN  LSDMAN  ENV-BO  3MCFLW  FAKE29  AG-CUR  GW-CUR
CO ARTIF  GW-FCT  NG-FCT  GWFFCF  NGFFCF  OP60T1  OP60T2  OP60T3  OP60T4  FAKEBA  BAY-00  BAY-01  BAY-02
CO ARTIF  BAY-03  SPMBHE  2CSSCT  SEADAT  OP1EXC  OP2EXC  OP3EXC  OP4EXC  OP1MIN  OP2MIN  OP3MIN  OP4MIN
CO ARTIF  MB1-SF  MB1-FF  MB2-SF  MB2-FF  MB3-SF  MB3-FF  MB4-SF  MB4-FF  ENVCAP  EUS-01  EUS-02  EUS-03
CO ARTIF  EUS-04  EUS-05  EUS-06  EUS-07  EUS-08  EUS-09  EUS-10  EUS-11  EUS-12  DRTNUM  DRTCON  DRTKEY
CO ARTIF  MBHEFL
CO ARTIF  NJSEVT  NJSVD1  NJSVT2  NJSVT3  NJBDRY
CO ARTIF  GCE-TW  GCE-AR  DLYGCE  FAKEAO
WO ARTIF     STPDUMMYNO1     STPDUMMYNO2     STPDUMMYNO3     STPDUMMYNO4     11405731IV1     11405731BR1
```

INEV option 6 activated in *JO* record field 2 (Table 2.8) instructs *SIM* or *SIMD* to read *IN* and *EV* records from the DSS hydrology time series input DSS file. The conventional unmodified *CP* records include information specifying which control points have *IN* or *EV* records to be read.

The ones entered in columns 20 and 28 for DSSFA and DSSHI in the *JO* record of Table 2.8 specify that *FA* and *HI* records are to be read from the hydrology time series input DSS file. Flow adjustment quantities for each of the 924 months of the 1940-2016 hydrologic period-of-analysis are stored on *FA* records in the hydrology time series DSS file for each of the 13 control points listed on the DAT file *FA* records of Table 2.8. Hydrologic index quantities for each of the 924 months are stored in the DSS file on a *HI* record with control point identifier G50000. *HI* records are read from the DSS file for all control points listed on *HI* records in the DAT file.

The original DAT file has *FAD* option 1 activated in *JO* record field 1. FAD option 1 adds *FA* record flow adjustments to flows at all control points located downstream of the control point on the *FA* record, but not at the control point on the *FA* record. All other *FA* record options, including the modified WAM dataset, add the *FA* record flow adjustments to flows at the control point on the *FA* record as well as all downstream control points. This distinction is not significant for the Colorado WAM for the following reason. With the exception of control point E40260, there are no water rights located at the 13 control points listed on the *FA* records. A very small *WR* record water right is located at E40260. Otherwise, the control points on the *FA* records serve only as sites for the adjustments to enter the river system. The flow adjustments are applied at all downstream control points with any of the flow adjustment options.

The discussion above focuses on *SIM* reading time series records from the DSS input file. *SIM* also includes capabilities for converting *IN*, *EV*, *FA*, and *HI* records in FLO, EVA, FAD, and HIS files to DSS versions of the records stored in a DSS file. DSS(4) on the *OF* record activates a feature for transferring *IN* and *EV* records from FLO and EVA files to the DSS file. DSSFA and DSSHI on the *JO* record include options for creating DSS versions of *FA* and *HI* records from FAD and HIS files.

Artificial Reservoirs, Control Points, and Water Rights

Use of artificial reservoirs along with artificial water rights and control points to model various complexities of water management dates back to the original 2001 Colorado WAM and continued with subsequent updates. Many of the artificial water rights, reservoirs, and control points were devised in conjunction with simulating the LCRA Water Management Plan discussed earlier in this chapter.

The term "*dummy*" water rights and reservoirs has been used in the past rather than the term "*artificial*". The term "*dummy*" is used in comment records inserted in the original DAT file. The modeling concept of artificial or dummy model components involves devising schemes for performing water accounting computations using *SIM* features differently than the manner the features were originally designed to be used. The devised water accounting computational schemes are designed to simulate various water management complexities.

The effects of artificial water rights, reservoirs, and control points on totals of *SIM* input DAT file quantities are illustrated by Table 2.9. As indicated by Table 2.9, the Colorado WAM has 2,457 control points, which include 2,315 control points representing actual physical locations in the stream system. An additional 142 artificial control points are used in *SIM* water accounting computations to model certain water right complexities, rather than defining physical locations.

The WAM includes 526 reservoirs with storage capacities that sum to 250,248,500 acre-feet of which 42 reservoirs are artificial and thus used only in the water accounting computations. The storage capacities of the 42 artificial (dummy) reservoirs are arbitrary large numbers and account for most of the total storage capacity of the 526 reservoirs in the WAM. The WAM simulates 484 actual physical reservoirs providing an authorized total storage capacity of 5,263,900 acre-feet. The storage volumes plotted in Figure 2.9 on page 29 are summations of storage in the 484 actual reservoirs, which excludes the 42 artificial reservoirs.

Table 2.9
Comparison of Totals of WAM Artificial Versus Real River/Reservoir System Quantities

Quantity	Entire Dataset	Artificial	Actual (Real)
Number of Control Point *CP* Records	2,457	142	2,315
Number of Water Right *WR* Records	2,167	437	1,730
Total Diversion (*WR* AMT, acre-feet/year)	792,461,000	787,140,600	5,320,400
Number of Reservoirs	526	42	484
Total Storage Capacity (acre-feet)	250,248,500	244,984,600	5,263,900
Most Junior Water Right Priority	0	0	18641231
Most Senior Water Right Priority	99999999	99999999	20501231

WRAP Features for Designating Artificial
Control Points, Water Rights, and Reservoirs

Artificial (dummy) control points, water rights, and reservoirs can complicate the interpretation of the input dataset and the simulation results. The following recently developed *SIM* and *TABLES* features have been activated in conjunction with the present Colorado WAM endeavor in order to provide greater clarity in analyzing the *SIM* input DAT file and *SIM* simulation results. Actual numerical values of individual variables are not altered, but inclusion or exclusion in aggregation or summation of quantities can be better controlled. Analyses of the input dataset and simulation results are performed more efficiently, conveniently, and thoroughly.

The modification to the *SIM* input DAT file consists of adding 17 control point output *CO* records and one water right output *WO* record with the ARTIF option activated [2]. These *CO* and *WO* records are replicated in Table 2.8. WRAP automatically defines any water right or reservoir located at a *CO* record designated artificial control point as being an artificial water right or reservoir. Additionally, water rights on a *WO* record with the ARTIF option activated are also designated as being artificial water rights.

The *SIM* and *SIMD* simulation models employ the model-user categorization of artificial components only for selection of simulation results to be included in output files. *SIM* and *SIMD* employ artificial designations as follows. Simulation results consist of time series quantities for many variables associated with either water rights, control points, or reservoirs. Choices of which water right, control point, or reservoir simulation results to include in the OUT, CRM, and DSS output files are controlled by parameters on the *JD*, *RO*, *WO*, *GO*, *CO* and *OF* input records. The variety of options for recording the time series of simulation results includes, among other options, inclusion or exclusion of all or some artificial quantities along with inclusion of other normal quantities or inclusion of only artificial quantities.

SIM and *SIMD* output files are read by programs *TABLES* and *HEC-DSSVue*. Therefore, data tabulations, summary tables, and plots developed with *TABLES* and *HEC-DSSVue* include or exclude quantities connected to artificial control points, water rights, and reservoirs as specified by the *SIM/SIMD* options controlling the *SIM/SIMD* output file contents.

The WRAP program *TABLES* also includes options for reading *SIM* or *SIMD* input files and organizing and displaying the data read from these files. The 1RES, 1SRT, and 1SUM records control *TABLES* options for reading a *SIM/SIMD* input DAT file and creating various tables in various formats. *TABLES* reads the *CO* records listing the artificial control points and automatically designates water rights and reservoirs located at the artificial control points as also being artificial. Water rights listed on *WO* records are also designated as artificial. Choices of data for inclusion in the tabulations created by *TABLES* include the artificial designations along with various other criteria.

Artificial Control Points, Reservoirs, and Water Rights in the Colorado WAM

The 17 *CO* records added to the Colorado WAM DAT file to designate 142 selected control points as being artificial are replicated as Table 2.8. The entry ARTIF in the second field of the *CO* records activates the artificial designation. *SIM* automatically classifies all reservoirs and water rights located at *CO* record designated artificial control points as also being artificial.

The ARTIF option on *WO* records can also be employed to designate artificial water rights. The *WO* record in Table 2.8 lists six water rights that are located at the same non-artificial control points as other non-artificial water rights. These six water rights along with other water rights located at any of the artificial control points are classified as being artificial water rights for purposes of organizing simulation results and data summations and tabulations.

Other control points in the Colorado WAM reflect computational accounting schemes rather than physical locations in the river basin and thus could appropriately be designated as artificial. However, the control points selected for the artificial designation are the only ones that affect the reservoir storage volumes and stream flows in the simulation results presented in this report. Water supply diversion reliability metrics representing summations of all diversion rights in the WAM are not included in this report due complexities that involve both "artificial" water accounting schemes and conventional applications of target setting options. A variety of water supply diversion target setting schemes are employed in the Colorado WAM to simulate complex water management strategies.

The 2,457 control point *CP* records consist of 2,315 control points that represent locations of reservoirs and/or other physical water right features and 142 *CP* records used in employing artificial reservoirs and water rights in the water accounting computations used to simulate water management. CPID(cp,2) and CPIN(cp) in *CP* record fields 3 and 7 denote the next downstream control point and the source of naturalized flows. The *CP* records of the 142 artificial control points have entries for CPID(cp,2) and CPIN(cp) of OUT and ZERO or NONE. Thus, the artificial control points are not connected to the stream network and have no naturalized stream flow.

The WAM dataset contains 2,167 *WR* records and 901 *WS* records supplemented by other auxiliary supporting DAT file input records that define 526 reservoirs. Forty-two of the 526 reservoirs defined by *WR*/*WS* records in the DAT file are classified as artificial. Most of the other 484 reservoirs are individual actual existing reservoirs. As noted earlier (Table 2.3), though treated as only one of the 526 reservoirs defined by *WS* records, and one of the 484 reservoirs not designated on *CO* records as being artificial, LCRA water right permit 5731 authorizes 500,000 acre-feet of storage capacity that may be divided into multiple off-channel reservoirs to be designed and constructed in the future. As indicated by Table 2.9, the 42 artificial reservoirs contain a total storage capacity of 244,984,600 acre-feet, which is 97.9 percent of the total storage capacity (250,248,500 acre-feet) of the 526 reservoirs defined by water right *WR* records and water right storage *WS* records in the *SIM* input DAT file.

The reservoir data tabulation of Table 2.10 was created with *TABLES* using a 1RES record with the specified options of including all artificial reservoirs and only artificial reservoirs, defined as those reservoirs assigned to the control points listed on the *CO* records of Table 2.8. *WO* records are also processed by *TABLES*. However, the six water rights on the *WO* record of Table 2.9 add no reservoir storage volume though they do have diversion quantities. Program *TABLES* reads the *CO*, *WO*, *WR*, and *WS* records from the *SIM* input DAT file to compile the 1RES record reservoir tabulation. Table 2.10 is a direct copy of a table created by the program *TABLES* as specified by a 1RES record.

Multiple water rights defined by water right *WR* and water right storage *WS* records may be associated with the same reservoir. Each line in the tabulation of Table 2.10 represents a *WR/WS* record water right assigned to an artificial control point.

Table 2.10
Artificial Reservoirs

RESERVOIR INFORMATION COMPILED WITH 1RES RECORD
Each line in the table represents a WS record. The data were read
from each WS record and its preceding WR or IF record.
The DAT file contains 901 WS records representing 526 reservoirs.
The listing is controlled by artificial reservoir ART option 3.

Reservoir	Storage Capacity (acre-feet)	Inactive Storage	Water Right	Control Point	WR Priority	WR Type
DRTNUM	1000000	0	DRTNUM	DRTNUM	10	1
DRTCON	10000	0	DRT-SEQ-3	DRTCON	10	3
DRTCON	10000	0	DRT-SEQ-4	DRTCON	10	1
DRTKEY	10000	0	DRT-SEQ-8	DRTKEY	10	3
DRTKEY	10000	0	DRT-SEQ-9	DRTKEY	10	1
EUS-01	999999	0	EUS-01-IM	EUS-01	10	1
EUS-01	999999	0	EUS-01-SH	EUS-01	19260350	3
EUS-02	999999	0	EUS-02-IM	EUS-02	10	1
EUS-02	999999	0	EUS-02-SH	EUS-02	19260350	3
EUS-03	999999	0	EUS-03-IM	EUS-03	10	1
EUS-03	999999	0	EUS-03-SH	EUS-03	19260350	3
EUS-04	999999	0	EUS-04-IM	EUS-04	10	1
EUS-04	999999	0	EUS-04-SH	EUS-04	19260350	3
EUS-05	999999	0	EUS-05-IM	EUS-05	10	1
EUS-05	999999	0	EUS-05-SH	EUS-05	19260350	3
EUS-06	999999	0	EUS-06-IM	EUS-06	10	1
EUS-06	999999	0	EUS-06-SH	EUS-06	19260350	3
EUS-07	999999	0	EUS-07-IM	EUS-07	10	1
EUS-07	999999	0	EUS-07-SH	EUS-07	19260350	3
EUS-08	999999	0	EUS-08-IM	EUS-08	10	1
EUS-08	999999	0	EUS-08-SH	EUS-08	19260350	3
EUS-09	999999	0	EUS-09-IM	EUS-09	10	1

EUS-09	999999	0	EUS-09-SH	EUS-09	19260350	3
EUS-10	999999	0	EUS-10-IM	EUS-10	10	1
EUS-10	999999	0	EUS-10-SH	EUS-10	19260350	3
EUS-11	999999	0	EUS-11-IM	EUS-11	10	1
EUS-11	999999	0	EUS-11-SH	EUS-11	19260350	3
EUS-12	999999	0	EUS-12-IM	EUS-12	10	1
EUS-12	999999	0	EUS-12-SH	EUS-12	19260350	3
ENVCAP	66000	0	ENVCAP-DP	ENVCAP	10	3
ENVCAP	66000	0	ENVCAP-IM	ENVCAP	10	1
ENVCAP	66000	0	HLI-AC-ASUB	ENVCAP	19260327	3
ENVCAP	66000	0	HLS-AC-ASUB	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-BAVG	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-BDRY	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-BSUB	ENVCAP	19260327	3
ENVCAP	66000	0	HLS-AC-BSUB	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-CAVG	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-CDRY	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-CSUB	ENVCAP	19260327	3
ENVCAP	66000	0	HLS-AC-CSUB	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-WAVG	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-WDRY	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-WSUB	ENVCAP	19260327	3
ENVCAP	66000	0	HLS-AC-WSUB	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-BTHR	ENVCAP	19260327	3
ENVCAP	66000	0	HLS-AC-BTCO	ENVCAP	19260327	3
ENVCAP	66000	0	HLI-AC-OP60	ENVCAP	19260327	3
SYSCNT	9999999	0	LCRA-DRT-EST	A-ZERO	1	1
SYSCNT	9999999	0	LCRA-DRT-IMP	A-ZERO	1	1
SYSCNT	9999999	0	LCRA-DRT-DMP	A-ZERO	0	3
CUMINF	99999992	0	TRAV-TI-EST	A-ZERO	19260324	1
CUMINF	99999992	0	TRAV-TI-IMP	A-ZERO	19260324	1
CUMINF	99999992	0	TRAV-TI-DMP	A-ZERO	0	3
50SINF	99999992	0	50S-TI-IMP	A-ZERO	19260324	1
50SINF	99999992	0	50S-TI-DMP	A-ZERO	0	3
STOMAR	9999999	0	EST&DMP-STOM	AR STOMAR	19260324	1
STOMAR	9999999	0	FILL-STOMAR	STOMAR	19260324	1
STOJUL	9999999	0	EST&DMP-STOJ	UL STOJUL	19260324	1
STOJUL	9999999	0	FILL-STOJUL	STOJUL	19260324	1
EXDH14	9	0	IMP-EXDT1	EXDH14	19260324	0
EXDH14	9	0	DMP-EXDT1	EXDH14	19260323	3
EXTMAN	3	0	EXDMAN-LIFTE	D A-ZERO	19260324	3
EXTMAN	3	0	EXTDRT-IMP	A-ZERO	19260324	0
EXTMAN	3	0	EXTDRT-DMP	A-ZERO	0	3
LSDH14	9	0	IMP-LSDT1	LSDH14	19260324	0
LSDH14	9	0	DMP-LSDT1	LSDH14	19260323	3
LSDH15	9	0	IMP-LSDT2	LSDH15	19260324	0
LSDH15	9	0	DMP-LSDT2	LSDH15	19260323	3
LSDMAN	2	0	LSDINI-IMP	A-ZERO	19260324	0
LSDMAN	2	0	LSDMAN-LIFTE	D A-ZERO	19260324	3
LSDMAN	2	0	LSDDRT-IMP	A-ZERO	19260324	0
LSDMAN	2	0	LSDDRT-DMP	A-ZERO	0	3
DRT-US	999990	0	USEABLE-IMP	A-ZERO	19260324	1
DRT-US	999999	0	US-PREP	A-ZERO	19260323	3
GWFFCF	10000	0	GW-FFCF-DP	GWFFCF	19260326	3
GWFFCF	10000	0	GW-FFCF-IM	GWFFCF	19260326	0
NGFFCF	10000	0	NG-FFCF-DP	NGFFCF	19260326	3
NGFFCF	10000	0	NG-FFCF-IM	NGFFCF	19260326	0
NGW-IC	20000	0	NGW-INIT-CON	D A-ZERO	19260325	3
OP6-IC	2	0	OP60-INIT-CO	ND A-ZERO	19260325	3

BASAIC	54226	0	BASA-ISF-INI	A-ZERO	19260325	3
COLAIC	100618	0	COLA-ISF-INI	A-ZERO	19260325	3
WHAAIC	101844	0	WHAA-ISF-INI	A-ZERO	19260325	3
ANYNOR	100	0	ANY-NOR-REF	ANYNOR	19260325	1
ANYNOR	100	0	ANY-NOR-ENG	ANYNOR	19260325	3
ANYLSD	100	0	ANY-LSD-REF	ANYLSD	19260325	1
ANYLSD	100	0	ANY-LSD-ENG	ANYLSD	19260325	3
STPLIM	102000	0	STPLIM-ESTAB	STPLIM	3	1
STPLIM	102000	0	STP-RR-TRACK	STPLIM	19740610	1
STPLIM	102000	0	STP-BU-TRACK	STPLIM	19740610	1
SWGLIM	100000	0	RESET-SWG-LI	M A-ZERO	0	3
SWGLIM	100000	0	IMP-ALLOC	SWGLIM	19260327	0
SWGLIM	100000	0	AC-SW-GWLIM1	SWGLIM	19871101	3
SW-LIM	178000	0	RESET-SW-LIM	SW-LIM	0	3
SW-LIM	178000	0	EST-SW-LIM	SW-LIM	0	1
SW-LIM	178000	0	IMP-NOR SW-L	IM SW-LIM	19260327	1
SW-LIM	178000	0	IMP-LSD SW-L	IM SW-LIM	19260327	1
SW-LIM	244000	0	AC-SW-GCLIM1	SW-LIM	19871101	3
SW-LIM	244000	0	AC-SW-GCLIM1	SW-LIM	19871101	3
SW-LIM	244000	0	AC-SW-GCLIM2	SW-LIM	19871101	3
SW-LIM	244000	0	AC-SW-LS1LIM	1 SW-LIM	19871101	3
SW-LIM	244000	0	AC-SW-LS1LIM	2 SW-LIM	19871101	3
SW-LIM	244000	0	AC-SW-PRLIM1	SW-LIM	19871101	3
SW-LIM	244000	0	AC-SW-LS2LIM	1 SW-LIM	19871101	3
GCE-TW	114285	0	GCE-OCR-ACC-	EST GCE-TW	1	0
GCE-TW	114285	0	GCE-OCR-JAN-	REF GCE-TW	1	0
GCE-TW	114285	0	GCE-OCR-DEC-	EMP GCE-TW	99999999	3
GCE-TW	114285	0	GCE-OCR-ACC-	S GCE-TW	19130631	3
GCE-TW	114285	0	GCE-OCR-ACC-	1 GCE-TW	19001201	3
GCE-TW	114285	0	GCE-OCR-ACC-	2 GCE-TW	19130629	3
GCE-TW	114285	0	GCE-OCR-ACC-	3 GCE-TW	19380308	3
GCE-TW	114285	0	GCE-OCR-ACC-	4 GCE-TW	19001201	3
GCE-TW	114285	0	GCE-OCR-ACC-	5 GCE-TW	19130629	3
GCE-TW	114285	0	GCE-OCR-ACC-	5 GCE-TW	19380308	3
ARBUCK	41440	0	GCE-NEW-OCR-	IMP GCE-AR	19130631	0
ARBUCK	41440	0	6GCE547600EO	CI GCE-AR	19001201	3
ARBUCK	41440	0	6GCE547600EO	CA GCE-AR	19001201	3
MBHEFL	1	0	OP60STEP3-3	MBHEFL	19260327	1
MBHEFL	1	0	OP60STEP3-4	MBHEFL	10	3
MBHEFL	1	0	OP60STEP3-5	MBHEFL	10	3

Number of WS records included in the tabulation = 121
Number of reservoirs included in the tabulation = 42
Total storage capacity (acre-feet) = 244984640.0

Number of reservoirs included in the DAT file = 526
Total storage capacity (acre-feet) = 250248464.0

Number of artificial control points on SIM CO records = 142
Number of artificial water rights on SIM WO records = 6

CHAPTER 3
CONVERSION OF MONTHLY COLORADO WAM TO DAILY

Actual real-world stream flow and other variables simulated in water availability modeling fluctuate continuously over time. Simulation computations dealing with continually varying variables are necessarily performed based on a fixed computational time interval. The monthly *SIM* employs a monthly computational time step, ignoring within-month variability. The daily *SIMD* employs a daily computational time step, ignoring within-day variability. The effects of computational time step choice on simulation results vary with different water management modeling situations and applications. Due to the extreme variability characteristic of stream flow, daily models are particularly relevant for modeling both the high flow pulse components of environmental flow standards and reservoir operations during floods [4].

Chapter 3 explains the conversion of the full authorization Colorado WAM described in Chapter 2 from a monthly to daily time step. Chapter 4 covers addition of flood control operations of O.C. Fischer, Twin Buttes, Hords Creek, and Travis Reservoirs to the daily WAM developed in Chapter 3. Chapter 5 describes the addition of environmental flow standards (EFS) adopted by the TCEQ in 2012 pursuant to the 1997 Senate Bill 3 (SB3). Various modeling options and issues are explored in the daily and monthly WAM simulations presented in Chapters 7 and 8.

Conversion of the monthly *SIM* simulation input dataset to a daily *SIMD* input dataset includes the following additions and modifications.

1. Alternative strategies and optional methods for performing various aspects of the simulation are evaluated, and the optimal options are selected, as discussed in the next section of this chapter and further investigated in the simulation studies presented in Chapters 7 and 8.
2. *DF* records of 1940-2016 daily flows at the 45 primary control points are compiled and stored in the DSS hydrology input file for use as pattern hydrographs in the *SIMD* disaggregation of monthly naturalized flows to daily. Flow disaggregation methods and compilation of daily flow pattern hydrographs are covered here in Chapter 3.
3. Calibrated lag and attenuation parameters at 30 control points are added on routing *RT* records in a daily input DIF file. Routing of daily flow changes, flow forecasting, and associated input parameters are discussed in Chapter 3. The effects of routing and forecasting on simulation results are investigated in Chapter 7.
4. USACE flood control operations of four reservoirs are modeled by adding *FR* and *FF* records to the DAT file as explained in Chapter 4. Other records are revised to facilitate addition of flood control pools and flood operations. Flood control features are explored in Chapter 7.
5. SB3 Environmental flow standards (EFS) at 14 control points established by TCEQ and science and stakeholder groups are modeled by adding instream flow *IF*, environmental standard *ES*, hydrologic condition *HC*, pulse flow *PF*, and pulse options *PO* records as described in Chapter 5. Chapter 8 also focuses on modeling and analysis of SB3 EFS.

The completed daily WAM is used to compute daily instream flow targets for SB3 EFS 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 used by *IF* record instream flow rights in the monthly *SIM* simulation model as described in Chapters 5 and 8.

Daily *SIMD* Simulation Input Dataset

All of the *SIM* input records in the monthly Colorado WAM dataset described in the preceding Chapter 2 are also included in the daily Colorado 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 [2]

	DAT File
JT, *JU*	Simulation job control options.
DW, *DO*	Daily water right data.
PF, *PO*	Pulse flow component of SB3 EFS.
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.

Nine of the 16 types of records listed in Table 3.1 are employed in the daily Colorado WAM. The following daily records are included in the daily Colorado WAM: *JT* and *JU* (simulation options), *FR* and *FF* (flood control), *RT* (routing), *DC* (disaggregation), *DF* (daily flows), and *PF* and *PO* (pulse flow component of environmental flow standards).

The daily Colorado WAM *SIMD* input dataset is composed of DAT, DIS, DIF, and DSS files. The original flow distribution DIS file (*FD* and *WP* records) described in Chapter 2 is used without modification in both the daily and expanded monthly versions of the WAM. The same DSS hydrology input file is shared by both the daily and expanded monthly versions of the WAM. The daily input DIF file is relevant only with the daily *SIMD*. *SIMD* will execute with or without the optional DIF file. With no DIF file, the routing and flow distribution options controlled by the DIF file records are not activated. A warning message in the *SIMD* message 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. *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, the daily *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 daily 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* [2]. *SIMD* input records applicable only in a daily *SIMD* simulation are explained in Chapter 4 of the *Users Manual* [2]. Although *OF* record field 4 entry DSS(3) has options that are relevant only to a daily simulation, the file options *OF* record is described in Chapter 3 of the *Users Manual*.

Table 3.2
SIMD DAT File Input Records for Controlling Daily Simulation Options

```
**       1         2         3         4         5         6         7         8
**34567890123456789012345678901234567890123456789012345678901234567890123456789012
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!
JD    77    1940       1       0       0               7                      18
JO     6           1       1                                2
JT
JU     1   1   0   0   2   3
OF     0   0   3                                     C3
DF        A30000  A10000  B20000  B10000  D40000  D20000  D10000  F10000  I40000
DF        I20000  I10000  J30000  J20000  J10000  K20000
DF        K10000  A20000  B40000  B30000  C70000  C60000  C50000  C40000  C30000
DF        C20000  C10000  D30000  E40000  E30000  E10000
DF        E20000  F30000  F20000  G20000  G50000  G40000  G30000  G10000   H2000
DF        H10000  I30000  J50000  J40000  L20000  L10000
```

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 [4]. *JO* record *ADJINC* options 4 or 6 are the recommended standards for monthly simulations or daily simulations without forecasting. Option 5 was adopted in the original monthly Colorado WAM.
- TL of 18 entered in *JD* record field 11 (column 80) increases the number of entries allowed in the *SV/SA* record storage-area table to 18 from the default of 12. This facilitates extending the storage-area tables to include the flood control pools of the four flood control reservoirs.
- INEV option 6 in *JO* record field 2 (column 8) instructs *SIM* and *SIMD* to read *IN* and *EV* records from the hydrology DSS input file. DSSFA and HSSHI of 1 in *JO* record fields 4 and 6 instructs *SIM* and *SIMD* to read *FA* and *HI* records from the DSS input file.
- DSS(3) option 3 is selected in *OF* record field 4 (column 16) to instruct *SIMD* to record daily and monthly simulation results in a DSS output file. A 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 C3 is entered in *OF* record field 12 to connect to the hydrology time series input file with filename C3HYD.DSS. 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.
- All fields of the *JT* record in Table 3.2 are blank. Several of these fields allow optional output tables to be created in the annual flood frequency AFF and daily message SMM files. An entry of 1 for SUBFILE in field 13 (column 52) activates the daily output SUB file.
- 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 stream flow sites. A *DC* record 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 Colorado River and its tributaries that have actual monthly naturalized stream flows.
- DFFILE option 1 is selected in *JU* record field 3 (column 12), meaning daily flow *DF* records are read from the hydrology input DSS file for the 45 control points listed on the DAT file *DF* records in Table 3.2.
- 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). Blank fields mean defaults are adopted.
- Forecasting with a forecast period of 3 days is activated by FCST and FRPD of 2 and 3 in *JU* record columns 24 and 28. The forecast period is easily set or changed. If FCST=2 and FRPD is blank, the forecast period FPRD is automatically computed within *SIMD*.

Other Groups of Daily *SIMD* Simulation Input Records

The following groups of input records are also added to the existing DAT file and new DIF and DSS input files in the process of converting the monthly Colorado WAM to daily.

Flood control operations of the four multiple-purpose reservoirs that have designated flood control pools are modeled as described in Chapter 4 by adding *FR* and *FF* records to the DAT file. The *SV/SA* record tables in the DAT file are extended to encompass the flood control pools. *IS/IP* records for *DI* record drought (storage) indices that include Lake Travis are extended to include the flood control pool.

Environmental flow standards at 14 sites established by the TCEQ in collaboration with a science team and stakeholder committee through a process created by the 1997 Senate Bill 3 are modeled by adding *IF*, *ES*, *HC*, *PF*, and *PO* records to the DAT file as described in Chapter 5.

Lag and attenuation routing coefficients used in routing flow adjustments for river reaches developed as described later in this chapter are recorded on *RT* records stored in a DIF file.

Daily flows for the control points listed on *DF* records in Table 3.2 are stored on *DF* records in the DSS input file along with the *IN*, *EV*, *FA*, and *HI* records. The *DF* record daily flows are used within *SIMD* for disaggregating monthly naturalized stream flows to daily. Naturalized flow volumes in acre-feet/month are distributed to daily volumes in acre-feet/day in proportion to the daily flow pattern hydrographs recorded on *DF* records in the DSS file as explained in the next section of this chapter.

Disaggregation of Monthly Naturalized Stream Flow to Daily

SIM and *SIMD* read monthly naturalized stream flow volumes from inflow *IN* records for the 45 primary control points (Table 2.3). Both the monthly *SIM* and daily *SIMD* simulation synthesize monthly naturalized flows at the over 2,200 non-artificial (Table 2.1) secondary control points based on the monthly naturalized flows at the 45 primary control points and parameters read from control point *CP*, flow distribution *FD*, and watershed parameter *WP* records. *SIMD* distributes the monthly naturalized flow volumes at each of the 2,315 non-artificial control points (Table 2.9) to the 28, 29 (February of leap years), 30, or 31 days in each of the 924 months of the 1940-2016 hydrologic period-of-analysis.

Control points K10000, L10000, and L20000 are near the outlets of the Colorado River, San Bernard River, and Boggy Creek which represent three separate watersheds. The procedure described in the next paragraph is activated by the following DIF file *DC* records for control points K10000, L10000, and L20000 with REPEAT and DFMETHOD options 2 and 4 activated.

```
DC K10000   2   4
DC L10000   2   4
DC L20000   2   4
```

Monthly naturalized stream flows at control points K10000, L10000, L20000, and over 2,200 control points located upstream of these three sites are disaggregated to daily using 1940-2016 daily flows at 45 control points stored as *DF* records in the hydrology input DSS file. Monthly volumes are distributed to daily volumes in proportion to daily flows while maintaining monthly volumes. 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.

DFMETH option 1 is selected in *JU* record field (column 8 in Table 3.2) to apply the uniform monthly-to-daily naturalized flow disaggregation option for all of the other control points not located upstream of control points K10000, L10000, and L20000. Thus, the selected default uniform disaggregation option (DFMETH=1) is applied to several control points in the coastal basin and all of the artificial control points that have monthly flows to disaggregate. Most artificial control points have zero naturalized flow, meaning disaggregation is not relevant.

The San Bernard River is the largest stream in the Brazos-Colorado Coastal Basin. Control point L10000 is included on the *DC* records discussed above. DFMETHOD(cp) option 4 is applied to L10000 and L20000 and control points in the coastal basin that are located above L10000 or L20000. Default DEMETH option 1 is applied to all other control points in the coastal basin.

As indicated by Table 2.9, the Colorado WAM has 2,457 control points of which about 2,315 represent actual physically connected locations within the river system and the other about 142 are artificial control points used in water accounting schemes. Input parameters CPID(cp,2) and CPIN(cp) in *CP* record fields 3 and 7 define stream system connectivity and sources of naturalized streamflow. The 142 artificial control points listed on the *CO* records of Table 2.5 have *CP* record entries of "OUT" for CPIN(cp) and "ZERO" or "NONE" for CPIN(cp) meaning no stream system connectivity and no naturalized stream flow.

Daily Flow Pattern Hydrographs

The dataset of *DF* records of daily 1940-2016 naturalized flow volumes in acre-feet at 45 control points stored in the *SIMD* hydrology DSS input file with filename C3HYD.DSS are developed from daily means in cubic feet per second (cfs) of observed flow rates at USGS gages. The daily quantities on *DF* records are used in the *SIMD* simulation to determine the proportion of monthly naturalized flow volume to distribute to each of the 28, 29, 30, or 31 days in each of the 924 months of the 1940-2016 hydrologic period-of-analysis at over 2,200 control point.

The daily flow *DF* records are employed in the *SIMD* simulation for the sole purpose of serving as pattern hydrographs used in disaggregating monthly naturalized flows to daily. Therefore, only the pattern of the quantities on the *DF* records within each of the 924 months, not the actual magnitude of the individual quantities for each day, affect *SIMD* simulation results. The *DF* record daily flows can be in any units and are not required to reflect a specific single site. However, the *DF* records for the Colorado WAM contain daily naturalized flows in acre-feet/day. The *DF* records of daily naturalized flows can be easily tabulated or plotted in *HEC-DSSVue*.

The following tasks were performed in developing the dataset of *DF* records of 1940-2016 daily flows at 45 control points.

1. Available daily observed flow data were explored to select control points for inclusion in the dataset of *DF* records. A determination was made to develop *DF* records for each of the 45 primary control points listed in Table 2.3 and shown in Figures 2.1 and 2.2.
2. Observed flows at relevant USGS gages as daily means in cfs were compiled as a DSS file from the U.S. Geological Survey (USGS) National Water Information System (NWIS) website using the data import feature of *HEC-DSSVue*.
3. The majority of the USGS gage sites do not have periods-of-record covering the entire WAM 1940-2016 hydrologic period-of-analysis. Gage records at two or more sites were combined as necessary to develop 1940-2016 sequences of observed daily flows in cfs for each of the 45 control points.
4. The 1940-2016 daily flows in cfs at 45 control points were converted within *HEC-DSSVue* to a *SIMD* input dataset of *DF* records with flows in cfs. *SIMD* was executed with this dataset. The *SIMD* simulation results included naturalized daily flows in acre-feet/day.
5. The daily naturalized flows recorded by *SIMD* in its simulation results DSS file were converted within *HEC-DSSVue* to another dataset of *DF* records. This final dataset of *SIMD* input *DF* records consists of 1940-2016 daily naturalized flows in acre-feet/day at 45 control points.

Observed Daily Flows at USGS Gages

The *DF* record daily flows are developed mainly from observed flows at the same USGS gages as the *IN* record monthly naturalized flows. Most of the sites in Tables 3.3 and 3.4 and Figure 3.1 correspond to the primary control points in Table 2.3 and Figures 2.1 and 2.2. Most of the WAM primary control points represent sites of USGS stream gage stations. However, naturalized monthly flows at three of the 45 primary control points in Table 2.3 are developed from reservoir releases. The *DF* record daily flows are all developed from observed flows at USGS gages, without any use of reservoir releases.

Table 3.3
USGS Gage Sites Investigated for Use in Developing the *DF* Record Daily Flow Dataset

WAM CP ID	USGS Gage No.	USGS Gage Location	Watershed Area (sq miles)	USGS Gage Period-of-Record
A30000	08119500	Colorado River near Ira	1,074	1947-1989
A10000	08121000	Colorado River at Colorado City	1,575	1923-present
B20000	08123850	Colorado River above Silver	4,560	1967-present
B10000	08124000	Colorado River at Robert Lee	5,046	1923-present
D40000	08126380	Colorado River near Ballinger	6,090	1907-present
D20000	08136700	Colorado River near Stacy	12,548	1968-present
D10000	08138000	Colorado River at Winchell	13,788	1923-2011
F10000	08147000	Colorado River near San Saba	19,830	1915-present
I20000	08154510	Colorado River below Mansfield Dam	27,357	1974-1990
I10000	08158000	Colorado River at Austin	27,611	1898-present
-	08160500	Colorado River at Lagrange	28,275	1938-present
J30000	08159200	Colorado River at Bastrop	28,580	1960-present
J20000	08159500	Colorado River at Smithville	29,062	1930-present
J10000	08161000	Colorado River at Columbus	30,244	1916-present
K20000	08162000	Colorado River at Wharton	30,601	1938-present
K10000	08162500	Colorado River near Bay City	30,862	1948-present
A20000	08120500	Deep Creek near Dunn	193	1953-present
B40000	08123600	Champion Creek near Colorado City	177	1947-1959
B30000	08123800	Beals Creek near Westbrook	1,974	1958-present
C70000	08134000	North Concho R near Carlsbad	1,202	1924-present
C60000	08128400	Middle Concho R nr Tankersley	1,613	1961-present
C50000	08129300	Spring Creek above Tankersley	340	1960-1995
C40000	08130500	Dove Creek at Knickerbocker	164	1960-2009
C30000	08128000	South Concho R at Christoval	258	1930-present
C20000	08136000	Concho River at San Angelo	4,139	1915-present
C10000	08136500	Concho River at Paint Rock	5,185	1915-present
D30000	08127000	Elm Creek at Ballinger	464	1932-present
E40000	08144500	San Saba River at Menard	1,137	1915-present
E30000	08144600	San Saba River near Brady	1,636	1979-present
E10000	08146000	San Saba River at San Saba	3,048	1915-present
E20000	08145000	Brady Creek at Brady	589	1939-present
F30000	08143500	Pecan Bayou at Brownwood	1,654	1923-1983
F20000	08143600	Pecan Bayou near Mullin	2,074	1967-present
G20000	08150800	Beaver Creek near Mason	215	1963-present
G50000	08148500	North Llano River near Junction	897	1915-present
G40000	08150000	Llano River near Junction	1,859	1915-present
G30000	08150700	Llano River near Mason	3,251	1968-present
G10000	08151500	Llano River at Llano	4,201	1939-present
H20000	08152900	Pedernales R near Fredericksburg	370	1979-present
H10000	08153500	Pedernales R near Johnson City	901	1939-present
I30000	08152000	Sandy Creek near Kingsland	346	1966-present
J50000	08158700	Onion Creek near Driftwood	124	1979-present
J40000	08159000	Onion Creek at U.S. Hwy 183	324	1924-present
L20000	08117900	Big Boggy Creek near Wadsworth	14	1970-1977
L10000	08117500	San Bernard River near Boling	725	1954-present

Table 3.4
Characteristics of the Observed Daily Flow Data Recorded at the USGS Gage Sites

WAM CP ID	Location	Watershed Area (sq miles)	Mean Flow (cfs)	USGS Gage Period-of-Record	Days of Data	Days Missing
A30000	Colorado River near Ira	1,074	15.05	1947-1989	13,148	14,978
A10000	Colorado River at Colorado City	1,575	34.00	1923-present	25,782	2,344
B20000	Colorado River above Silver	4,560	67.79	1967-present	18,023	10,103
B10000	Colorado River at Robert Lee	5,046	56.15	1923-present	23,590	4,536
D40000	Colorado River near Ballinger	6,090	118.4	1907-present	28,126	0
D20000	Colorado River near Stacy	12,548	123.7	1968-present	17,813	10,313
D10000	Colorado River at Winchell	13,788	356.7	1923-2011	24,653	3,473
F10000	Colorado River near San Saba	19,830	778.3	1915-present	28,126	0
I20000	Colorado River Mansfield Dam	27,357	1,460	1974-1990	5,843	22,283
I10000	Colorado River at Austin	27,611	1,769	1898-present	28,126	0
-	Colorado River at Lagrange	28,275	2,353	1938-present	16,234	11,892
J30000	Colorado River at Bastrop	28,580	2,095	1960-present	20,760	7,366
J20000	Colorado River at Smithville	29,062	2,269	1930-present	20,091	8,035
J10000	Colorado River at Columbus	30,244	2,754	1916-present	28,126	0
K20000	Colorado River at Wharton	30,601	2,670	1938-present	28,126	0
K10000	Colorado River near Bay City	30,862	2,650	1948-present	21,853	6,273
A20000	Deep Creek near Dunn	193	9.927	1953-present	17,876	10,250
B40000	Champion Creek, Colorado City	177	12.84	1947-1959	4,382	23,744
B30000	Beals Creek near Westbrook	1,974	22.17	1958-present	21,277	6,849
C70000	North Concho R near Carlsbad	1,202	16.81	1924-present	28,126	0
C60000	Middle Concho R nr Tankersley	1,613	12.37	1961-present	18,355	9,771
C50000	Spring Creek above Tankersley	340	13.09	1960-1995	12,783	15,343
C40000	Dove Creek at Knickerbocker	164	16.00	1960-2009	13,149	14,977
C30000	South Concho R at Christoval	258	23.37	1930-present	26,087	2,039
C20000	Concho River at San Angelo	4,139	49.43	1915-present	28,126	0
C10000	Concho River at Paint Rock	5,185	84.06	1915-present	28,126	0
D30000	Elm Creek at Ballinger	464	39.29	1932-present	28,126	0
E40000	San Saba River at Menard	1,137	47.94	1915-present	26,665	1,461
E30000	San Saba River near Brady	1,636	65.75	1979-2012	10,684	17,442
E10000	San Saba River at San Saba	3,048	174.3	1915-present	26,665	1,461
E20000	Brady Creek at Brady	589	13.16	1939-present	22,805	5,321
F30000	Pecan Bayou at Brownwood	1,654	108.0	1923-1983	15,984	12,142
F20000	Pecan Bayou near Mullin	2,074	170.2	1967-present	17,990	10,136
G20000	Beaver Creek near Mason	215	18.60	1963-present	19,512	8,614
G50000	North Llano River near Junction	897	49.78	1915-present	19,496	8,630
G40000	Llano River near Junction	1,859	174.3	1915-present	26,522	1,604
G30000	Llano River near Mason	3,251	291.5	1968-present	16,227	11,899
G10000	Llano River at Llano	4,201	362.4	1939-present	28,126	0
H20000	Pedernales R nr Fredericksburg	370	59.82	1979-present	11,925	16,201
H10000	Pedernales R near Johnson City	901	193.2	1939-present	28,126	0
I30000	Sandy Creek near Kingsland	346	65.09	1966-present	16,711	11,415
J50000	Onion Creek near Driftwood	124	52.26	1979-present	13,699	14,427
J40000	Onion Creek at U.S. Hwy 183	324	87.82	1924-present	14,894	13,232
L20000	Big Boggy Creek nr Wadsworth	14	12.75	1970-1977	2,673	25,453
L10000	San Bernard River near Boling	725	527.3	1954-present	22,891	5,235

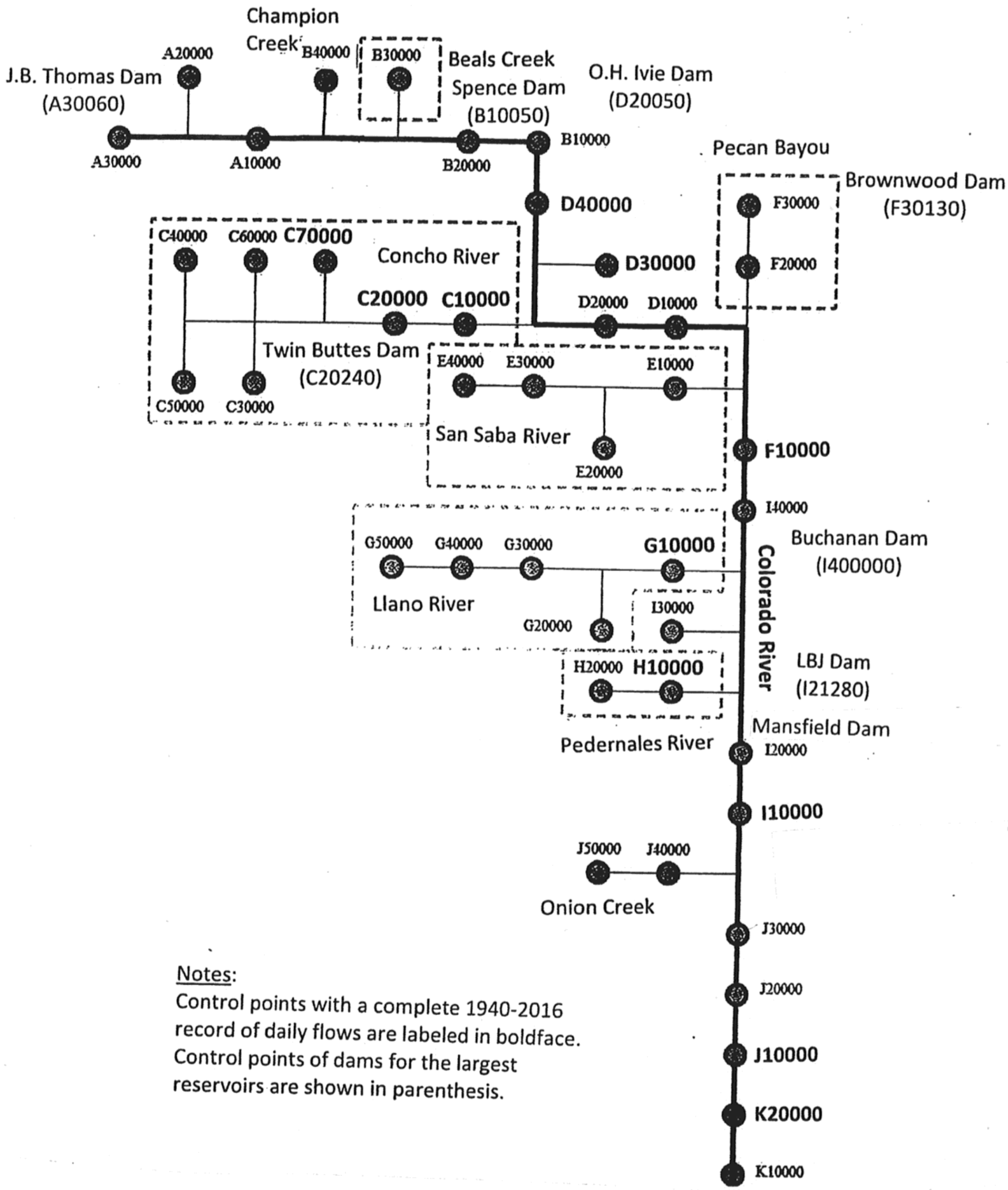

Figure 3.1 Control Points Relevant to Developing *DF* Record Daily Flows

The observed daily flow records were downloaded from the U.S. Geological Survey (USGS) National Water Information System (NWIS) website using the data import feature of

HEC-DSSVue. The data manipulations employed to develop the *DF* records of daily pattern hydrographs were performed using *HEC-DSSVue*. The data are stored in a DSS file.

The gage periods-of-record of available observed daily flow data are tabulated in the fifth column of Table 3.4. The quantities tabulated in columns 4, 6, and 7 of Table 3.4 cover the portion of the period-of-record that is contained within the 28,126 days of the 1940-2016 WAM hydrologic period-of-analysis. The means of the available daily flow quantities recorded during 1940-2016 are tabulated in the fourth column of Table 3.4. The next-to-last column in Table 3.4 shows the number of days during 1940-2016 for which daily recorded flows are available. The last column is the number of days during 1940-2016 for which daily recorded flows are missing. The last two columns sum to 28,126 days.

Ten of the USGS stream gage stations in Table 3.4 have complete records covering the 28,126 days of 1940-2016 with no missing data. The other 35 gages in Table 3.4 have multiple days of missing data during 1940-2016 ranging from 1,461 days to 25,453 days

<u>WAM Daily Pattern Hydrographs on *DF* Records</u>

Daily observed flows in cfs recorded at the USGS gages listed in Tables 3.3 and 3.4 are used to develop the dataset of *DF* records of daily naturalized flows. Daily gaged flow records are incomplete with gaps of missing data, which are synthesized as discussed later in this section. The final *DF* record daily flow volumes in acre-feet sum to *IN* record monthly volumes in acre-feet.

The final dataset of *DF* records consist of January 1940 through December 2016 daily naturalized stream flows at the 45 primary control points listed in Table 3.5. The first column of Table 3.5 is the WAM identifier for each control point. The last column shows the selected control points of the USGS gage sites for which observed daily flows were adopted for use in developing naturalized daily flows. In some cases, a complete record of 1940-2016 daily flows are provided by a single gage. In other cases, observed flows at two or three gages are combined as necessary to cover the entire 28,126-day 1940-2016 period. For control points (first column) with two or three gages listed in the last column, all of the data available at the first gage listed is used. Data at the second listed gage is used to fill in data gaps. The flows at the third gage are used if additional gaps still remain after combining the first two gages. No sites require more than three gages.

The resulting dataset of 1940-2016 observed daily flows in cfs at 45 control points were converted to *DF* records within *HEC-DSSVue*. *SIMD* was executed with this dataset. The *SIMD* simulation results included naturalized daily flows in acre-feet/day. The daily naturalized flows recorded by *SIMD* in the *SIMD* simulation results DSS file were converted within *HEC-DSSVue* to a dataset of DF records. This final dataset of *SIMD* input DF records consists of 1940-2016 daily naturalized flows in acre-feet/day at 45 control points.

As discussed in the last section of Chapter 1, DSS files with time series data were compiled in the process of developing the daily Colorado WAM simulation input dataset. The observed flows discussed here in Chapter 3 with periods-of-record through September 2021 are included in an auxiliary DSS file. The initial set of *IF* records consisting of observed flows in cfs extending through January 2021 are also included in the auxiliary DSS file. These data may useful in the future in extending the daily Colorado WAM period-of-analysis through 2020.

Table 3.5
USGS Gage Sources for Developing Daily Flows
on *DF* Records for the 45 Primary Control Points

WAM CP ID	USGS Gage No.	Location of WAM Control Point and USGS Gage	Control Point Locations of Gaged Observed Flows
A30000	08119500	Colorado River near Ira	A30000, A10000, B10000
A10000	08121000	Colorado River at Colorado City	A10000, B10000
B20000	08123850	Colorado River above Silver	B20000, B10000
B10000	08124000	Colorado River at Robert Lee	B10000, D40000
D40000	08126380	Colorado River near Ballinger	D40000
D20000	08136700	Colorado River near Stacy	D20000, D10000
D10000	08138000	Colorado River at Winchell	D10000, D20000
F10000	08147000	Colorado River near San Saba	F10000
I40000	-	Lake Buchanan Dam	F10000
I20000	08154510	Colorado River below Mansfield Dam	F10000
I10000	08158000	Colorado River at Austin	F10000
J30000	08159200	Colorado River at Bastrop	J30000, J20000
J20000	08159500	Colorado River at Smithville	J20000, J30000
J10000	08161000	Colorado River at Columbus	J10000
K20000	08162000	Colorado River at Wharton	K20000
K10000	08162500	Colorado River near Bay City	K1000, K20000
A20000	08120500	Deep Creek near Dunn	A20000, A30000
B40000	08123600	Champion Creek near Colorado City	B40000, A20000, A30000
B30000	08123800	Beals Creek near Westbrook	B30000, C70000
C70000	08134000	North Concho River near Carlsbad	C70000
C60000	08128400	Middle Concho River near Tankersley	C60000, C20000
C50000	08129300	Spring Creek above Tankersley	C50000, C70000
C40000	08130500	Dove Creek at Knickerbocker	C40000, C30000, C70000
C30000	08128000	South Concho River at Christoval	C30000, C70000
C20000	08136000	Concho River at San Angelo	C20000
C10000	08136500	Concho River at Paint Rock	C10000
D30000	08127000	Elm Creek at Ballinger	D30000
E40000	08144500	San Saba River at Menard	E40000, G10000
E30000	08144600	San Saba River near Brady	E30000, E10000
E10000	08146000	San Saba River at San Saba	E10000, G10000
E20000	08145000	Brady Creek at Brady	E20000, E10000, G10000
F30000	08143500	Pecan Bayou at Brownwood	F30000, F20000
F20000	08143600	Pecan Bayou near Mullin	F20000, F30000
G20000	08150800	Beaver Creek near Mason	G20000, G50000
G50000	08148500	North Llano River near Junction	G50000, G40000, G10000
G40000	08150000	Llano River near Junction	G40000, G10000
G30000	08150700	Llano River near Mason	G30000, G10000
G10000	08151500	Llano River at Llano	G10000
H20000	08152900	Pedernales River near Fredericksburg	H20000, H10000
H10000	08153500	Pedernales River near Johnson City	H10000
I30000	08152000	Sandy Creek near Kingsland	I300000, H10000
J50000	08158700	Onion Creek near Driftwood	J50000, J40000, H100000
J40000	08159000	Onion Creek at U.S. Hwy 183	J40000, J50000, H10000
L20000	08117900	Big Boggy Creek near Wadsworth	K20000
L10000	08117500	San Bernard River near Boling	L10000, K20000

Other Aspects of Monthly-to-Daily Disaggregation

Releases from reservoir flood control pools in accordance with *FR*, *FF*, *FV*, and *FQ* record specifications (Chapter 4) are computed on a daily basis in *SIMD*. Likewise, *SIMD* directly computes daily *IF* record instream flow targets for SB3 environmental flow standards based on *HC*, *ES*, *PF*, and *PO* record specifications as explained in Chapter 5, rather than disaggregating computed monthly targets to daily.

Monthly naturalized stream flows at the 45 primary control points in the Colorado WAM are distributed within a *SIM* or *SIMD* simulation to monthly naturalized flows at over 2,200 secondary control points as specified by input on *CP*, *FD*, and *WP* records. Next the monthly flow adjustments from the *FA* records are added by *SIM* or *SIMD* to the monthly naturalized flows. The *SIMD* monthly-to-daily disaggregation computations occur after the *FA* record flow adjustments have been added to the monthly naturalized flows. Thus, the monthly flow adjustments on the *FA* records are treated as components of the monthly naturalized flows and disaggregated to daily along with the monthly naturalized flows.

Stream flow is extremely variable, and capturing within-month daily variability in the monthly-to-daily disaggregation of naturalized stream flow is the key central component of converting a monthly WAM to daily. The monthly-to-daily naturalized flow disaggregation is highly non-uniform reflecting the great natural variability of stream flow.

All other monthly time series input data in the daily Colorado WAM are uniformly disaggregated from monthly to daily. *SIMD* includes no alternative other than a uniform distribution for monthly-to-daily disaggregation of *EV* record net evaporation-precipitation depths or *CI* record constant inflows. Likewise, the monthly hydrologic index quantities on a *HI* record are uniformly disaggregated by *SIMD* by the number of days (28, 29, 30, or 31) in each month.

Monthly water supply diversion targets are uniformly disaggregated to daily. Daily diversion targets in acre-feet/day are computed by *SIMD* by dividing monthly diversion target volumes by the number of days in each month. Likewise, with the exception of the instream flow targets for the SB3 EFS added as discussed in Chapter 5, *IF* record instream flow targets are uniformly distributed from monthly to daily. *SIMD* includes options for non-uniformly disaggregating monthly diversion and instream flow targets to daily, activated by input parameters on *JU*, *DW*, and *DO* records, but these options are not employed in the daily Colorado WAM.

River Flow Routing and Forecasting

Routing flows through stream reaches is treated differently than routing flows through reservoirs in a *SIM* or *SIMD* simulation. Simulation of reservoirs is based on water budget accounting algorithms that consider inflows, diversions, net evaporation-precipitation, and change in storage volume. The following discussion deals with propagation of flow changes over time through reaches of free-flowing streams and rivers. The associated topic of considering future days by forecasting stream flow availability for water supply and flood flow capacity is also covered.

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 river channel routing. The effects of upstream flow changes are assumed to occur within the current month. Likewise in a daily *SIMD* simulation without routing, the downstream effects of upstream streamflow changes occur in the same day that they originate. Optional daily *SIMD* routing consists of lag and attenuation adjustments to the timing of flow changes that occur as each water right is considered in the priority-based simulation. The adjustments are extended over future days as the flow changes propagate downstream.

<u>Forecasting of Water Availability and Non-Flooding River Flow Capacity</u>

Forecasting in *SIMD* 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 is relevant and should be activated 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 current time step on downstream flows and water availability in future time steps, as reflected in routing computations.

Lag and attenuation may result in stream flow depletions, return flows, and reservoir releases in the current time step affecting 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 senior water rights from the lagged effects of flow depletions of upstream junior water rights and (2) facilitating reservoir flood control operations by preventing releases 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 7, with a blank field 7 activating a *SIMD* routine that automatically computes a forecast period. Forecasting greatly increases computer execution time and can be switched off with a blank *JU* field 6 to reduce execution time.

<u>Routing Flow Changes</u>

Routing of flow changes through downstream control points during the current and future days is incorporated in a *SIMD* simulation by a DIF file with routing parameters on *RT* records. Routing can be switched off simply by activating the NORT option in *JU* record field 9 in the DAT file. Routing is not required. Without routing, streamflow changes propagate to the outlet in the same day that they originate in a daily *SIMD* simulation, analogously to streamflow changes propagating to the outlet in the same month in a monthly simulation.

The *SIMD* simulation model includes two alternative routing methods: (1) an adaption of the well-known Muskingum routing technique and (2) a lag and attenuation algorithm developed specifically for routing flow changes in *SIMD*. Both are explained in Chapter 3 of the *Daily Manual* [4]. The lag and attenuation method is the recommended standard option. Either or both of the two calibration approaches noted in the next paragraph are applicable for both of the two routing techniques. The lag and attenuation method is adopted for the daily Colorado WAM as well as the previously created daily Brazos, Trinity, and Neches WAMs [8, 9, 10].

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 on *RT* records. Lag and attenuation in days for normal water right operations (LAG and ATT) and flood control operations (LAGF and ATTF) are recorded on *RT* records in a DIF file. The parameters are for the river reach below the control point in *RT* record field 2.

The optional 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 Colorado WAM with 2,315 control points includes routing parameters at 30 control points.

Lag and Attenuation Routing Parameters

Methods for calibrating routing parameters are explained in *Daily Manual* [4] Chapter 4. Values for the lag parameters LAG and LAGF in days and attenuation parameters ATT and ATTF in days are estimated based on observed flow fluctuations between gaging stations for normal flows and high (flood) flows, respectively. LAG and ATT are applied in the *SIMD* simulation for normal water right operations. LAGF and ATTF are applied by *SIMD* for flood control operations.

Colorado WAM Calibrated Routing Parameters

The routing parameters for 30 reaches are contained on *RT* records in the DIF file replicated as Table 3.6. The LAG and LAGF are also tabulated in Table 3.7 along with additional information. LAG and LAGF reflect travel times that vary between reaches with differences in reach lengths, flow velocity, and wave celerity. Calibration studies resulted in ATT and ATTF values of 1.0 day for all of the 30 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 attenuation would be greater than 1.0 only for reaches with very long travel times.

The 30 reaches for which lag and attenuation parameters were calibrated are defined by the upstream and downstream control points listed in the first and second columns of Table 3.7. These are sites of USGS gaging stations and WAM primary control points. The routing computations occur at one selected control point within each of the calibration reaches. The routing parameters and calibration computations are assigned to the upstream control points in the WAM. The control point identifiers in the first column of Table 3.7 are entered in field 2 of the *RT* records. The lag (LAG) for normal flow operations and lag (LAGF) for flood flow operations tabulated in the fourth and fifth columns of Table 3.7 are entered on the *RT* records of Table 3.6.

Estimates of the approximate length of each reach in miles is tabulated in the third column of Table 3.7. The wave speed in miles per day corresponding to the normal flow lag and flood flow lag are tabulated in the last two columns of Table 3.7. The 30 calibration reaches have lengths that sum to 1,532 miles. The average speed for normal flows and high flows over the 1,532 miles of diverse stream reaches is 35.1 miles/day and 42.4 miles/day, respectively, which is equivalent to 2.14 feet/second and 2.59 feet/second. The longest continuous sequence of routing reaches extends through control points D40000, D20000, D10000, F10000, I40000, I20000, I10000, J30000, J20000, J10000, and K20000. The total estimated length of the reach composed of these 11 sub-reaches is 697 miles. The total normal lag is 15.52 days and flood lag is 39.04 days which reflect average speeds of 44.9 miles/day and 64.5 miles/day, respectively, for this 697 miles of river.

Table 3.6
SIMD Daily Input DIF File

RTD40000	1	1.24	1.0	1	1.00	1.0
RTD20000	1	1.09	1.0	1	1.00	1.0
RTD10000	1	1.96	1.0	1	1.01	1.0
RTF10000	1	1.30	1.0	1	0.67	1.0
RTI40000	1	2.16	1.0	1	1.11	1.0
RTI20000	1	1.13	1.0	1	1.07	1.0
RTI10000	1	1.06	1.0	1	1.00	1.0
RTJ30000	1	1.00	1.0	1	0.96	1.0
RTJ20000	1	1.93	1.0	1	1.04	1.0
RTJ10000	1	1.65	1.0	1	1.00	1.0
RTK20000	1	1.00	1.0	1	0.95	1.0
RTD30000	1	1.38	1.0	1	1.26	1.0
RTC50000	1	0.64	1.0	1	0.62	1.0
RTC20000	1	1.88	1.0	1	1.05	1.0
RTC10000	1	1.96	1.0	1	1.01	1.0
RTC40000	1	0.77	1.0	1	0.77	1.0
RTC60000	1	0.86	1.0	1	0.83	1.0
RTF30000	1	1.02	1.0	1	0.98	1.0
RTF20000	1	1.15	1.0	1	1.00	1.0
RTE30000	1	2.04	1.0	1	1.00	1.0
RTE10000	1	1.13	1.0	1	1.91	1.0
RTG50000	1	1.00	1.0	1	2.60	1.0
RTG40000	1	1.96	1.0	1	1.00	1.0
RTG30000	1	1.06	1.0	1	1.00	1.0
RTG10000	1	3.92	1.0	1	2.00	1.0
RTI30000	1	1.86	1.0	1	0.96	1.0
RTH20000	1	1.07	1.0	1	1.67	1.0
RTH10000	1	2.32	1.0	1	3.63	1.0
RTJ50000	1	1.11	1.0	1	1.00	1.0
RTJ40000	1	1.00	1.0	1	1.00	1.0
DCK10000	2	4				
DCL10000	2	4				
DCL20000	2	4				

Routing Parameter Calibration Studies

Most routing applications reported in the published and unpublished literature deal with modeling the attenuation of entire flood hydrographs, not changes in flows resulting from flow depletions or additions. Stream flow routing is generally viewed as computing the entire hydrograph at a downstream location given the hydrograph at an upstream location. Conversely, routing in *SIMD* propagates depletions in stream flow resulting from individual daily diversions or storage refilling and additions to stream flow resulting from return flows and reservoir releases.

WRAP includes two alternative strategies for calibrating routing parameters described in Chapter 4 of the *Daily Manual* [4]. An optimization-based calibration procedure initially developed for the daily WRAP modeling system is implemented by the WRAP program *DAYH* documented by Appendix B of the *Daily Manual*. A more recently developed calibration procedure based on statistical analysis of fluctuations in observed flows between two gage sites is implemented by the WRAP program *DAY* documented by Appendix A of the *Daily Manual*.

Table 3.7
Lag and Related Metrics

Upstream Control Point	Downstream Control Point	Reach Length (miles)	Normal Lag (days)	Flood Lag (days)	Normal Speed (miles/day)	Flood Speed (miles/day)
D40000	D20000	62	1.24	1.00	50.0	62.0
D20000	D10000	45	1.09	1.00	41.3	45.0
D10000	F10000	87	1.96	1.01	44.4	86.1
F10000	I40000	58	1.30	0.67	44.6	86.6
I40000	I20000	96	2.16	1.11	44.4	86.5
I20000	I10000	59	1.13	1.07	52.2	55.1
I10000	J30000	55	1.06	1.00	51.9	55.0
J30000	J20000	25	1.00	0.96	25.0	26.0
J20000	J10000	78	1.93	1.04	40.4	75.0
J10000	K20000	67	1.65	1.00	40.6	67.0
K20000	K10000	65	1.00	0.95	65.0	68.4
D30000	D20000	57	1.38	1.26	41.3	45.2
C50000	C20000	21	0.64	0.62	32.8	33.9
C20000	C10000	42	1.88	1.05	22.3	40.0
C10000	D20000	44	1.96	1.01	22.4	43.6
C40000	C20000	25	0.77	0.77	32.5	32.5
C60000	C20000	28	0.86	0.83	32.6	33.7
F30000	F20000	33	1.02	0.98	32.4	33.7
F20000	F10000	53	1.15	1.00	46.1	53.0
E30000	E10000	55	2.04	1.00	27.0	55.0
E10000	F10000	22	1.13	1.91	19.5	11.5
G50000	G40000	30	1.00	2.60	30.0	11.5
G40000	G30000	54	1.96	1.00	27.6	54.0
G30000	G10000	31	1.06	1.00	29.2	31.0
G10000	I20000	108	3.92	2.00	27.6	54.0
I30000	I20000	83	1.86	0.96	44.6	86.5
H20000	H10000	40	1.07	1.67	37.4	24.0
H10000	I20000	87	2.32	3.63	37.5	24.0
J50000	J40000	34	1.11	1.00	30.6	34.0
J40000	J30000	50	1.00	1.00	50.0	50.0

The calibration methodology implemented in the WRAP program *DAYH* documented in *Daily Manual* [4] Appendix B employs a conventional approach of determining values for routing parameters that minimize deviations between computed and observed daily flow hydrographs [20]. This methodology was applied in research studies that included developmental versions of several daily WAMs including a daily Colorado WAM [16, 18, 19]. The initial optimization based calibration approach has been replaced with a methodology documented in Appendix A of the *Daily Manual* that is based on statistical analyses of fluctuations in observed stream flows

Routing parameters for the Brazos, Trinity, Neches, and Colorado River Basins were developed in a research study that tested the new calibration methodology along with exploring stream flow characteristics relevant to routing [21]. The routing parameters incorporated in the daily Brazos, Trinity, and Neches WAMs [8, 9, 10, 21] were derived from this work. Routing parameters developed with this methodology were also adopted for the daily Colorado WAM and are tabulated in Tables 3.6 and 3.7.

Both the earlier optimization based calibration methodology and the more recently adopted statistical analysis based calibration methodology resulted in ATT and ATTF values of 1.0 for all reaches in the daily Colorado WAM. The earlier optimization based approach resulted in generally higher values for LAG and LAGF than the adopted values tabulated in Tables 3.6 and 3.7.

Routing and Forecasting Complexities and Approximations

Routing of flow changes through free-flowing river reaches is very approximate with inherent simplifications, uncertainties, inaccuracies, and variabilities. However, in general, this may not be a major concern if simulation results are not 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 complexities and inaccuracies are briefly noted as follows.

Forecasting in *SIMD* is designed to mitigate the effects of routing on the water right priority system and flood control operations. Forecasting is relevant only if routing is employed. Over-constraining of water availability due to approximations inherent in forecast computations is a key fundamental concern. Although for different reasons, forecasting future stream flows is inherently inaccurate in both real-world water management operations and model computations.

The effects on stream flow during future months resulting from appropriation of water by water right holders in the current month are modeled in a monthly *SIM* simulation in only two ways: (1) reservoir storage and (2) next-month return flow and hydropower release options. Routing computations are a third mechanism for propagating effects of water right appropriations to future time steps which is added in the *SIMD* daily simulation model.

Impoundment of water by dams and reservoirs is the predominant mechanism by which water right appropriations in the current time step affect stream flow in future time steps. Reservoir storage dampens or averages out fluctuations in stream flow over time. For reservoirs with flood control pools, with the conservation pool full to capacity, flood flows are lagged and attenuated by operations modeled in *SIMD* with *FR*, *FF*, *FV*, and *FQ* records. Surcharge storage in reservoirs can also be modeled using *FV/FQ* record reservoir storage volume versus outflow tables. Otherwise, with no flood control pool, outflow equals inflow in days of the *SIMD* simulation with conservation storage full to capacity. Outflow also equals inflow (flow passes through reservoir) if and as necessary to prevent adverse effects on downstream senior water rights.

The routing methods discussed in this section are relevant for river reaches (reservoirs) controlled by dams only during days in which reservoir outflows equal inflows without the routing computations. Otherwise, the downstream propagation of upstream flow changes translates to decreases or increases in reservoir storage content. The Colorado River and its tributaries are highly regulated by many reservoir projects with large storage volumes. Reservoir operations largely control river flows. This tends to significantly reduce the effects of the *SIMD* routing computations described in this chapter.

Another key consideration is that calibrating routing parameters and performing routing computations in *SIMD* 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 calibrated reaches.

In addition to facilitating parameter calibration, the statistical analyses of fluctuations in observed flows in river reaches between gage sites provides insights regarding routing in general. Propagation of observed flows through river reaches has been found to be extremely variable and apparently largely random. The highly variable, highly unpredictable characteristics of actual observations of real flows indicate that simulation of the propagation of flow fluctuations using routing computations is necessarily very approximate.

The effects of diverting water for supply needs or depleting streamflow to refill reservoir storage propagate downstream over time. Lag of these flow changes represents a wave celerity, not a mean velocity. Flow velocities vary at points across a river cross-section. The mean velocity (ft/s) is the flow discharge rate (ft^3/s) divided by cross-section flow area (ft^2). Wave celerity is normally faster than mean velocity. The lags in Tables 3.6 and 3.7 were determined based on statistical analyses of many identified flow fluctuations between USGS gaging stations. Lag estimates are highly variable and approximate.

Travel speeds (wave celerity) in miles/day corresponding to lag times are tabulated in Table 3.7 for general information. The travel speeds in Table 3.7 are computed by dividing reach length in miles by lag time in days. Travel speeds provide insight on river flow characteristics and whether estimates of lag appear to be reasonably valid.

Lag times during floods (LAGF) may be longer or shorter than lag times during normal flow conditions (LAG). High flows in a main channel are expected to normally have greater velocities and shorter lag times than low flows. The flood lag (LAGF) for some reaches in Table 3.7 is longer than the normal lag (LAG), presumably due to average flow rates through overbank flood plains being slower than average flows in a main channel. The metrics in Table 3.7 exhibit significant variability.

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.

Effects of routing on simulation results are explored in the reports documenting daily WAMs for the Brazos, Trinity, and Neches River Basins [8, 9, 10]. Likewise, the effects of routing in the daily Colorado WAM are investigated in Chapter 7 of this report.

CHAPTER 4
RESERVOIR FLOOD CONTROL OPERATIONS

Converting the monthly Colorado WAM to daily allows incorporation of reservoir flood control operations. Relatively small computational time steps are required to accurately simulate 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 those discussed in this chapter. Accurate modeling of smaller stream systems may require hourly or smaller time steps not available in *SIMD*.

The Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE), in partnership with nonfederal water management entities, is responsible for flood control operations of four multiple-purpose reservoirs in the Colorado River Basin. Operations of the flood control pools of these four projects are incorporated in the daily WAM as described in this chapter. The effects of flood control operations are explored in the simulation study presented in Chapter 7.

Flood Control Reservoir Operations in the Colorado River Basin

The four multiple-purpose reservoirs with designated flood control pools simulated in the daily Colorado WAM are listed in Table 4.1. Non-federal entities own the first two reservoirs listed in the table and control use of the conservation pools. The U.S. Bureau of Reclamation constructed the two reservoir projects. The USACE is responsible for flood control operations of federal projects. The other two reservoirs are owned by the federal government and maintained and operated by the USACE FWD. Descriptions of the reservoirs along with the quantities in Table 4.1 are found at the following Texas Water Development Board (TWDB) website.

https://www.twdb.texas.gov/surfacewater/rivers/reservoirs/index.asp

Table 4.1
Major Multiple-Purpose Reservoirs in the Colorado River Basin with Flood Control Pools

Reservoir	Stream Location of Dam	Drainage Area (sq miles)	Elevation (feet)		Storage Capacity (acre-feet)		
			Conser vation	Flood Control	Top of Conservation	Top of Flood Control	Flood Control
Travis	Colorado River	26,230	681.6	714.6	1,134,956	1,921,731	786,775
Twin Buttes	South Concho River	2,672	1,940.2	1,969.1	186,200	640,000	453,800
O. C. Fisher	North Concho River	1,488	1,908	1,938.5	115,743	392,717	276,974
Hords Creek	Hords Creek	48	1,900	1,920	8,640	25,310	16,670

The Mansfield Dam and Lake Travis project owned and operated by the Lower Colorado River Authority (LCRA) was constructed by the U.S. Bureau of Reclamation and transferred to nonfederal ownership. The project was originally called Marshall Ford Dam and Reservoir. Flood control operations are a collaborative responsible of the LCRA and USACE FWD. Water supply storage capacity of 1,170,752 acre-feet is authorized by a LCRA water right permit. The actual water supply capacity is 1,115,076 acre-feet according to a 2021 volumetric survey [13]. The storage capacity of 1,134,956 acre-feet in the TWDB data in Table 4.1 reflects a 2008 volumetric survey. The flood control storage capacity in Table 4.1 is the difference in volume between the top of flood control pool and top of conservation pool. Lake Travis has water surface areas of 19,300 acres and 29,160 acres at the top of conservation and flood control pools, respectively.

The Twin Buttes Dam and Reservoir project was also constructed by the U.S. Bureau of Reclamation. The project is owned by the federal government and managed by the City of San Angelo. The USACE FWD is responsible for flood control operations. Twin Buttes Dam consists of two separate embankments on the Middle Concho River and South Concho River. The two lakes impounded by the two dams are connected by a channel and have the same pool levels.

The USACE FWD maintains and operates the federal Hords Creek Dam and Reservoir and O. C. Fisher Dam and Reservoir for flood control, water supply, and recreation. Hords Creek Reservoir is by far the smallest USACE reservoir in Texas. The Central Colorado River Authority has contracted with the federal government for the water supply storage of Hords Creek Reservoir, which is used to supply the City of Coleman. The Upper Colorado River Authority has contracted for the water supply storage of O.C. Fisher Reservoir.

Historical Actual Observed Reservoir Storage Levels

The historical records of the storage contents of each of the four reservoirs plotted by the TWDB (https://www.twdb.texas.gov/surfacewater/rivers/reservoirs/index.asp) are replicated as Figures 4.1, 4.2 4.3, and 4.4. The historical records of water surface elevation plotted by the USACE FWD (https://www.swf-wc.usace.army.mil/) are replicated as Figures 4.5 and 4.6. Impoundment began in 1940, 1962, 1952, and 1948, respectively, for Travis, Twin Buttes, O. C. Fisher, and Hords Creek Reservoirs. The dashed line in the figures represents the top of conservation pool, which is also the bottom of the flood control pools.

Storage levels have encroached into the Lake Travis flood pool frequently. O.C. Fisher has stored water in its flood control pool during only one flood (October 1957) since its initial impoundment. O.C. Fischer and Twin Buttes have been severely drawn-down during much of their project lives. The flood control pool capacity has never been exceeded at any of the four reservoirs.

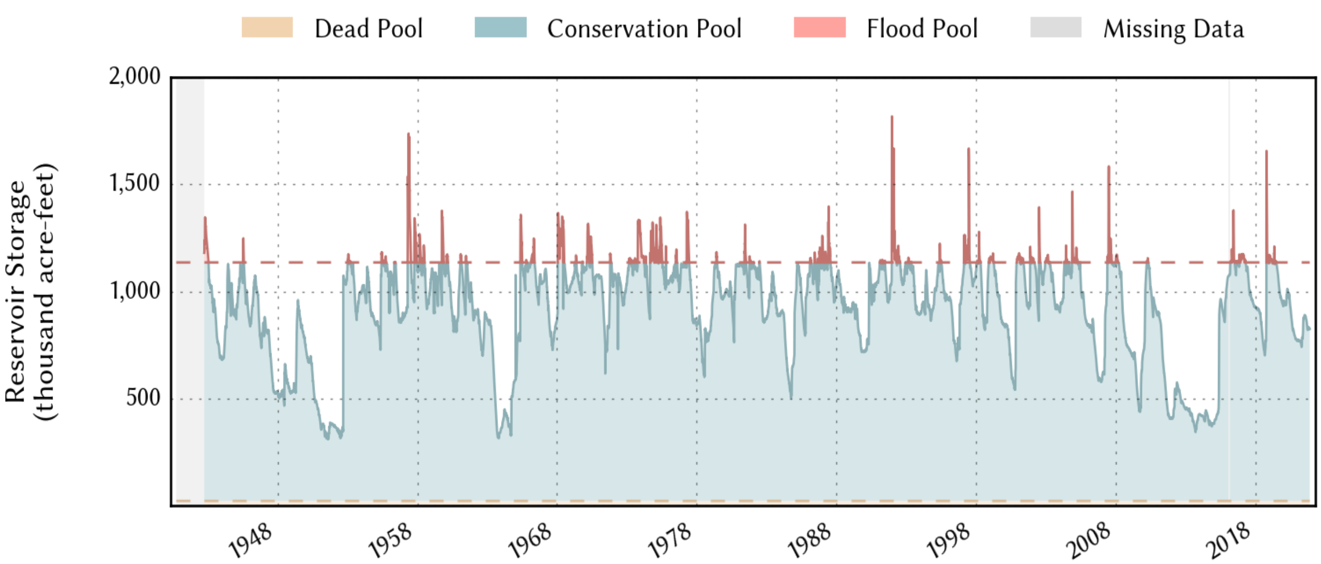

Figure 4.1 Historical Storage Contents in acre-feet of Lake Travis (Marshal Ford Reservoir)

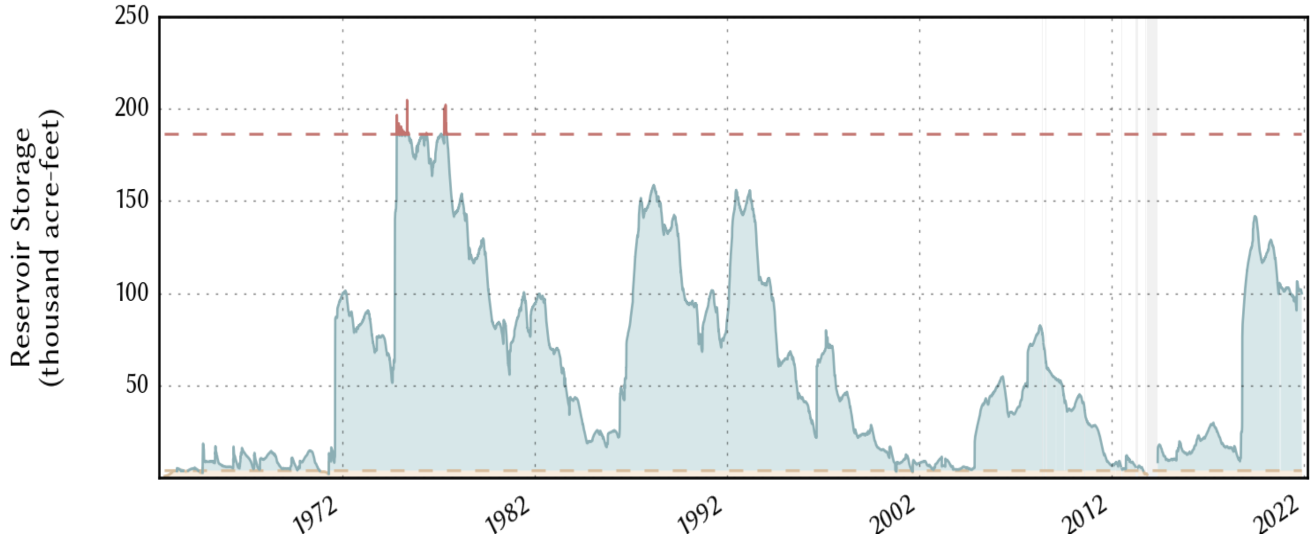

Figure 4.2 Historical Storage Contents in acre-feet of Twin Buttes Reservoir (TWDB)

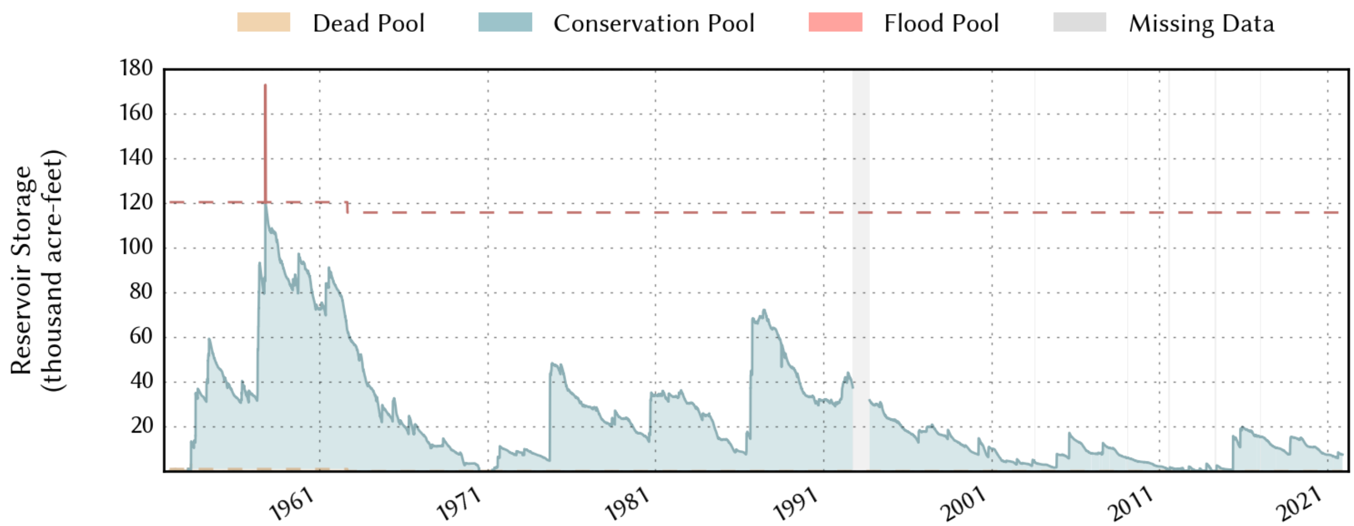

Figure 4.3 Historical Storage Contents in acre-feet of O. C. Fisher Reservoir (TWDB)

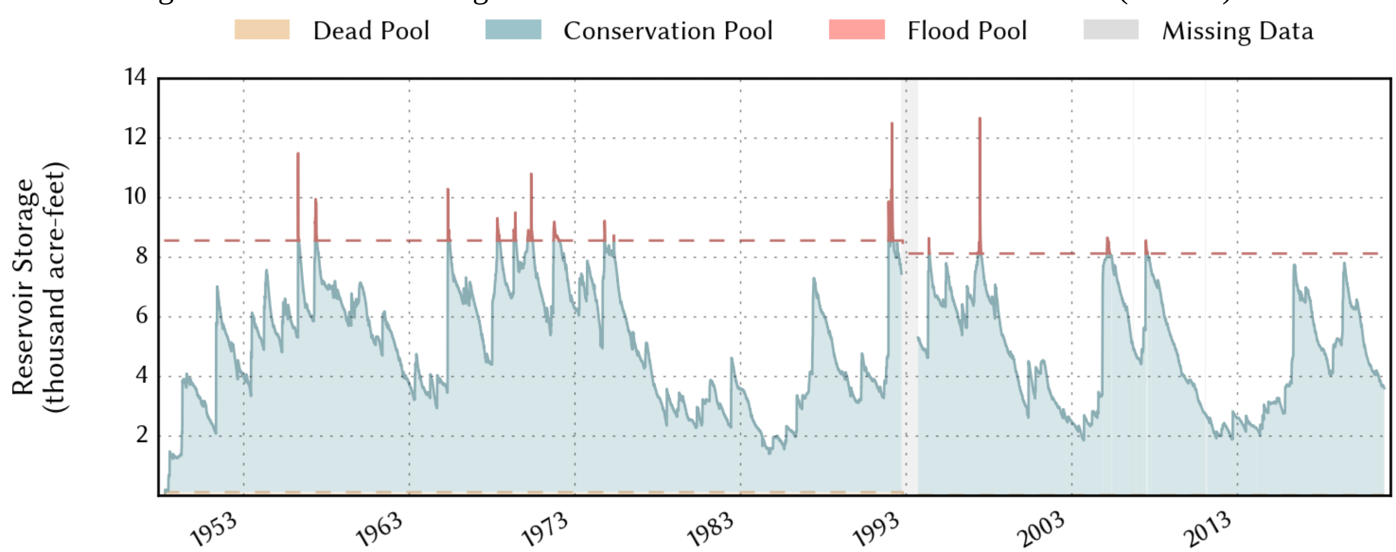

Figure 4.4 Historical Storage Contents in acre-feet of Hords Creek Reservoir (TWDB)

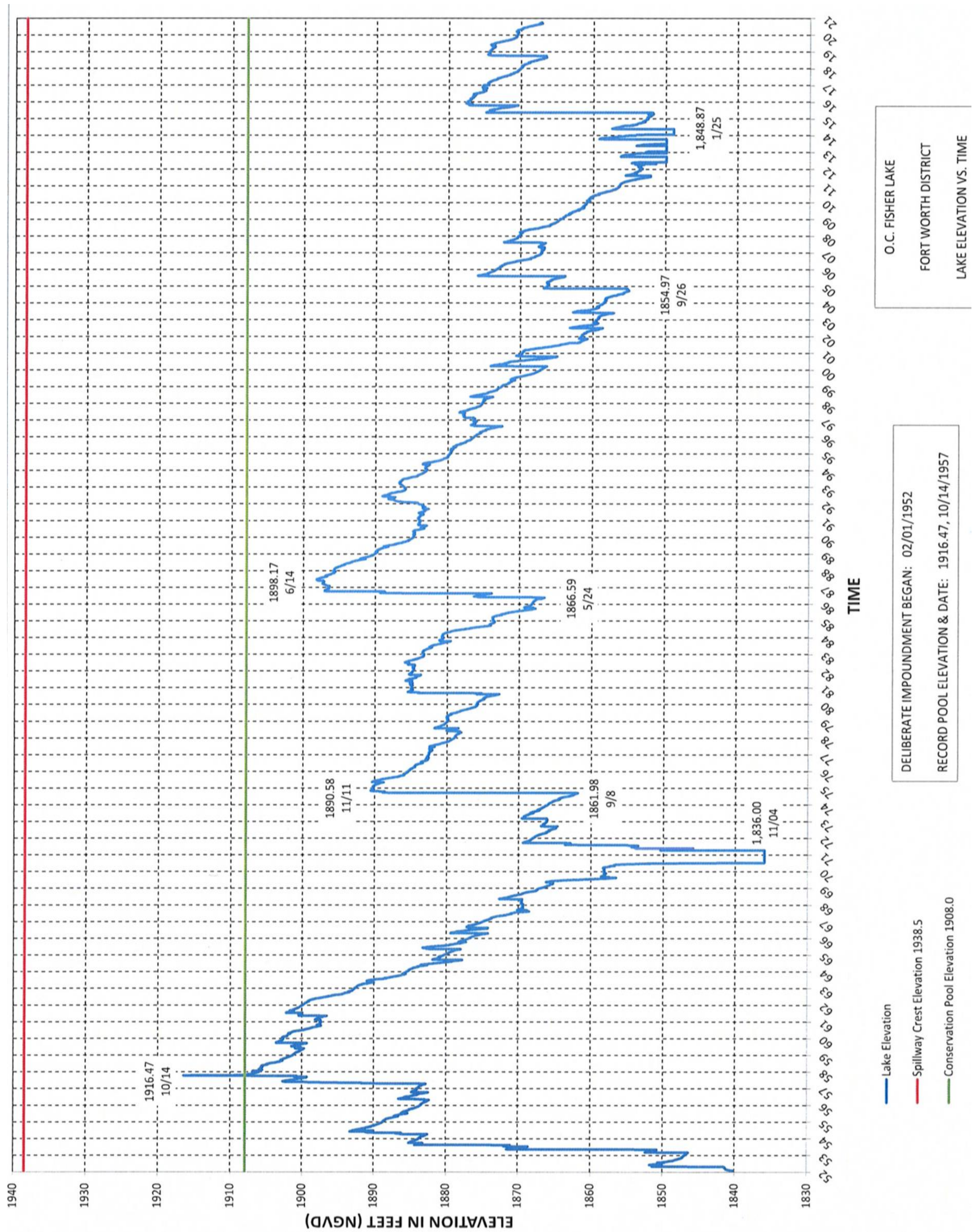

Figure 4.5 Historical Water Surface Elevation of O. C. Fisher Reservoir (USACE FWD)

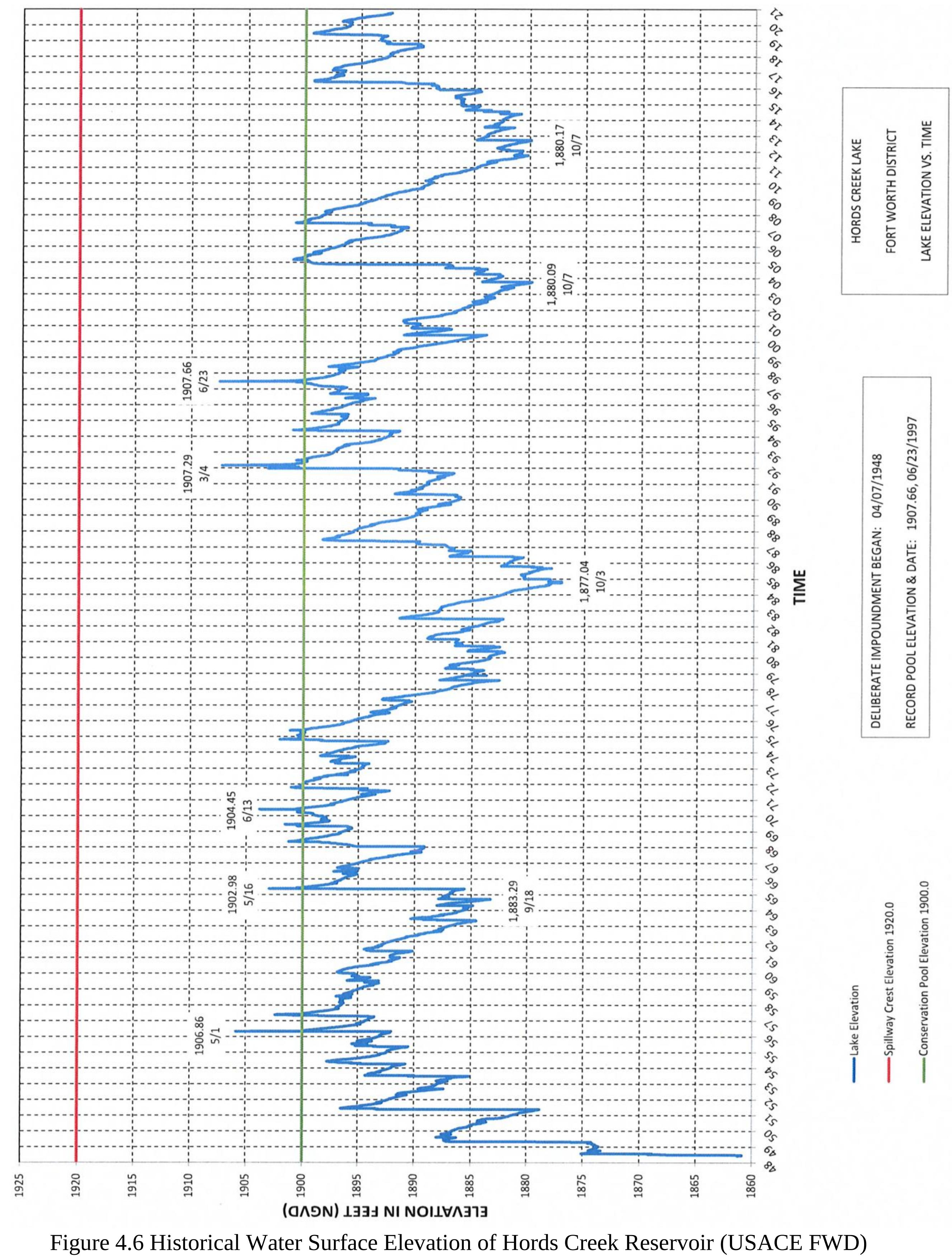

Figure 4.6 Historical Water Surface Elevation of Hords Creek Reservoir (USACE FWD)

Flood Control Operation Procedures and Criteria

Pertinent data sheets, flood control operating criteria, current and historical water surface elevations, and other data for federal reservoirs operated by the Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE) are found at: http://www.swf-wc.usace.army.mil. The USACE FWD operates the flood control pools of four multiple-purpose reservoirs in the Colorado River Basin employing the criteria tabulated in Table 4.2. Whenever the water surface level is above the top of conservation pool elevation and below the top of flood control pool elevation, operations are based on emptying the flood control pool as expeditiously as feasible without contributing to flows exceeding the maximum allowable flow rates shown in Table 4.2.

Table 4.2
USACE FWD Flood Control Operations Criteria for the Colorado River Basin
https://www.swf-wc.usace.army.mil/pertdata/COLORADO.htm

Reservoir Project	Reservoir Surface Elevation (feet msl)	% Flood Pool Storage (percent)	S. Concho River at Twin Buttes (cfs)	Concho River at San Angelo (cfs)	Concho River at Paint Rock (cfs)	Hords Creek at Coleman (cfs)
Hords Creek	1900.0 - 1920.0	0 - 100				10,000
O.C. Fisher	1908.0 - 1938.5	0 - 100		25,000	25,000	
Twin Buttes	1940.2 - 1944.8	0 - 10	3,000	25,000	25,000	
	1944.8 - 1950.4	10 - 25	5,000	25,000	25,000	
	1950.4 - 1969.1	25 - 100		25,000	25,000	

Reservoir Project	Reservoir Surface Elevation (feet msl)	% Flood Pool Storage	Minimum Release (cfs)	Maximum Release (cfs)	Colorado River at Austin (cfs)	Colorado River at Bastrop (cfs)	Colorado River at Columbus (cfs)
Marshall	681.0-683.0	0 - 5	3,000	7,500	30,000	45,000	50,000
Ford (Travis)	683.0-685.0	5 - 10	5,000		30,000	45,000	50,000
	685.0-691.0	10 - 26	5,000		30,000	45,000	50000
	691.0-710.0	26 - 86	5,000		30,000	45000	50,000
	710.0-714.0	86 - 100	5,000		50,000	50,000	50,000

Flood control operations are guided by two sets of operating rules: regular operations and emergency operations [22]. Regular operations are based on the criteria tabulated in Table 4.2. Maximum allowable discharge rates are specified at the dams and at USGS stream gaging stations located downstream of the dams. The allowable flow limits at some gages vary with storage contents of an upstream reservoir. If the flood control pool capacity is exceeded, emergency operations are activated to protect the dam following release rules that assure that the designated maximum design water surface is never overtopped, even though the releases contribute to downstream flooding. The emergency operating rules are not included in the WAM or this report.

The top of conservation (bottom of flood control) pool of Hords Creek Reservoir is 1,900.0 feet above mean sea level (msl). The flood control pool extends vertically from 1,900 to 1,920 feet above msl. If the reservoir storage level rises above 1,900 feet, releases are based on emptying the flood control pool as expeditiously as possible without contributing to flow rates exceeding 10,000 cubic feet per second (cfs) at the USGS gage on Hords Creek at Coleman (Table 4.2).

O.C. Fisher Reservoir has designated top of conservation and flood control pool elevations of 1,908.0 and 1938.5 feet above msl. Whenever the reservoir water surface is above elevation 1,908 feet, releases are based on emptying the flood control pool as quickly as possible subject to the constraint of allowing no releases that contribute to flows exceeding 25,000 cfs at USGS gages on the Concho River at San Angelo and Paint Rock.

Twin Buttes Reservoir has designated top of conservation and flood control pool elevations of 1,940.2 feet and 1969.1 feet. Stream flow limits representing non-damaging flows or channel capacities are specified for gages on the South Concho River at Twin Buttes and the Concho River at San Angelo and Paint Rock. The flow limits at gages on the Concho River at San Angelo and Paint Rock are included in operating rules for both Twin Buttes and O. C. Fisher Reservoirs. The USACE FWD operating criteria for Twin Buttes Reservoir replicated in Table 4.2 includes setting the downstream flow limits as a function of reservoir storages contents. However, the flow limits in Table 4.2 are the same for all reservoir storage levels above 1844.8 feet.

Lake Travis was originally named Marshall Ford Reservoir, and federal documents still use the original name. The USACE FWD and LCRA are jointly responsible for flood control operations. Top of conservation and flood pool elevations are 681.6 and 714.6 feet in the TWDB data of Table 4.1. The operating criteria in Table 4.2 are activated whenever storage levels are between 681.0 feet and 714.0 feet. Minimum and maximum releases at the dam are specified in Table 4.2. The operating criteria include maximum flow targets at gages on the Colorado River at Austin, Bastrop, and Columbus. Flood control operations are based on emptying the flood control pool as expeditiously as feasible without releases that contribute to exceeding the flow limits.

The flood control operating objective for the four reservoirs is to empty the flood control pools as expeditiously as possible without making releases that contribute to river flows exceeding the predetermined allowable flow limits tabulated in Table 4.2. The flow limits at downstream gages specified in the operating plans may be exceeded by unregulated inflows entering the rivers below the dams even with no releases from the reservoirs. Regular operations employing the criteria in Table 4.2 continue as long as flood control pool storage capacities are not exceeded. During rare extreme flood events expected to exceed the controlled (gated) flood control storage capacity, emergency operation will be activated with larger releases based on protecting the dam from overtopping or otherwise structurally failing rather than the downstream allowable flood flow limits. The emergency operating plans can 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 Colorado WAM. If the flood control pool is overtopped in the model, the excess flows pass through the reservoir without storage attenuation.

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 *SIMD* input records designed specifically for flood control. These records are described in Chapter 4 of the *Users Manual* [2]. *FR*, *WS*, 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 and/or FCMAX on the *FR* record can be used to model outlet structure discharge capacities for flood control operations. *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 4.7. *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 with flood releases controlled by a gates operated by people based on downstream stream flows are referred to in *SIMD* as controlled flood control pools. Pools with releases governed by an ungated spillway or specified rules based only on storage are called uncontrolled flood control pools in *SIMD*.

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.

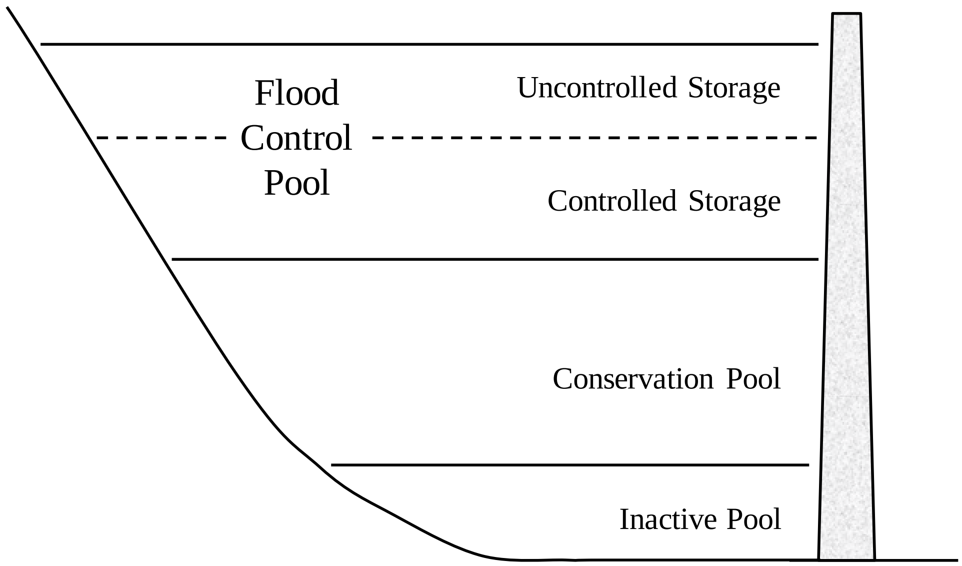

Figure 4.7 Reservoir Pools Defined by *SIMD WS* and *FR* Records

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. FCMAX and *FF* records are used in the Colorado WAM, but *FV*/*FQ* records are not used.

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 Colorado WAM, the modeling features activated by *FR* and *FF* records are applied only to flood control operations of the four reservoirs that contain flood control pools. Surcharge storage above the controlled flood control pool is not modeled. 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. 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 Colorado WAM.

For reservoirs with no flood control pool, *SIMD* sets outflow equal to inflow when storage contents exceed the conservation storage capacity unless *FV/FQ* record storage-outflow tables are employed. Likewise, without *FV/FQ* records, for reservoirs with a flood control pool, outflow equals inflow when storage contents exceed the flood control pool storage capacity. *FV/FQ* record storage-outflow tables are not used in the daily Colorado WAM presented in this report.

Forecasting of Future Flows

Forecasting is activated by input parameter FCST in *JU* record field 6 as discussed in the preceding Chapter 3. Forecasting should be activated only if routing is activated on one or more *RT* records. The *SIMD* forecast simulation computes downstream future water availability for use with curtailing current day water availability for *WR* record rights [4]. The forecast simulation also records 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.

Imperfect forecasting (prediction) of stream flows to occur in the future is an issue in *SIMD* modeling as well as in actual real-world reservoir operations. Imperfections in forecasting may result in water being stored in greater quantities and longer than necessary. Future days extending past the forecast period are not considered in operating decisions. Routed reservoir releases could contribute to flooding at downstream locations in future days after the end of the forecast period.

Colorado WAM Simulation of Reservoir Flood Control Operations

Flood control operations of the four multiple-purpose reservoirs containing designated flood control pools are based both in actual reality and in the *SIMD* simulation model on maintaining empty flood control pools except during and immediately following flood events. The flood control pools are emptied as expeditiously as feasible without contributing to regulated flows exceeding specified maximum flows at downstream gaging stations. Metrics employed in the operating rules are tabulated in Tables 4.1 and 4.2. The metrics adopted in the Colorado WAM *SIMD* input DAT file tabulated in Tables 4.3 and 4.4 represent the real-world metrics in Tables 4.1 and 4.2 organized for inclusion in the *SIMD* input DAT file.

Reservoir Topographic Information

The conservation storage capacities on *WS* records are the volumes authorized in water right permits. The monthly WAM contains volume versus area tables on *SV* and *SA* records that extend from zero storage to the authorized storage capacity. Storage capacities of Lakes Travis and Buchanan on *DI/IP/IS* record drought indices also terminate at the authorized storage capacity. Relevant *SV/SA* and *IP/IS* tables are extended to the top of flood control pool in the daily WAM.

Relationships between reservoir water surface elevation, surface area, and volume vary over time with sedimentation. Volumetric surveys are performed periodically to update elevation-area-volume tables. Elevation/area/volume quantities for the flood control pools were obtained from the TWDB website (https://www.twdb.texas.gov/surfacewater/rivers/reservoirs/index.asp). The data at the TWDB website are from the following sources with volumetric surveys performed at the dates shown: Lake Travis (TWDB, July 2008), Twin Buttes (USBR, January 1964), O. C. Fisher (USACE, August 2003), and Hords Creek Reservoir (USACE, November 1992).

SV/SA and *IP/IS* records are not modified from zero storage up to the storage volume at the top of conservation pool, but are extended to the top of flood control pool. For selected water surface elevations above the top of conservation pool elevation, elevation/area/ volume tables from the TWDB website were used to compute the additional volume and area in the flood control pool. These additional areas and volumes were added to the original WAM top of conservation pool volumes and areas. *JD* record field 11 was changed to 18 to allow extra entries on the *SV* and *SA* records. Flood control pool storage capacities were computed from these quantities. The *IS* record combined storage volumes of Lakes Travis and Buchanan on *DI/IP/I*S record drought indices were also extended to include the total storage capacity including the Lake Travis flood control pool.

Flood Control Operating Rules and Criteria in the Daily Colorado WAM

The total storage capacities in the full authorization daily WAM below the top of conservation pool are tabulated in Tables 2.3 and 4.3. Conservation storage capacities are from the full authorization monthly TCEQ WAM as reflected in water right permits. The flood control storage capacities in Table 4.3 were computed using the surface elevation versus storage volume data from the TWDB website as described in the preceding two paragraphs. The total storage capacity below the top of flood control pool is the summation of conservation pool and flood control pool storage capacities.

Table 4.3
Storage Capacities of Flood Control Reservoirs in the Colorado WAM

	Storage Capacity		Storage Capacity at Top of	
Reservoir	Conservation	Flood Control	Conservation	Flood Control
	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)
Travis	1,170,752	798,253	1,170,752	1,969,005
Twin Buttes	186,200	454,364	186,200	640,564
O. C. Fisher	119,200	276,974	119,200	396,174
Hords Creek	7,959	17,303	7,959	25,262

Flood control operations in the *SIMD* simulation are based on the metrics in Tables 4.4 and 4.5. Flood control operations of a reservoir are activated whenever the storage level is in the flood control pool, defined as above the top of conservation pool and below the top of flood control pool. With the flood control pool full to capacity, outflows are set equal to inflows. The cumulative storage capacity at the top of conservation pool and top of flood control pool in Table 4.4 are entered as input parameters FCBOTTOM and FCTOP in *FR* record fields 10 and 8 [2]. The maximum limit on daily release rates from the flood control pool FCMAX in the last column of Table 4.4 is entered in *FR* record field 7.

Table 4.4
Flood Control Reservoir *FR* Record Input Parameters

Reservoir	Reservoir Identifier	Control Point ID	Flood Control Pool FCBOTTOM	FCTOP	Limit FCMAX
			(ac-ft)	(ac-ft)	(cfs)
Travis	TRAVIS	I20000	1,170,752	1,969,005	7,500
Twin Buttes	TWINBU	C20240	186,200	640,564	-
O. C. Fisher	OCFISH	C20040	119,200	396,174	-
Hords Creek	HORDSC	F30370	7,959	25,262	-

Table 4.5
Maximum Allowable Flood Flow Limits at USGS Stream Gage Stations

Control Point	Stream	Nearest City	Drainage Area	Flood Flow Limit
			(sq miles)	(cfs)
C20000	Concho River	San Angelo	4,139	25,000
C10000	Concho River	Paint Rock	5,185	25,000
F30300	Hords Creek	Coleman	107	10,000
I10000	Colorado River	Austin	27,611	30,000
J30000	Colorado River	Bastrop	28,580	45,000
J10000	Colorado River	Columbus	30,244	50,000

Maximum allowable flow limits at downstream gages are tabulated in Tables 4.2 and 4.5. 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 4.4 and 4.5, which are generated from the actual USACE operating criteria outlined in Table 4.2. The flow limits from Table 4.5 are input on the flood flow *FF* records in Table 4.6. The minimum releases at Lake Travis in Table 4.2 are not incorporated in the flood control operations.

The gage on the South Concho River at Twin Buttes was not incorporated in the WAM operations of Twin Buttes Reservoirs. This gage is below one but not both of the dams impounding Twin Buttes Reservoir. The allowable non-damaging flows of 30,000 cfs, 45,000 cfs, and 50,000 cfs at the three gages downstream of Lake Travis were incorporated in the WAM, without the increase to 50,000 cfs at Austin and Bastrop when the flood control pool level is near full capacity.

<u>Multiple Reservoir System Operations</u>

Flexible options for defining multiple-reservoir operating rules are provided in *SIMD* and explained in the *Daily Manual* [4]. However, the only multiple-reservoir system operations necessitated by the criteria in Table 4.2 are the flow limits at the gages on the Concho River at San Angelo and Paint Rock, which are applicable to operation of both O. C. Fisher and Twin Buttes Reservoirs. Actual real-world flood control operations of Lake Travis are essentially independent of the operations of the other three projects due to their location very long distances upstream of Lake Travis. Likewise, Lake Travis operations modeled in the daily WAM are independent of operations of the other three flood control reservoirs.

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 any day of the forecast period.

Storage and release priorities are entered separately on the *FR* record. The flood release priority for a 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 are incorporated into the daily *SIMD* input dataset developed in the preceding Chapter 3 as described in the present Chapter 4. The following 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.
- Forecasting parameters FCST and APRD on the *JU* record are applicable to flood control operations as well as normal operations.
- Relevant *SV/SA* record volume/area tables and *DI/IP/IS* drought indices are extended to encompass the flood control storage pools above the top of conservation pools.
- *FR* and *FF* records are added to model operation of the flood control pools of the four reservoirs based on reservoir storage levels and flows at downstream control points. Priorities are set on *FR* records. *WS* records are used with *FR* records to provide reservoir identifiers.
- The maximum release limit of 7,500 cfs in Table 4.2 for Lake Travis is specified as FCMAX on the *FR* record for Lake Travis.

Flood Reservoir *FR* and Flood Flow *FF* Records in the DAT File

Reservoir flood control operation specifications are adapted to *SIMD* input *FR* and *FF* records, which are explained in Chapter 5 of the *Daily Manual* [4] and Chapter 4 of the *Users Manual* [2]. The *FF* records replicated as Table 4.6 are added immediately after the other water right records in the DAT file. The flood control reservoir *FR* records in Table 4.7 are inserted in the DAT file following the *FF* records.

Table 4.6
Flood Flow Limit *FF* Records

```
**       1         2         3         4
**345678901234567890123456789012345678901234
**     |       |       |       |       |
FFC20000  25000.                FFLIM-C20000
FFC10000  25000.                FFLIM-C10000
FFF30300  10000.                FFLIM-F30300
FFI10000  30000.                FFLIM-I10000
FFJ30000  45000.                FFLIM-J30000
FFJ10000  50000.                FFLIM-J10000
```

Table 4.7
FR and *WS* Records for Full Authorization Daily WAM

```
**       1         2         3         4         5         6         7         8         9        10
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
**     |       |       |       |       |       |       |       |       |       |                   |
FRI200009100000092000000       2   7500.1969005.        1170752.                TRAVIS-FRSTOR   TRAVIS-FRREL
WSTRAVIS
FRC202409100000092000000       2         640564.         186200.                TWINBU-FRSTOR   TWINBU-FRREL
WSTWINBU
FRC200409100000092000000       2         396174.         119200.                OCFISH-FRSTOR   OCFISH-FRREL
WSOCFISH
FRF303709100000092000000       2          25262.           7959.                LEWDA1-FRSTOR   HORDSC-FRREL
WSHORDSC
```

The *FF* records in Table 4.6 set daily targets in cfs equal to the flow rates shown in Table 4.5. *FF* records are treated in the *SIMD* simulation as a type of water right. The optional water right identifiers in the last field of the *FF* records have no effect on the simulation but facilitate identifying simulation results in output files. The blank column 32 means that the option to use storage index *DI/IS/IP* records to vary flow limits with reservoir storage levels is not adopted. Forecasting of remaining flow capacity is controlled by *JU* record parameters FCST and APRD. A blank *FF* record field 4 (columns 17.24) defaults to the remaining flood control channel capacity forecasting period APRD set on the *JU* record.

The priority numbers for flood control storage and release on the *FR* records are junior to other water rights in the Colorado WAM except artificial rights (Table 2.9 of Chapter 2). Optional identifiers are assigned for both storage and release "water rights". *FCDEP* option 2 is selected in *FR* record field 6 (column 32) for all four flood control reservoirs. *FCDEP* option 2 means that downstream control points are not considered in the determination of stream flow available for storage in flood control pools.

CHAPTER 5
ENVIRONMENTAL FLOW STANDARDS

The following topics are covered in this chapter.

1. Environmental flow standards (EFS) at 14 gage sites in the Colorado River Basin established by the TCEQ in collaboration with a science team and stakeholder committee following procedures established by the 2007 Senate Bill 3 (SB3) are described.
2. Addition of the SB3 EFS to the daily Colorado WAM using *IF*, *ES*, *HC*, *PF*, and *PO* input records inserted in the *SIMD* input DAT file is explained.
3. A procedure is outlined in which daily *IF* record instream flow targets for the SB3 EFS computed in a daily *SIMD* simulation are summed to monthly totals and incorporated in the monthly *SIM* input dataset for the Colorado WAM. This procedure is applied in Chapter 8.

Environmental Flow Standards Established Pursuant to Senate Bill 3 Process

Senate Bill 3 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. Information regarding the process created by the 2007 Senate Bill 3 (SB3) for establishing environmental instream flow standards (EFS) and the EFS that have been adopted to date can be found at the following TCEQ website.

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

The SB3 EFS established to date are published as Subchapters B through F of Chapter 298 of Title 30 of the Texas Administrative Code. EFS for different river systems are published as subsections of Chapter 298. Modifications to existing standards and establishment of standards for additional regions and river reaches are expected in the future. The SB3 EFS for the Colorado River Basin are found in "*Subchapter D: Colorado and Lavaca Rivers and Matagorda and Lavaca Bays*" which was adopted August 8, 2012 and became effective on August 30, 2012 [11]. The priority date for these EFS and the associated set-asides to be incorporated in the water availability modeling system is March 1, 2011.

The expanded regulatory process created by the 2007 SB3 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 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. SB3 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.* Environmental flow standards (EFS) established through the Senate Bill 3 (SB3) process are based on flow regimes that include subsistence flows, base flows, and high flow pulses.

The geographic area covered by "*Subchapter D* of Chapter 298 of Title 30 of the Texas Administrative Code [11] consists of the Colorado and Lavaca Rivers and their tributaries, bays, and estuaries. SB3 EFS have been established at the locations of 21 USGS stream flow gages, including 14 sites in the Colorado River Basin, five in the Lavaca River Basin, and two sites in the Colorado-Lavaca and Lavaca-Guadalupe Coastal Basins. The TCEQ established the EFS based on recommendations submitted by an expert science team and stakeholder committee in reports [24, 25] available at the TCEQ website shown below. The priority date for the EFS is March 1, 2011, the date the Basin and Bay Expert Science Team submitted its recommendations [24].

Colorado and Lavaca Rivers and Matagorda and Lavaca Bays: Stakeholder Committee and Expert Science Team - Texas Commission on Environmental Quality - www.tceq.texas.gov

SB3 EFS at 14 USGS Gaging Stations in the Colorado River Basin

The EFS for the 14 locations in the Colorado River Basin are incorporated in the daily Colorado WAM as described later in this chapter. The 14 locations with SB3 EFS in the Colorado River Basin are listed with descriptive information in Table 5.1. Locations of the 14 SB3 EFS sites in relation to the ten largest reservoirs in the river basin are shown on the map of Figure 5.1. The 14 gage sites with SB3 EFS are all included in the 45 primary control points listed in Table 2.2 of Chapter 2. Descriptive information regarding the reservoirs in Figure 5.1 is found in Table 2.3.

Table 5.1
Locations of SB3 EFS in the Colorado River Basin

WAM CP ID	USGS Gage No.	Gage and Control Point Location	Watershed Area (square miles)
B20000	08123850	Colorado River above Silver	1,575
C30000	08128000	South Concho River at Christoval	5,046
C10000	08136500	Concho River at Paint Rock	5,046
D40000	08126380	Colorado River near Ballinger	13,788
D30000	08127000	Elm Creek at Ballinger	464
E10000	08146000	San Saba River at San Saba	3,048
F20000	08143600	Pecan Bayou near Mullin	19,830
F10000	08147000	Colorado River near San Saba	19,830
G10000	08151500	Llano River at Llano	19,830
H10000	08153500	Pedernales River near Johnson City	901
J50000	08158700	Onion Creek near Driftwood	30,244
J30000	08159200	Colorado River at Bastrop	27,611
J10000	08161000	Colorado River at Columbus	27,611
K20000	08162000	Colorado River at Wharton	30,601

The SB3 EFS criteria are designed somewhat differently for the three gage sites on the Colorado River downstream of Lake Travis (control points J30000, J10000, and K20000) than for the eleven other locations listed in Table 5.1 from several perspectives noted in the following description of the SB3 EFS at the 14 sites [11].

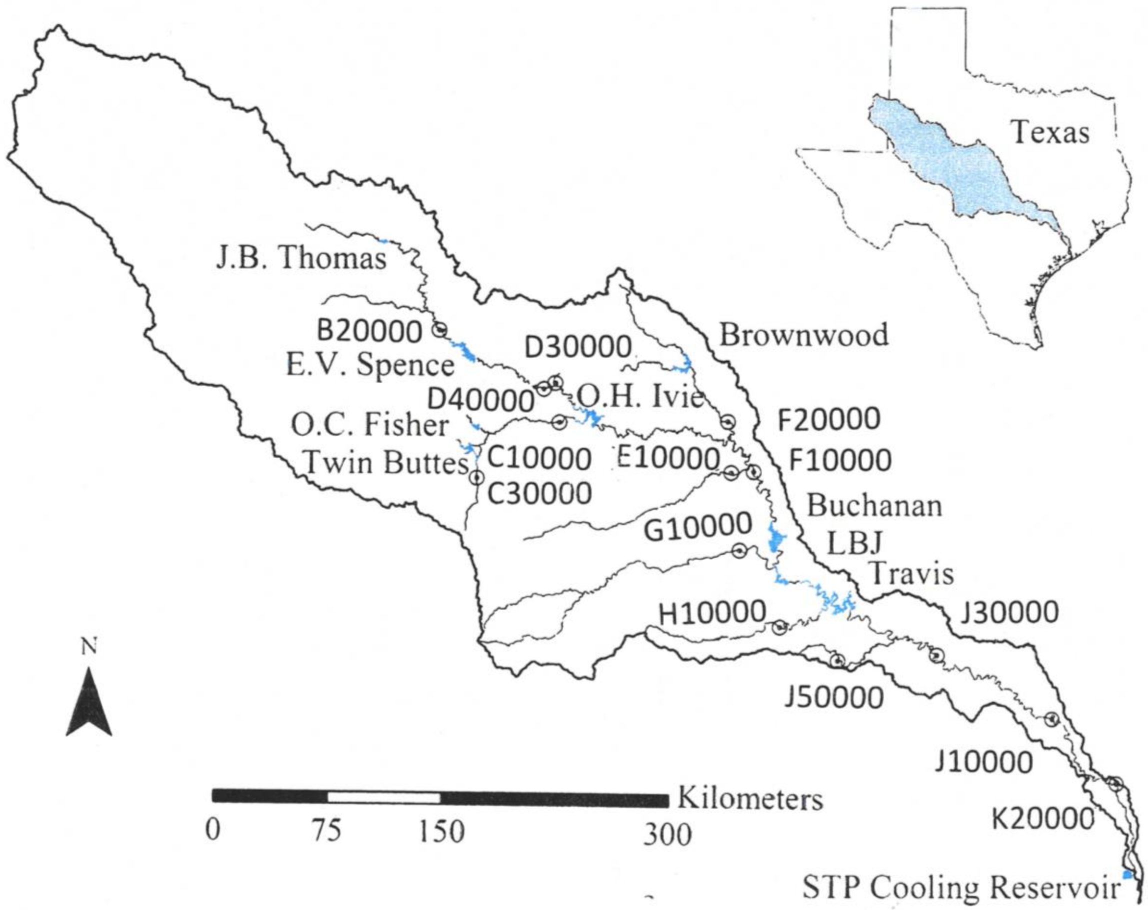

Figure 5.1 Locations of 14 Environmental Flow Standards and 10 Largest Reservoirs

The EFS established through the process created by the 2007 SB3 consist of subsistence flow, base flow, and high flow pulse components that vary seasonally and with hydrologic conditions [11]. Seasons are defined in Table 5.2. The cumulative stream flow and reservoir storage metrics used to designate hydrologic conditions are outlined in Tables 5.3 and 5.4. For locations on the Colorado River above Lake Travis or on tributaries, the month of November is included in the Winter season and hydrologic conditions are determined using cumulative stream flow for the previous 12 months. For the three SB3 EFS gage sites (control points J30000, J10000, and K20000) located on the Colorado River below Lake Travis, the month of November is included in the Fall season and hydrologic conditions are determined using the combined reservoir storage contents of Lakes Travis and Buchanan. For all 14 locations, the hydrologic condition for a season is determined based on conditions on the last day of the preceding season. The hydrologic condition for a season of the year is evaluated once and applied for the entire season.

For control points located on the Colorado River above Lake Travis and tributaries, the hydrologic condition parameters were selected by the science team and stakeholder committee such that severe conditions occur approximately 5% of the time, dry conditions occur approximately 20% of the time, average conditions occur approximately 50% of the time, and wet conditions occur approximately 25% of the time. For control points located on the Colorado River below Lake Travis, the hydrologic condition parameters were selected with severe conditions occurring approximately 5% of the time, dry conditions about 45% of the time, and average conditions approximately 50% of the time [11, 22, 23].

Table 5.2
Seasons Defined in the EFS

Season	Above Lake Travis	Below Lake Travis
Winter	November, December, January, February	December, January, February
Spring	March, April, May, June	March, April, May, June
Summer	July, August	July, August
Fall	September, October	September, October, November

Table 5.3
Stream Flow Metrics Defining Hydrologic Conditions for the
SB3 EFS Gage Sites on the Colorado River Upstream of Lake Travis or on Tributaries

WAM Control Point	Hydrologic Condition			
	Severe	Dry	Average	Wet
	Cumulative Streamflow Volume During Preceding 12 Months (acre-feet)			
	less than	between	between	greater than
B20000	4,090	4,090 − 16,600	16,600 − 57,490	57,490
C30000	5,270	5,270 − 7,380	7,380 − 21,660	21,660
C10000	7,110	7,110 − 17,000	17,000 − 49,900	49,900
D40000	3,120	3,120 − 11,150	11,150 − 67,700	67,700
D30000	820	820 − 4,990	4,990 − 46,560	46,560
E10000	40,550	40,550 − 61,100	61,100 − 149,890	149,890
F20000	11,860	11,860 − 26,700	26,700 − 187,740	187,740
F10000	80,510	80,510 − 205,110	205,110 − 568,970	568,970
G10000	90,810	90,810 − 145,660	145,660 − 364,540	364,540
H10000	27,710	27,710 − 70,210	70,210 − 222,700	222,700
J50000	810	810 − 10,460	10,460 − 59,610	59,610

Table 5.4
Reservoir Storage Volumes Defining Hydrologic Conditions for the
SB3 EFS Gage Sites on the Colorado River Downstream of Lake Travis

WAM Control Point	Hydrologic Condition		
	Severe	Dry	Average
	Combined Storage in Lakes Travis and Buchanan (acre-feet)		
	less than	between	greater than
J30000	1,103,700	1,103,700 − 1,737,460	1,737,460
J10000	1,103,700	1,103,700 − 1,737,460	1,737,460
K20000	1,103,700	1,103,700 − 1,737,460	1,737,460

Subsistence and Base Flow Standards

The subsistence standards with flow limits tabulated in Tables 5.5 and 5.6 are applicable during severe hydrologic conditions when flow at a gage site is less than the dry base flow standards. If actual flow is below the designated dry base flow limit and above the defined subsistence flow limit during severe hydrologic conditions, a water right holder may divert water as long as the diversion does not cause the flow to drop below the subsistence flow level [11].

Table 5.5
Flow Limits (cfs) in the Subsistence Flow Standards for the
Colorado River above Lake Travis and Tributaries for Severe Hydrologic Condition

WAM	Seasonal Flow Limits (cfs)			
Control Point	Winter (cfs)	Spring (cfs)	Summer (cfs)	Fall (cfs)
B20000	1	1	1	1
C30000	2	3	2	2
C10000	1	1	1	1
D40000	1	1	1	1
D30000	1	1	1	1
E10000	29	22	3	13
F20000	1	1	1	1
F10000	50	50	30	30
G10000	44	35	3	20
H10000	7	4	1	1
J50000	1	1	1	1

Table 5.6
Subsistence Flow Standards for the Colorado River below Lake Travis

Season	Month	Hydrologic	Control Point		
		Condition	J30000	J10000	K20000
			(cfs)	(cfs)	(cfs)
Winter	December	Severe	186	301	202
	January	Severe	208	340	315
	February	Severe	274	375	303
Spring	March	Severe	274	375	204
	April	Severe	184	299	270
	May	Severe	275	425	304
	June	Severe	202	534	371
Summer	July	Severe	137	342	212
	August	Severe	123	190	107
Fall	September	Severe	123	279	188
	October	Severe	127	190	147
	November	Severe	180	202	173

For control points located on the Colorado River upstream of Lake Travis or on tributaries, the subsistence flow standards vary seasonally as shown in Table 5.5. For control points located on the Colorado River downstream of Lake Travis, the subsistence flow standards vary monthly as shown in Table 5.6. In both cases, the subsistence standards are applied only when the hydrologic condition is categorized as severe.

The flow criteria for base flow standards are tabulated in Tables 5.7 and 5.8 [11]. For control points located on the Colorado River above Lake Travis or on tributaries, base flow standards vary seasonally and are specified according to four hydrologic conditions: severe, dry, average, and wet. For control points located on the Colorado River below Lake Travis, base flow standards vary monthly and are specified according to three hydrologic conditions: severe, dry, and average.

For all locations, the dry base flow standard applies during severe hydrologic conditions. If flow at a control point is below applicable high flow pulse trigger levels and above the applicable base flow standard, a water right holder may divert water as long as the diversion does not cause the flow to drop below the applicable base flow standard.

Table 5.7
Stream Flow Limits (cfs) Defining Base Flow Standards
Colorado River above Lake Travis and Tributaries

WAM	Winter				Spring				Summer				Fall			
CP ID	Sev	Dry	Avg	Wet	Sev	Dry	Avg	Wet	Sev	Dry	Avg	Wet	Sev	Dry	Avg	Wet
B20000	2	2	4	7	2	2	5	12	1	1	3	8	1	1	4	10
C30000	9	9	15	22	9	9	15	22	7	7	12	22	7	7	12	22
C10000	8	8	20	36	4	4	14	27	1	1	4	12	5	5	16	29
D40000	4	4	9	14	3	3	9	19	2	2	6	14	4	4	9	17
D30000	1	1	1	4	1	1	1	5	1	1	1	1	1	1	1	1
E10000	56	56	81	110	56	56	81	110	32	32	46	62	40	40	64	87
F20000	3	3	7	12	3	3	9	19	2	2	4	8	3	3	7	12
F10000	95	95	150	210	120	120	190	360	72	72	120	210	95	95	150	210
G10000	100	100	150	190	100	100	150	190	67	67	92	130	87	87	120	190
H10000	23	23	45	80	29	29	60	110	16	16	29	49	16	16	29	49
J50000	2	2	6	26	4	4	12	34	1	1	3	7	1	1	3	7

High Flow Pulse Standards

The high flow pulse components of the SB3 EFS are outlined in Tables 5.9 and 5.10 [11]. High flow pulse criteria for the three locations on the Colorado River downstream of Lake Travis are presented in Table 5.10. The criteria metrics for the other eleven gage sites are in Table 5.9. For these eleven WAM control points (USGS gage sites), high pulse criteria are specified for a two-per-season pulse, a one-per-season pulse, and an annual pulse. For the three control points on the Colorado River below Lake Travis, criteria are specified for a two-per-season pulse, a one per 18-month pulse, and a one per two-year pulse.

Table 5.8
Base Flow Standards for Colorado River below Lake Travis

Season	Month	Hydrologic Condition	J30000 (cfs)	J10000 (cfs)	K20000 (cfs)
Winter	December	Severe	311	464	470
		Dry	311	464	470
		Average	450	737	746
	January	Severe	313	487	492
		Dry	313	487	492
		Average	433	828	838
	February	Severe	317	590	597
		Dry	317	590	597
		Average	497	895	906
Spring	March	Severe	274	525	531
		Dry	274	525	531
		Average	497	1,020	1,036
	April	Severe	287	554	561
		Dry	287	554	561
		Average	635	977	1,011
	May	Severe	579	966	985
		Dry	579	966	985
		Average	824	1,316	1,397
	June	Severe	418	967	984
		Dry	418	967	984
		Average	733	1,440	1,512
Summer	July	Severe	347	570	577
		Dry	347	570	577
		Average	610	895	906
	August	Severe	194	310	314
		Dry	194	310	314
		Average	381	516	522
Fall	September	Severe	236	405	410
		Dry	236	405	410
		Average	423	610	617
	October	Severe	245	356	360
		Dry	245	356	360
		Average	433	741	749
	November	Severe	283	480	486
		Dry	283	480	486
		Average	424	755	764

When the high flow pulse trigger level is reached, that flow level is protected by curtailing junior water rights until either the specified volume or duration criteria in Table 5.9 is met. For the three sites in Table 5.10, duration is the only termination criterion; volume is not used. Junior rights can appropriate excess stream flow exceeding the trigger level at any of the 14 sites.

Table 5.9
High Flow Pulse Standards
Colorado River above Lake Travis and Tributaries

WAM CP ID	Season	Pulse Flow Criteria	Frequency		
			2 per season	1 per season	Annual
B20000	Winter	Trigger (cfs)	18	42	3,000
		Volume (ac-ft)	120	300	13,600
		Duration (days)	13	15	17
	Spring	Trigger (cfs)	600	1,800	
		Volume (ac-ft)	2,500	7,900	
		Duration (days)	9	11	
	Summer	Trigger (cfs)	100	330	
		Volume (ac-ft)	350	1,400	
		Duration (days)	6	9	
	Fall	Trigger (cfs)	100	430	
		Volume (ac-ft)	400	1,800	
		Duration (days)	6	9	
C30000	Winter	Trigger (cfs)	none	none	420
		Volume (ac-ft)	none	none	1,400
		Duration (days)	none	none	9
	Spring	Trigger (cfs)	none	none	
		Volume (ac-ft)	none	none	
		Duration (days)	none	none	
	Summer	Trigger (cfs)	none	none	
		Volume (ac-ft)	none	none	
		Duration (days)	none	none	
	Fall	Trigger (cfs)	none	45	
		Volume (ac-ft)	none	190	
		Duration (days)	none	7	
C10000	Winter	Trigger (cfs)	61	160	3,000
		Volume (ac-ft)	400	1,200	13,500
		Duration (days)	10	16	19
	Spring	Trigger (cfs)	500	1,400	
		Volume (ac-ft)	2,000	5,700	
		Duration (days)	8	11	
	Summer	Trigger (cfs)	32	110	
		Volume (ac-ft)	140	520	
		Duration (days)	6	8	
	Fall	Trigger (cfs)	74	300	
		Volume (ac-ft)	330	1,300	
		Duration (days)	7	10	

Table 5.9 (Continued)
High Flow Pulse Standards
Colorado River above Lake Travis and Tributaries

WAM CP ID	Season	Pulse Flow Criteria	Frequency		
			2 per season	1 per season	Annual
D40000	Winter	Trigger (cfs)	27	96	3,200
		Volume (ac-ft)	180	660	13,700
		Duration (days)	11	17	10
	Spring	Trigger (cfs)	1,300	3,200	
		Volume (ac-ft)	5,300	13,700	
		Duration (days)	9	10	
	Summer	Trigger (cfs)	130	630	
		Volume (ac-ft)	490	2,600	
		Duration (days)	6	9	
	Fall	Trigger (cfs)	250	1,500	
		Volume (ac-ft)	950	5,700	
		Duration (days)	8	10	
D30000	Winter	Trigger (cfs)	10	40	1,900
		Volume (ac-ft)	71	270	7,200
		Duration (days)	10	1	18
	Spring	Trigger (cfs)	380	1,000	
		Volume (ac-ft)	1,400	3,800	
		Duration (days)	10	12	
	Summer	Trigger (cfs)	6	74	
		Volume (ac-ft)	25	300	
		Duration (days)	6	9	
	Fall	Trigger (cfs)	10	190	
		Volume (ac-ft)	46	850	
		Duration (days)	9	15	
E10000	Winter	Trigger (cfs)	150	330	5,500
		Volume (ac-ft)	980	2,300	27,400
		Duration (days)	14	18	21
	Spring	Trigger (cfs)	810	2,000	
		Volume (ac-ft)	3,600	9,200	
		Duration (days)	9	12	
	Summer	Trigger (cfs)	none	210	
		Volume (ac-ft)	none	1,100	
		Duration (days)	none	9	
	Fall	Trigger (cfs)	150	500	
		Volume (ac-ft)	600	2,300	
		Duration (days)	8	12	

Table 5.9 (Continued)
High Flow Pulse Standards
Colorado River above Lake Travis and Tributaries

WAM CP ID	Season	Pulse Flow Criteria	Frequency		
			2 per season	1 per season	Annual
F20000	Winter	Trigger (cfs)	52	250	3,500
		Volume (ac-ft)	230	1,500	25,800
		Duration (days)	7	14	26
	Spring	Trigger (cfs)	710	2,100	
		Volume (ac-ft)	3,600	13,200	
		Duration (days)	10	17	
	Summer	Trigger (cfs)	21	100	
		Volume (ac-ft)	73	440	
		Duration (days)	4	7	
	Fall	Trigger (cfs)	36	250	
		Volume (ac-ft)	110	1,200	
		Duration (days)	3	9	
F10000	Winter	Trigger (cfs)	520	1,600	18,900
		Volume (ac-ft)	3,100	11,100	129,100
		Duration (days)	9	15	23
	Spring	Trigger (cfs)	5,800	11,000	
		Volume (ac-ft)	31,300	70,200	
		Duration (days)	9	13	
	Summer	Trigger (cfs)	510	1,400	
		Volume (ac-ft)	1,900	6,500	
		Duration (days)	4	7	
	Fall	Trigger (cfs)	890	3,800	
		Volume (ac-ft)	3,500	19,200	
		Duration (days)	6	12	
G10000	Winter	Trigger (cfs)	390	1,100	9,100
		Volume (ac-ft)	2,500	6,800	46,100
		Duration (days)	13	16	18
	Spring	Trigger (cfs)	1,800	4,800	
		Volume (ac-ft)	8,500	23,200	
		Duration (days)	10	13	
	Summer	Trigger (cfs)	none	560	
		Volume (ac-ft)	none	2,600	
		Duration (days)	none	9	
	Fall	Trigger (cfs)	370	1,400	
		Volume (ac-ft)	1,600	6,300	
		Duration (days)	8	11	

Table 5.9 (Continued)
High Flow Pulse Standards
Colorado River above Lake Travis and Tributaries

WAM CP ID	Season	Pulse Flow Criteria	Frequency		
			2 per season	1 per season	Annual
H10000	Winter	Trigger (cfs)	270	860	6,980
		Volume (ac-ft)	1,300	4,700	28,320
		Duration (days)	9	15	15
	Spring	Trigger (cfs)	1,700	3,700	
		Volume (ac-ft)	6,300	14,400	
		Duration (days)	8	10	
	Summer	Trigger (cfs)	none	290	
		Volume (ac-ft)	none	1,100	
		Duration (days)	none	7	
	Fall	Trigger (cfs)	160	860	
		Volume (ac-ft)	620	3,000	
		Duration (days)	6	8	
J50000	Winter	Trigger (cfs)	none	170	1,200
		Volume (ac-ft)	none	1,900	8,700
		Duration (days)	none	20	34
	Spring	Trigger (cfs)	200	620	
		Volume (ac-ft)	1,100	3,700	
		Duration (days)	11	19	
	Summer	Trigger (cfs)	none	none	
		Volume (ac-ft)	none	none	
		Duration (days)	none	none	
	Fall	Trigger (cfs)	18	120	
		Volume (ac-ft)	70	560	
		Duration (days)	5	11	

Table 5.10
High Flow Pulse Standards
Colorado River below Lake Travis

WAM CP ID	Pulse Flow Criteria	Frequency		
		2 per season	1 per 18 months	1 per 2 years
J30000	Trigger (cfs)	3,000	8,000	none
	Duration (days)	4	2	none
J10000	Trigger (cfs)	3,000	8,000	27,000
	Duration (days)	4	2	2
K20000	Trigger (cfs)	3,000	8,000	27,000
	Duration (days)	4	2	2

For all of the 14 locations, high flow pulses are independent of hydrologic conditions, and each season is independent of other seasons. If a requirement for a pulse event is satisfied during a season, a high flow pulse requirement is considered to be satisfied for each smaller event in that season. For example, if an annual pulse flow requirement is met in a season, then a one-per-season pulse flow and a two-per-season pulse flow requirements are met for that season.

Water right holders are not required to cease diverting water or release stored water to produce a high flow pulse event if the trigger criterion is not met during a season. High flow pulses are preserved but not created. Water that was previously stored as authorized by a water right may be diverted or released regardless of applicable environmental flow requirements.

Water Right Permit Conditions Affecting Applicability of SB3 EFS

Administrative Code Chapter 298, Subchapter D, Section §298.335 entitled "*Water Right Permit Conditions*" deals only with water right permits issued after the August 30, 2012 effective date of the SB3 EFS [11]. The SB3 EFS may constrain water availability for diversions and storage authorized by permits issued after August 30, 2012. The rules defining applicability of the SB3 EFS vary between water right permits located downstream of Lake Travis versus those located upstream. For water right permits that authorize diversions and/or storage at locations on the Colorado River above Lake Travis and tributaries, all of the SB3 EFS are applicable [11].

For water right permits that authorize diversions and/or storage at locations on the Colorado River below Lake Travis, all of the subsistence and base flow standards are applicable. However, §298.335 indicates that applicability of the high flow pulse components of the environmental flow standards vary depending on the diversion rate and on-channel storage volume authorized by a new water right permit. Preservation of high flow pulses is required only for new water rights with authorized diversions exceeding 500 cfs or storage exceeding 2,500 acre-feet (Table 5.11).

Table 5.11 Conditions for the Application of High Flow Pulse Standards for New Water Right Permits Located on the Colorado River below Lake Travis

Diversion Rate (cfs)		On-Channel Storage (acre-feet)	Applicable High Flow Pulse Standards
> 500	or	> 2,500	One-per-year event and smaller events protected.
> 800	or	> 2,500	Prevent impairment* of one per 18-month event
> 2,700	or	> 2,500	One-per-two-year event is protected.

*Note: Impairment is defined as reduction in the frequency or average volume of the one per 18-month event by more than 10% based on the WAM period-of-record at the time the first water right permit subject to the EFS is evaluated.

Applicability of high flow pulse components of the SB3 EFS at the three sites on the Colorado River below Lake Travis depend upon the location and diversion and storage amounts authorized by a new water right permit for which water availability is being determined. The SB3 EFS high flow pulse components are incorporated in the WAM as separate *IF* record rights allowing them to be easily deactivated by the model-user as appropriate for the new junior water permit for which water availability is being evaluated.

Other Instream Flow Requirements in the Colorado WAM

The existing *IF* record water rights in the monthly Colorado WAM are not altered in the conversion to a daily WAM other than uniformly distributing the monthly instream flow targets to the 28, 29, 30, or 31 days in each month. The 120 *IF* records in the Colorado WAM last updated by TCEQ in 2020 are listed in Table 2.5 of Chapter 2. The instream flow *IF* record rights are listed in priority order with priorities ranging from December 31, 1904 (19041231) to August 4, 2010 (20100804). Priorities dates are tabulated in the last column of Table 2.5. The SB3 EFS added to the daily WAM as described in Chapter 5 have a priority date of March 1, 2011 (20110301). Although many artificial rights have priorities of 99999999, the most junior *WR* record diversion right with a priority based on the date in a permit has a priority of 20011116 (November 16, 2001).

The LCRA Water Management Plan (WMP) includes releases of water from Lakes Travis and Buchanan to supply environmental needs for instream flows of the Colorado River between Lake Travis and the outlet and inflows to Matagorda Bay as discussed in Chapter 2. The LCRA WMP and SB3 EFS are overlapping but protect environmental flows differently. The LCRA WMP includes protection of environmental flows as part of the LCRA reservoir system operating plan. The SB3 EFS constrain appropriation of set-asides by junior more junior water right applicants but does not affect LCRA reservoir system operations or other more senior water rights.

The SB3 EFS [11] and LCRA WMP [13] include the same targets for bay and estuary freshwater inflows to Matagorda Bay. Cumulative inflow volumes in acre-feet are specified for three-month Spring and Fall seasons and the intervening six-month period for four levels of ecosystem protection. The LCRA WMP freshwater inflow requirements are modeled in the monthly WAM last updated in February 2020. LCRA WMP provisions for freshwater inflows are assumed to control. These requirements are not repeated as SB3 EFS in the daily WAM.

Subsistence and base flows at the USGS gages on the Colorado River at Columbus, Wharton, and Bay City are specified in the LCRA WMP. Subsistence flows of the Colorado River at Austin are also protected by the WMP. Subsistence and base flow rates at the gages on the Colorado River at Columbus, Wharton, and Bay City specified in the LCRA WMP are the same as the rates specified in the SB3 EFS. However, unlike the SB3 EFS, the WMP environmental flows are supplied as necessary by releases of stored water based on three levels of instream flow criteria that decrease releases as combined storage levels in Lakes Buchanan and Travis decrease.

The LCRA WMP also includes releases of water from reservoir storage to protect the environmental health of Matagorda Bay as discussed in Chapter 2. Five levels of criteria are defined in the WMP that vary with drought severity and water availability. For each criteria level, requirements for reservoir releases decrease as combined storage levels in Lakes Buchanan and Travis decrease along with curtailment of interruptible stored water for agriculture.

Instream flow requirements are modeled with the 120 *IF* records in Table 2.5 using various combinations of options. In many cases, instream flow requirements are modeled using only input parameters entered on the *IF* record. In other cases, instream flow requirements are modeled by combining *IF* record specifications with additional options activated using *UC, WS, TO, FS,* and/or *DI/IS/IP/IM* records. *WR* record type 8 water rights are also used in combination with *TO* records to develop instream flow targets for *IF* record water rights.

The May 2019 and later versions of the WRAP simulation models *SIM* and *SIMD* include environmental standard *ES*, hydrologic condition *HC*, pulse flow *PF*, and pulse flow options *PO* records that are designed for modeling environmental instream flow requirements formulated in the format adopted by the 2007 SB3 process. Both *SIM* and *SIMD* include *ES* and *HC* records. *PF* and *PO* records are applicable only in a daily *SIMD* simulation.

The monthly Colorado WAM last updated by the TCEQ in February 2020 has no high flow pulse components of instream flow requirements that would be relevant to *PF* and *PO* records. Although also applicable for daily or monthly instream flow requirements other than SB3 EFS, the new *ES* and *HC* records are not used for any of the 120 *IF* record rights listed in Table 2.5 of Chapter 2. The addition of SB3 EFS to the daily *SIMD* input DAT file as described in the following section employs only *IF*, *ES*, *HC*, *PF*, and *PO* records.

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 *WRAP Reference Manual* [1] and Chapter 6 of the *Daily Manual* [4] and illustrated by the SB3 EFS for the Colorado River Basin as described in this chapter.

Environmental standard *ES*, hydrologic condition *HC*, 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. Chapter 3 of the *Users Manual* [2] defines the input parameters entered on the types of input records that are applicable to both the monthly *SIM* and daily *SIMD*, which includes the *ES* and *HC* records. Chapter 4 of the *Users Manual* covers additional daily *SIMD* input records that are not applicable to the monthly *SIM*, including the *PF* and *PO* records.

An example of modeling SB3 EFS is presented in Chapter 8 of the *Daily Manual* [4]. SB3 EFS have been previously added to the Brazos, Trinity, and Neches daily WAMs [8, 9, 10] using the same methodologies applied with the daily Colorado WAM described here in Chapter 5. Daily and monthly instream flow targets for *IF* record rights representing SB3 EFS computed in *SIMD* simulations are presented in Chapter 6 of this report.

The *SIMD* DAT file input records reproduced as Table 5.12 control the computation of daily instream flow targets at the 14 control points in the Colorado WAM representing the SB3 EFS gage sites. These *IF* record instream flow targets are minimum flow limits that may constrain appropriation of stream flow by *WR* record water rights with junior priorities.

The *IF* record 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 supplemental information that facilitates tracking the *ES* and *PF* record computations. These message file options are not activated in the dataset of Table 5.12, but can be easily activated whenever needed.

The set of input records replicated in Table 5.12 are inserted with the other sets of *WR* and *IF* record water rights in the *SIMD* input file. Each *IF* record instream flow right in Table 5.12 has a set of *HC*, *ES*, *PF*, and *PO* records that provide the metrics found in Tables 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8, 5.9, and 5.10. The subsistence/base flows and pulse flows are organized as separate water rights in Table 5.12 but can be combined as discussed in the next section of this chapter.

Table 5.12
Instream Flow Rights that Model the SB3 EFS in the Daily Colorado WAM DAT File

```
**       1         2         3         4         5         6         7         8         9        10
**34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
**     !       !       !       !       !       !       !       !       !       !       !       !       !
IFB20000     -9.        20110301   2            B20000ES
HCB20000      RF  12  M   J S N       0.    4090.  16000.  57400.     -9.
ES SUBS1     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE1     2.0     2.0     2.0     2.0     2.0     2.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE2     2.0     2.0     2.0     2.0     2.0     2.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE3     4.0     4.0     5.0     5.0     5.0     5.0     3.0     3.0     4.0     4.0     4.0     4.0
ES BASE4     7.0     7.0    12.0    12.0    12.0    12.0     8.0     8.0    10.0    10.0     7.0     7.0
**
IFB20000     -9.        20110301   2            B20000PF
HCB20000      RF  12  M   J S N       0.    4090.  16000.  57400.     -9.
ES PFES
PF   1 0     18.    120.  13   2      11   2            2
PO            2
PF   1 0    600.   2500.   9   2       3   6            2
PO            2
PF   1 0    100.    350.   6   2       7   8            2
PO            2
PF   1 0    100.    400.   6   2       9  10            2
PO            2
PF   1 0     42.    300.  15   1      11   2            2
PO            2
PF   1 0   1800.   7900.  11   1       3   6            2
PO            2
PF   1 0    330.   1400.   9   1       7   8            2
PO            2
PF   1 0    430.   1800.   9   1       9  10            2
PO            2
PF   1 0   3000.  13600.  17   1       1  12            2
PO            2
**
IFC30000     -9.        20110301   2            C30000ES
HCC30000      RF  12  M   J S N       0.    5270.   7380.  21660.     -9.
ES SUBS1     2.0     2.0     3.0     3.0     3.0     3.0     2.0     2.0     2.0     2.0     2.0     2.0
ES BASE1     9.0     9.0     9.0     9.0     9.0     9.0     7.0     7.0     7.0     7.0     7.0     7.0
ES BASE2     9.0     9.0     9.0     9.0     9.0     9.0     7.0     7.0     7.0     7.0     7.0     7.0
ES BASE3    15.0    15.0    15.0    15.0    15.0    15.0    12.0    12.0    12.0    12.0    12.0    12.0
ES BASE4    22.0    22.0    22.0    22.0    22.0    22.0    22.0    22.0    22.0    22.0    22.0    22.0
**
IFC30000     -9.        20110301   2            C30000PF
HCC30000      RF  12  M   J S N       0.    5270.   7380.  21660.     -9.
ES PFES
PF   1 0     45     190.   7   1       9  10            2
PO            2
PF   1 0    420    1400.   9   1       1  12            2
PO            2
**
IFC10000     -9.        20110301   2            C10000ES
HCC10000      RF  12  M   J S N       0.    7110.  17000.  49900.     -9.
ES SUBS1     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE1     8.0     8.0     4.0     4.0     4.0     4.0     4.0     4.0    12.0    12.0     8.0     8.0
ES BASE2     8.0     8.0     8.0     8.0     8.0     8.0    20.0    20.0    36.0    36.0     8.0     8.0
ES BASE3    20.0    20.0    14.0    14.0    14.0    14.0     4.0     4.0    16.0    16.0    20.0    20.0
ES BASE4    36.0    36.0    27.0    27.0    27.0    27.0    12.0    12.0    16.0    16.0    36.0    36.0
```

```
**
IFC10000     -9.        20110301   2            C10000PF
HCC10000      RF  12  M   J S N       0.   7110.  17000.  49900.     -9.
ES PFES
PF   1 0     61.    100.  10   2      11   2           2
PO            2
PF   1 0    500.   2000.   8   2       3   6           2
PO            2
PF   1 0     32.    140.   6   2       7   8           2
PO            2
PF   1 0     74.    330.   7   2       9  10           2
PO            2
PF   1 0    160.   1200.  16   1      11   2           2
PO            2
PF   1 0   1400.   5700.  11   1       3   6           2
PO            2
PF   1 0    110.    520.   8   1       7   8           2
PO            2
PF   1 0    300.   1300.  10   1       9  10           2
PO            2
PF   1 0   3000.  13500.  19   1       1  12           2
PO            2
**
IFD40000     -9.        20110301   2            D40000ES1
HCD40000      RF  12  M   J S N       0.   3120.  11150.  67700.     -9.
ES SUBS1     1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0
ES BASE1     4.0      4.0      3.0      3.0      3.0      3.0      2.0      2.0      4.0      4.0      4.0      4.0
ES BASE2     4.0      4.0      3.0      3.0      3.0      3.0      2.0      2.0      4.0      4.0      4.0      4.0
ES BASE3     9.0      9.0      9.0      9.0      9.0      9.0      6.0      6.0      9.0      9.0      9.0      9.0
ES BASE4    14.0     14.0     19.0     14.0     14.0     14.0     14.0     14.0     17.0     17.0     14.0     14.0
**
IFD40000     -9.        20110301   2            D40000PF
HCD40000      RF  12  M   J S N       0.   3120.  11150.  67700.     -9.
ES PFES
PF   1 0     27.    180.  11   2      11   2           2
PO            2
PF   1 0   1300.   5300.   9   2       3   6           2
PO            2
PF   1 0    130.    490.   6   2       7   8           2
PO            2
PF   1 0    250.    950.   8   2       9  10           2
PO            2
PF   1 0     96.    660.  17   1      11   2           2
PO            2
PF   1 0   3200.  13700.  10   1       3   6           2
PO            2
PF   1 0    630.   2600.   9   1       7   8           2
PO            2
PF   1 0   1500.   5700.  10   1       9  10           2
PO            2
PF   1 0   3200.  13700.  10   1       1  12           2
PO            2
**
IFD30000     -9.        20110301   2            D30000ES
HCD30000      RF  12  M   J S N       0.    820.   4990.  46560.     -9.
ES SUBS1     1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0
ES BASE1     1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0
ES BASE2     1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0
ES BASE3     1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0      1.0
ES BASE4     4.0      4.0      5.0      5.0      5.0      5.0      1.0      1.0      1.0      1.0      4.0      4.0
**
IFD30000     -9.        20110301   2            D30000PF
HCD30000      RF  12  M   J S N       0.    820.   4990.  46560.     -9.
ES PFES
```

```
PF   1 0     10.     71.  10   2      11   2           2
PO           2
PF   1 0    380.   1400.  10   2       3   6           2
PO           2
PF   1 0      6.     25.   6   2       7   8           2
PO           2
PF   1 0     10.     46.   9   2       9  10           2
PO           2
PF   1 0     40.    270.   1   1      11   2           2
PO           2
PF   1 0   1000.   3800.  12   1       3   6           2
PO           2
PF   1 0     74.    300.   9   1       7   8           2
PO           2
PF   1 0    190.    850.  15   1       9  10           2
PO           2
PF   1 0   1900.   7200.  18   1       1  12           2
PO           2
**
IFE10000     -9.       20110301   2          E10000ES
HCE10000      RF  12  M   J S N       0.  40550.  61100. 149890.     -9.
ES SUBS1    29.0    22.0    22.0    22.0    22.0    22.0     3.0     3.0    13.0    13.0    29.0    29.0
ES BASE1    56.0    56.0    56.0    56.0    56.0    56.0    32.0    32.0    40.0    40.0    56.0    56.0
ES BASE2    56.0    56.0    56.0    56.0    56.0    56.0    32.0    32.0    40.0    40.0    56.0    56.0
ES BASE3    81.0    81.0    81.0    81.0    81.0    81.0    46.0    46.0    64.0    64.0    81.0    81.0
ES BASE4   110.0   110.0   110.0   110.0   110.0   110.0    62.0    62.0    87.0    87.0   110.0   110.0
**
IFE10000     -9.       20110301   2          E10000PF
ES PFES
HCE10000      RF  12  M   J S N       0.  40550.  61100. 149890.     -9.
PF   1 0    150.    980.  14   2      11   2           2
PO           2
PF   1 0    810.   3600.   9   2       3   6           2
PO           2
PF   1 0    150.    600.   8   2       9  10           2
PO           2
PF   1 0    330.   2300.  18   1      11   2           2
PO           2
PF   1 0   2000.   9200.  12   1       3   6           2
PO           2
PF   1 0    210.   1100.   9   1       7   8           2
PO           2
PF   1 0    500.   2300.  12   1       9  10           2
PO           2
PF   1 0   5500.  27400.  21   1       1  12           2
PO           2
**
IFF20000     -9.       20110301   2          F20000ES
HCF20000      RF  12  M   J S N       0.  11860.  26700. 187740.     -9.
ES SUBS1     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE1     3.0     3.0     3.0     3.0     3.0     3.0     2.0     2.0     3.0     3.0     3.0     3.0
ES BASE2     3.0     3.0     3.0     3.0     3.0     3.0     2.0     2.0     3.0     3.0     3.0     3.0
ES BASE3     7.0     7.0     9.0     9.0     9.0     9.0     4.0     4.0     7.0     7.0     7.0     7.0
ES BASE4    12.0    12.0    19.0    19.0    19.0    19.0     8.0     8.0    12.0    12.0    12.0    12.0
**
IFF20000     -9.       20110301   2          F20000PF
ES PFES
PF   1 0     52.    230.   7   2      11   2           2
PO           2
PF   1 0    710.   3600.  10   2       3   6           2
PO           2
PF   1 0     21.     73.   4   2       7   8           2
PO           2
PF   1 0     36.    110.   3   2       9  10           2
```

```
PO          2
PF   1 0   250.   1500.  14   1      11   2           2
PO          2
PF   1 0  2100.  13200.  17   1       3   6           2
PO          2
PF   1 0   100.    440.   7   1       7   8           2
PO          2
PF   1 0   250.   1200.   9   1       9  10           2
PO          2
PF   1 0  3500.  25800.  26   1       1  12           2
PO          2
**
IFF10000     -9.       20110301   2           F10000ES
HCF10000      RF  12  M   J S N       0.  11860.  26700. 187740.     -9.
ES SUBS1    50.0    50.0    50.0    50.0    50.0    50.0    30.0    30.0    30.0    30.0    50.0    50.0
ES BASE1    95.0    95.0   120.0   120.0   120.0   120.0    72.0    72.0    95.0    95.0    95.0    95.0
ES BASE2    95.0    95.0   120.0   120.0   120.0   120.0    72.0    72.0    95.0    95.0    95.0    95.0
ES BASE3   150.0   150.0   190.0   190.0   190.0   190.0   120.0   120.0   150.0   150.0   150.0   150.0
ES BASE4   210.0   210.0   360.0   360.0   360.0   360.0   210.0   210.0   210.0   210.0   210.0   210.0
**
IFF10000     -9.       20110301   2           F10000PF
ES PFES
PF   1 0   520.   3100.   9   2      11   2           2
PO          2
PF   1 0  5800.  31300.   9   2       3   6           2
PO          2
PF   1 0   510.   1900.   4   2       7   8           2
PO          2
PF   1 0   890.   3500.   6   2       9  10           2
PO          2
PF   1 0  1600.  11100.  15   1      11   2           2
PO          2
PF   1 0 11100.  70200.  13   1       3   6           2
PO          2
PF   1 0  1400.   6500.   7   1       7   8           2
PO          2
PF   1 0  3800.  19200.  12   1       9  10           2
PO          2
PF   1 0 18900. 129200.  23   1       1  12           2
PO          2
**
IFG10000     -9.       20110301   2           G10000ES
HCG10000      RF  12  M   J S N       0.  90810. 145660. 364540.     -9.
ES SUBS1    44.0    44.0    35.0    35.0    35.0    35.0     3.0     3.0    20.0    20.0    44.0    44.0
ES BASE1   100.0   100.0   100.0   100.0   100.0   100.0    67.0    67.0    87.0    87.0   100.0   100.0
ES BASE2   100.0   100.0   100.0   100.0   100.0   100.0    67.0    67.0    87.0    87.0   100.0   100.0
ES BASE3   150.0   150.0   150.0   150.0   150.0   150.0    92.0    92.0   120.0   120.0   150.0   150.0
ES BASE4   190.0   190.0   190.0   190.0   190.0   190.0   130.0   130.0   190.0   190.0   190.0   190.0
**
IFG10000     -9.       20110301   2           G10000PF
HCG10000      RF  12  M   J S N       0.  90810. 145660. 364540.     -9.
ES PFES
PF   1 0   390.   1100.  13   2      11   2           2
PO          2
PF   1 0  1800.   8500.  10   2       3   6           2
PO          2
PF   1 0   370.   1600.  10   2       9  10           2
PO          2
PF   1 0  1100.   6800.  16   1      11   2           2
PO          2
PF   1 0  4800.  23200.  13   1       3   6           2
PO          2
PF   1 0   560.   2600.   9   1       7   8           2
PO          2
```

```
PF   1 0   1400.  63400.  11   1       9  10           2
PO          2
PF   1 0   9100.  46100.  18   1       1  12           2
PO          2
**
IFH10000     -9.       20110301   2           H10000ES
HCH10000      RF  12  M   J S N       0.  27710.  70210. 222700.     -9.
ES SUBS1     7.0     7.0     4.0     4.0     4.0     4.0     1.0     1.0     1.0     1.0     7.0     7.0
ES BASE1    23.0    23.0    29.0    29.0    29.0    29.0    16.0    16.0    16.0    16.0    23.0    23.0
ES BASE2    23.0    23.0    29.0    29.0    29.0    29.0    16.0    16.0    16.0    16.0    23.0    23.0
ES BASE3    45.0    45.0    60.0    60.0    60.0    60.0    29.0    29.0    29.0    29.0    45.0    45.0
ES BASE4    80.0    80.0   110.0   110.0   110.0   110.0    49.0    49.0    49.0    49.0    80.0    80.0
**
IFH10000     -9.       20110301   2           H10000PF
HCH10000      RF  12  M   J S N       0.  27710.  70210. 222700.     -9.
ES PFES
PF   1 0    270.   1300.   9   2      11   2           2
PO          2
PF   1 0   1700.   6300.   8   2       3   6           2
PO          2
PF   1 0    160.    620.   6   2       9  10           2
PO          2
PF   1 0    860.   4700.  15   1      11   2           2
PO          2
PF   1 0   3700.  14400.  10   1       3   6           2
PO          2
PF   1 0    290.   1100.   7   1       7   8           2
PO          2
PF   1 0    860.   3000.   8   1       9  10           2
PO          2
PF   1 0   6980.  28320.  15   1       1  12           2
PO          2
**
IFJ50000     -9.       20110301   2           J50000ES
HCJ50000      RF  12  M   J S N       0.    810.  10460.  59610.     -9.
ES SUBS1     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE1     2.0     2.0     4.0     4.0     4.0     4.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE2     2.0     2.0     4.0     4.0     4.0     4.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE3     6.0     6.0    12.0    12.0    12.0    12.0     3.0     3.0     3.0     3.0     6.0     6.0
ES BASE4    26.0    26.0    34.0    34.0    34.0    34.0     7.0     7.0     7.0     7.0    26.0    26.0
**
IFJ50000     -9.       20110301   2           J50000PF
HCJ50000      RF  12  M   J S N       0.    810.  10460.  59610.     -9.
ES PFES
PF   1 0    200.   1100.  11   2       3   6           2
PO          2
PF   1 0     18.     70.   5   2       9  10           2
PO          2
PF   1 0    170.   1900.  20   1      11   2           2
PO          2
PF   1 0    620.   3700.  19   1       3   6           2
PO          2
PF   1 0    120.    560.  11   1       9  10           2
PO          2
PF   1 0   1200.   8700.  34   1       1  12           2
PO          2
**
IFJ30000     -9.       20110301   2           J30000ES
HC  HCCP      ST       M   J S  D      0. 1103700 1737460     -9.
HCCP   2  I20000  I40000
ES SUBS1    208.    274.    274.    184.    275.    202.    137.    123.    123.    127.    180.    186.
ES BASE1    313.    317.    274.    287.    579.    418.    347.    194.    236.    245.    283.    311.
ES BASE2    313.    317.    274.    287.    579.    418.    347.    194.    236.    245.    283.    311.
ES BASE3    433.    497.    497.    635.    824.    733.    610.    381.    423.    433.    424.    450.
```

```
IFJ30000     -9.        20110301   2            J30000PF
HC  HCCP       ST       M   J S  D      0. 1103700 1737460    -9.
HCCP   2  I20000  I40000
ES PFES
PF   1 0   3000.      0.   4   2      12   2           2
PO            2
PF   1 0   3000.      0.   4   2       3   6           2
PO            2
PF   1 0   3000.      0.   4   2       7   8           2
PO            2
PF   1 0   3000.      0.   4   2       9  11           2
PO            2
PF   1 0   8000.      0.   2   1   17                  2
PO            2
**
IFJ10000     -9.        20110301   2            J10000ES
HC  HCCP       ST       M   J S  D      0. 1103700 1737460    -9.
HCCP   2  I20000  I40000
ES SUBS1    340.    375.    375.    299.    425.    534.    342.    190.    279.    190.    202.    301.
ES BASE1    487.    590.    525.    554.    966.    967.    570.    310.    405.    356.    480.    464.
ES BASE2    313.    317.    274.    287.    579.    418.    347.    194.    236.    245.    283.    311.
ES BASE3    828.    895.   1020.    977.   1316.   1440.    895.    516.    610.    741.    755.    737.
**
IFJ10000     -9.        20110301   2            J10000PF
HC  HCCP       ST       M   J S  D      0. 1103700 1737460    -9.
HCCP   2  I20000  I40000
ES PFES
PF   1 0   3000.      0.   4   2      12   2           2
PO            2
PF   1 0   3000.      0.   4   2       3   6           2
PO            2
PF   1 0   3000.      0.   4   2       7   8           2
PO            2
PF   1 0   3000.      0.   4   2       9  11           2
PO            2
PF   1 0   8000.      0.   2   1   17                  2
PO            2
PF   1 0  27000.      0.   2   1   23                  2
PO            2
**
IFK20000     -9.        20110301   2            K20000ES
HC  HCCP       ST       M   J S  D      0. 1103700 1737460    -9.
HCCP   2  I20000  I40000
ES SUBS1    315.    303.    204.    270.    304.    371.    212.    107.    188.    147.    173.    202.
ES BASE1    492.    597.    531.    561.    985.    984.    577.    314.    410.    360.    486.    470.
ES BASE2    492.    597.    531.    561.    985.    984.    577.    314.    410.    360.    486.    470.
ES BASE3    828.    895.   1020.    977.   1316.   1440.    895.    516.    610.    741.    755.    737.
**
IFK20000     -9.        20110301   2            K20000PF
HC  HCCP       ST       M   J S  D      0. 1103700 1737460    -9.
HCCP   2  I20000  I40000
ES PFES
PF   1 0   3000.      0.   4   2      12   2           2
PO            2
PF   1 0   3000.      0.   4   2       3   6           2
PO            2
PF   1 0   3000.      0.   4   2       7   8           2
PO            2
PF   1 0   3000.      0.   4   2       9  11           2
PO            2
PF   1 0   8000.      0.   2   1   17                  2
PO            2
PF   1 0  27000.      0.   2   1   23                  2
PO            2
```

Multiple Instream Flow Targets or Target Components at the Same Control Point

The sets of *IF*, *HC*, *ES*, *PF*, and *PO* records replicated in Table 5.12 are inserted in the DAT file employed in the daily *SIMD* simulations presented in Chapter 8. In the dataset of Table 5.12 and simulation studies of Chapter 8, the pulse flow components are modeled as separate *IF* record rights to facilitate recording pulse flow targets in the simulation results separately from the subsistence/base flow targets. This does not affect the total target quantities but rather allows the components of each target to be recorded separately in output files [2, 4].

Table 5.12 includes 28 *IF* record water rights since the pulse flow components of the 14 EFS are separated from the subsistence/base flow components. However, subsidence, base flows, and high flows pulses can be combined reducing the SB3 EFS to 14 *IF* record water rights simply by removing the *IF*, *HC*, and *ES* record for each of the high flow pulse components. For example, the first two water rights in Table 5.12 labeled with water right identifiers B20000ES and B20000PF are instream flow requirements at control point B20000. These two water rights are combined into a single water right in Table 5.13. With this format, all components of the SB3 EFS at a site can be modeled as a single *IF* record water right, with the only difference in simulation results being that combined rather that separate water right targets and target shortages are recorded in the *SIMD* output OUT and DSS files.

Table 5.13
Instream Flow Right that Models the SB3 EFS at Control Point B20000
with *ES* and *PF* Record Components Combined as a Single *IF* Record Right

```
IFB20000     -9.        20110301   2          B20000ES
HCB20000      RF  12  M   J S N      0.   4090.  16000.  57400.     -9.
ES SUBS1     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE1     2.0     2.0     2.0     2.0     2.0     2.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE2     2.0     2.0     2.0     2.0     2.0     2.0     1.0     1.0     1.0     1.0     1.0     1.0
ES BASE3     4.0     4.0     5.0     5.0     5.0     5.0     3.0     3.0     4.0     4.0     4.0     4.0
ES BASE4     7.0     7.0    12.0    12.0    12.0    12.0     8.0     8.0    10.0    10.0     7.0     7.0
**
PF   1 0     18.    120.  13   2      11   2           2
PO            2
PF   1 0    600.   2500.   9   2       3   6           2
PO            2
PF   1 0    100.    350.   6   2       7   8           2
PO            2
PF   1 0    100.    400.   6   2       9  10           2
PO            2
PF   1 0     42.    300.  15   1      11   2           2
PO            2
PF   1 0   1800.   7900.  11   1       3   6           2
PO            2
PF   1 0    330.   1400.   9   1       7   8           2
PO            2
PF   1 0    430.   1800.   9   1       9  10           2
PO            2
PF   1 0   3000.  13600.  17   1       1  12           2
PO            2
```

The table on page 47 of the January 2021 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 5.14 below. The second column of Table 5.14 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 5.14. The DSS pathname part C labels in the third column are adopted in the following discussion for referring to the quantities listed in Table 5.14.

Table 5.14
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. An 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.

Any number of instream flow *IF* record water rights can be located at the same WAM control point regardless of the various records used with the *IF* records for computing instream flow targets. Various options can be employed to combine targets computed for multiple *IF* records. 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 5.15.

Table 5.15
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. Pulse flow *PF* and subsistence/base flow *ES* records can be defined separately or alternatively combined as a single *IF* record instream flow water right at a control point as discussed in the preceding paragraphs. 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 as indicated in Table 5.15. The options for combining consecutive *PF* record targets for a single *IF* record right are also listed in Table 5.15. Multiple instream flow targets at the same control point are combined in the Colorado WAM always using the option of adopting the largest target.

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 for a monthly WAM is introduced in the last section of Chapter 6 of the *Daily Manual* [4]. The methodology is illustrated in an example in *Daily Manual Chapter 8* and has been employed with the Brazos, Trinity, and Neches daily WAMs [8, 9, 10] The methodology is applied with the Colorado WAM as described in Chapter 8 of this report.

Daily instream flow targets in acre-feet/day for the SB3 EFS computed in the daily *SIMD* simulation are summed by *SIMD* to monthly totals in acre-feet/month that are included in the *SIMD* simulation results. These time series of monthly targets are converted to target series *TS* records within *HEC-DSSVue* and incorporated in the input DSS file read in a monthly *SIM* simulation.

The target series *TS* records of monthly instream flow targets in acre-feet/month stored in the DSS file have the pathname identifiers listed in Table 5.16. The target series *TS* records in the DSS file are referenced by *TS* records in the DAT file which are replicated in Table 5.17.

Table 5.16
Pathnames for *TS* Records for the SB3 EFS in the Hydrology Input DSS File

Part A	Part B	Part C	Part D	Part E
C3	B20000	TS	01Jan1940-31Dec2016	1MON
C3	C30000	TS	01Jan1940-31Dec2016	1MON
C3	C10000	TS	01Jan1940-31Dec2016	1MON
C3	D40000	TS	01Jan1940-31Dec2016	1MON
C3	C30000	TS	01Jan1940-31Dec2016	1MON
C3	E10000	TS	01Jan1940-31Dec2016	1MON
C3	F20000	TS	01Jan1940-31Dec2016	1MON
C3	F10000	TS	01Jan1940-31Dec2016	1MON
C3	G10000	TS	01Jan1940-31Dec2016	1MON
C3	H10000	TS	01Jan1940-31Dec2016	1MON
C3	J50000	TS	01Jan1940-31Dec2016	1MON
C3	J30000	TS	01Jan1940-31Dec2016	1MON
C3	J10000	TS	01Jan1940-31Dec2016	1MON
C3	K20000	TS	01Jan1940-31Dec2016	1MON

Table 5.17
Instream Flow Rights that Model the SB3 EFS in the DAT File of the Monthly WAM

```
IFB20000                20110301   2            B20000ES
TS       DSS
IFC30000                20110301   2            C30000ES
TS       DSS
IFC10000                20110301   2            C10000ES
TS       DSS
IFD40000                20110301   2            D40000ES
TS       DSS
IFD30000                20110301   2            D30000ES
TS       DSS
IFE10000                20110301   2            E10000ES
TS       DSS
IFF20000                20110301   2            F20000ES
TS       DSS
IFF10000                20110301   2            F10000ES
TS       DSS
IFG10000                20110301   2            G10000ES
TS       DSS
IFH10000                20110301   2            H10000ES
TS       DSS
IFJ50000                20110301   2            J50000ES
TS       DSS
IFJ30000                20110301   2            J30000ES
TS       DSS
IFJ10000                20110301   2            J10000ES
TS       DSS
IFK20000                20110301   2            K20000ES
TS       DSS
```

A daily *SIMD* simulation is performed with the set of *IF*, *ES*, *PF*, and *PO* records in Table 5.12 inserted in the DAT file to control computation of IFT and TIF (Table 5.14) daily instream flow targets for the SB3 EFS at the 14 USGS gaging stations (WAM control points). The daily TIF instream flow targets in acre-feet/day are summed to monthly quantities in acre-feet/month, which are included in the simulation results DSS file. The DSS records of monthly targets are copied from the daily *SIMD* simulation results DSS output file to the *SIM/SIM* hydrology input DSS file and the pathnames are revised using *HEC-DSSVue*.

The DSS file pathnames for the target series *TS* records are listed in Table 5.16. The *TS* records in the monthly *SIM* DAT file replicated in Table 5.17 reference the DSS file target series employed by the *IF* record water rights. IFM(if,2) option 2 in *IF* record field 7 activates the option to combine multiple *IF* record instream flow targets at the same control point by selecting the largest. With only one *IF* record at a control point, the IFM(if,2) option is not relevant. The results for daily and monthly simulations presented in Chapter 8 include daily and aggregated monthly instream flow targets for the SB3 EFS.

Parameter DSSTS on the *JO* record activates reading of *TS* records from the DSS input file. Control point identifiers can be included on the *TS* records. However, blank control point fields on the *TS* records of Table 5.17 default to assigning the control points from the *IF* records.

CHAPTER 6
HISTORICAL RIVER SYSTEM HYDROLOGY

Past observations of hydrologic variables reflecting river basin hydrology are presented in Chapter 6 prior to discussing WAM simulation studies in Chapters 7 and 8. Selected historical time series of monthly precipitation and reservoir surface evaporation depths, daily observed and naturalized stream flows, and actual historical reservoir storage contents are presented to provide general insight regarding the hydrologic characteristics of the Colorado River Basin. These data demonstrate continuous, annual, and seasonal variability and show the timing and hydrologic severity of past droughts and floods. Precipitation rates appear to have been relatively stationary over the past many decades, but river flow characteristics have changed significantly with population growth and accompanying water resources development and use. Actual observed reservoir storage contents and river flow rates reflect combinations of natural hydrology and water resources development and management.

Monthly Precipitation and Reservoir Surface Evaporation Depths

The Texas Water Development Board (TWDB) maintains datasets of monthly precipitation depths and reservoir surface evaporation depths in inches for each of 92 one degree latitude by one degree longitude quadrangles that cover the state of Texas. This database is accessible through the TWDB website. https://waterdatafortexas.org/lake-evaporation-rainfall

The annually updated monthly precipitation rates begin in January 1940. The reservoir evaporation rates date back to January 1954. The plots presented in this chapter extend through December 2020. The quadrangles that encompass the Colorado River Basin are delineated in Figure 2.5 of Chapter 2. The three-digit identifiers assigned by the TWDB to label the quadrangles are included in Figure 2.5. The estimated spatially averaged precipitation and evaporation rates for the entire Colorado River Basin plotted in Figures 6.1 through 6.6 were computed as the average of the depths averaged over each of the following 12 quadrangles: 506, 507, 508, 606, 607, 608, 609, 707, 708, 709, 710, and 811. This spatial averaging approach is approximate but reasonable.

Monthly precipitation and evaporation depths in inches for the Colorado River Basin are plotted in Figures 6.1 and 6.3, respectively. Annual totals of the monthly depths are plotted in Figures 6.2 and 6.4. Mean annual 1940-2020 precipitation and 1954-2020 evaporation depths in inches/year for each of the quadrangles used in the basin-wide spatial averaging are as follows: 506 (precip 20.6 inches, evap 70.6 inches); 507 (22.7, 65.9); 508 (26.4, 63.2); 606 (18.0, 69.0); 607 (21.4, 66.1); 608 (24.7, 66.1), 609 (29.0, 56.5); 707 (22.5, 62.1); 708 (25.4, 57.3); 709 (30.4, 53.9); 710 (33.2, 52.1); and quadrangle 811 (precipitation 41.7 inches, evaporation 49.9 inches).

Annual precipitation during 1940-2020 for the Colorado River Basin varies from a minimum of 11.5 inches during 2011 to a maximum of 40.4 inches in 2004, with a 1940-2020 mean of 26.3 inches. Annual reservoir evaporation during 1954-2020 varies from 55.6 inches during 2007 to 77.9 inches in 2011, with a 1940-2020 mean of 61.1 inches.

Hydrologic conditions since the end of the WAM hydrologic period-of-analysis of January 1940 through December 2016 is of interest in regard to needs for an extension (update) past 2016. Annual basin-wide precipitation depths during 2017, 2018, 2019, and 2020 are 26.8, 33.4, 22.9, and 24.5 inches with a 2017-2020 mean of 26.9 inches. The 2017-2020 mean annual precipitation of 26.9 inches is close to the 1940-2020 mean of 26.3 inches. The 1954-2020 mean annual reservoir evaporation is 64.4 inches which is higher than the 1954-2020 mean of 61.1 inches.

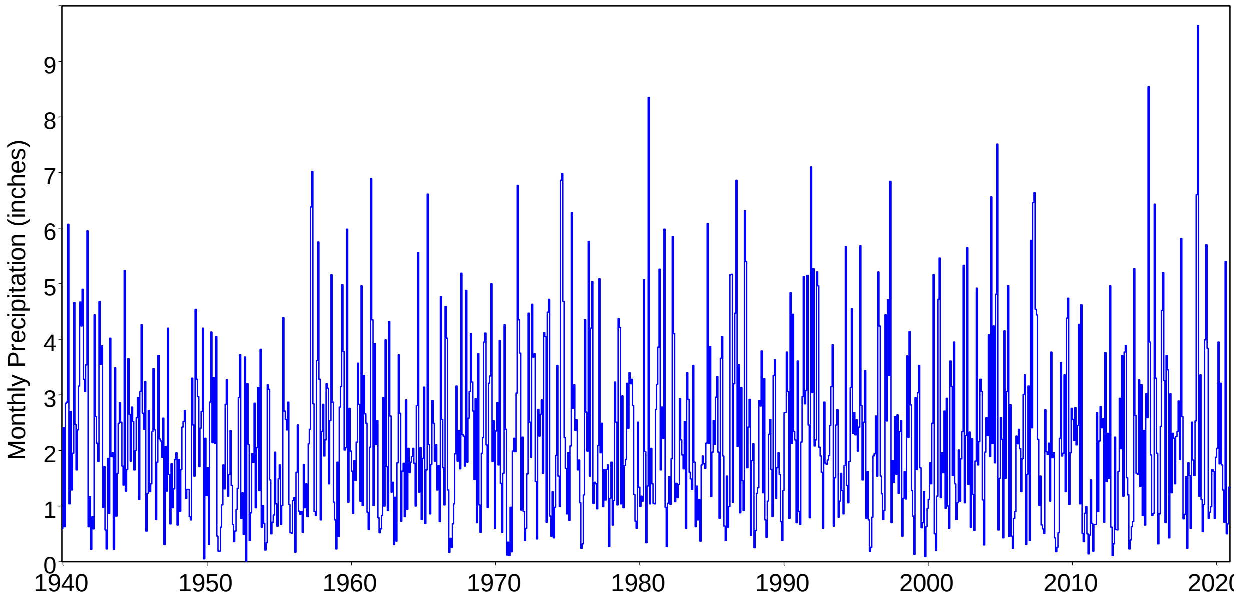

Figure 6.1 Monthly Precipitation Depths for the Colorado River Basin during 1940-2020

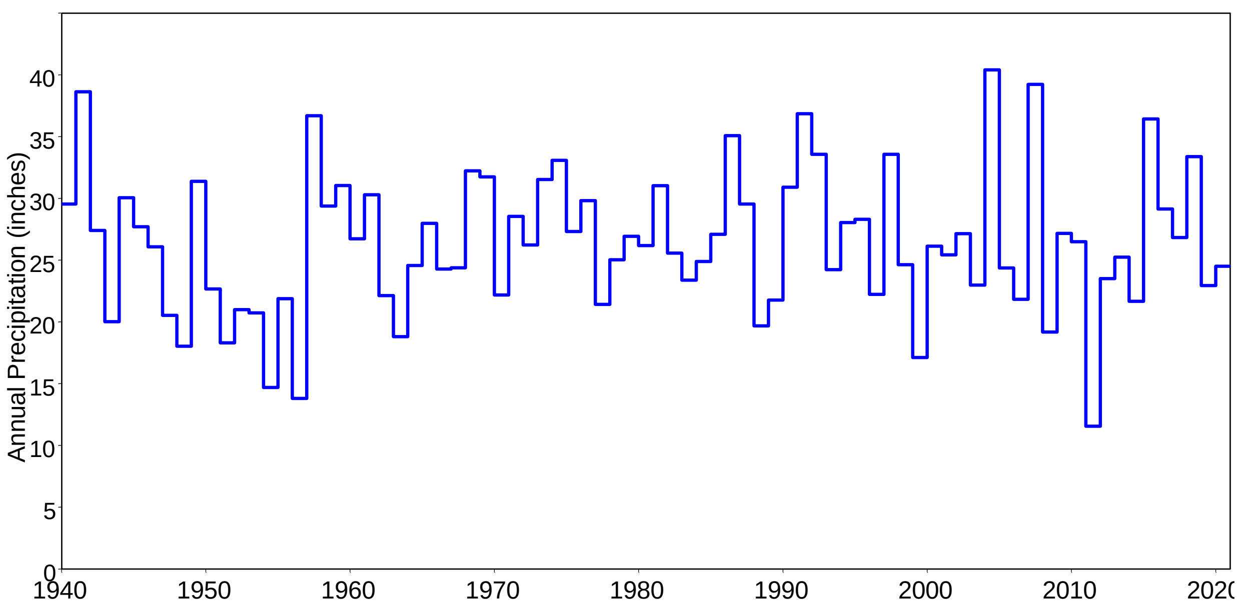

Figure 6.2 Annual Precipitation Depths for the Colorado River Basin during 1940-2020

Monthly and annual precipitation appears to be essentially stationary. Long-term permanent changes in precipitation characteristics, if they have actually occurred, are hidden by the great monthly and annual variability. Reservoir evaporation rates appear to be perhaps nearly stationary though possibly increasing over the past one or two decades. These observations are consistent with similar statewide analyses [5, 24].

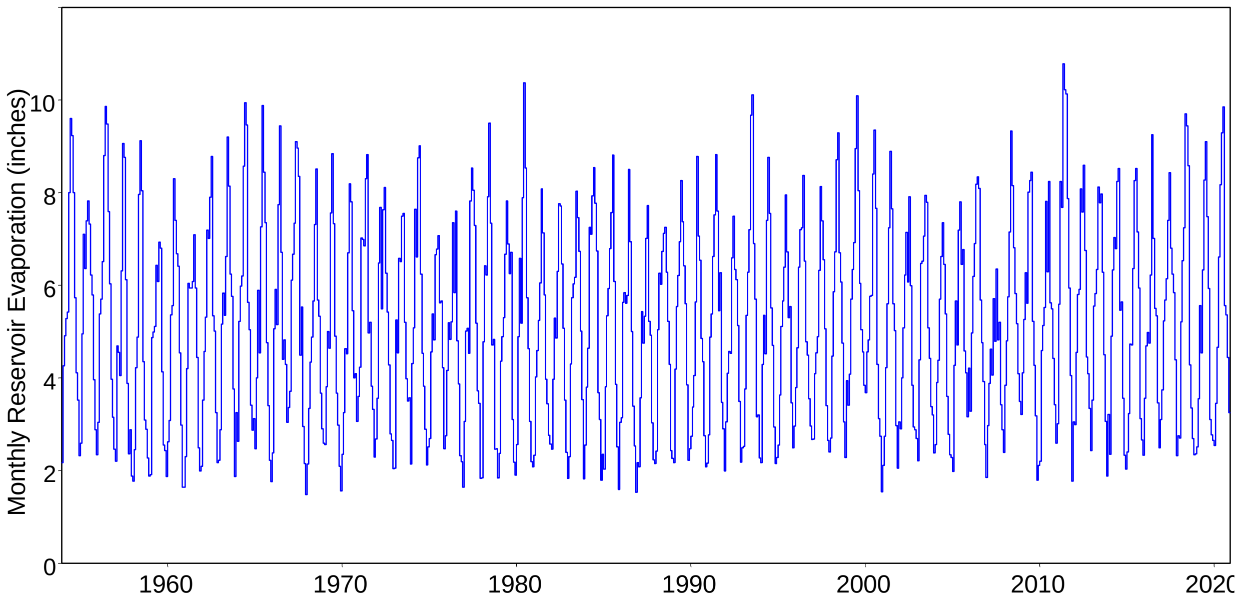

Figure 6.3 Monthly Evaporation Depths for the Colorado River Basin during 1940-2020

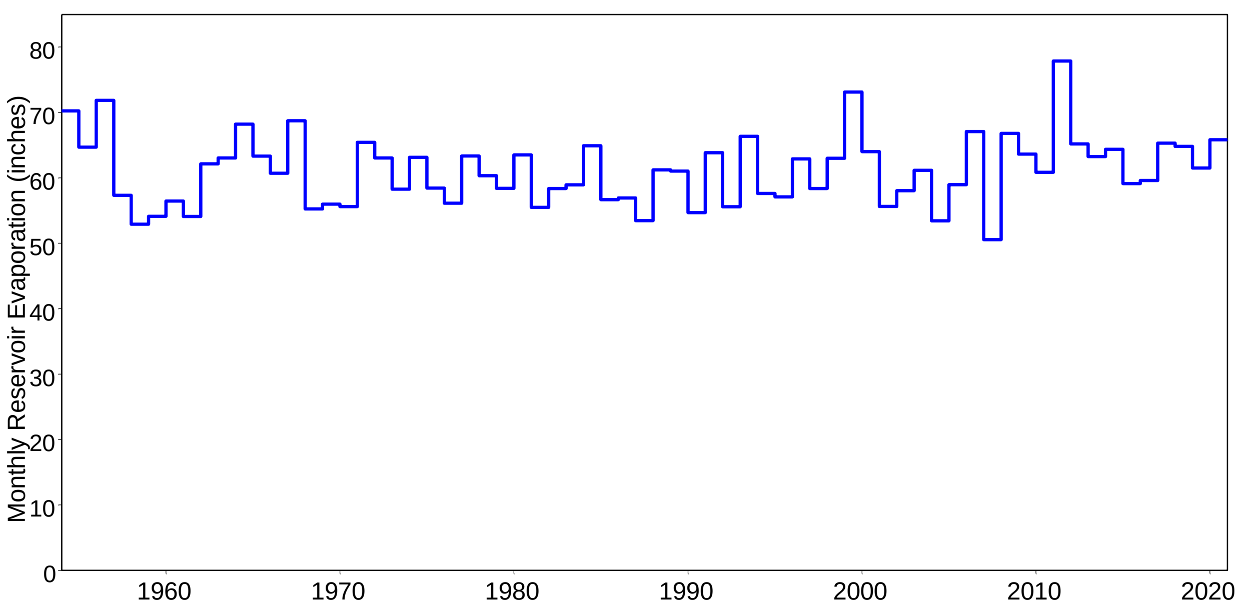

Figure 6.4 Annual Evaporation Depths for the Colorado River Basin during 1940-2020

Observed Flows at USGS Gages on the Colorado River

Daily mean stream flows in cubic feet per second (cfs) are downloaded from the National Water Information System (NWIS) website maintained by the U.S. Geological Survey (USGS).

https://waterdata.usgs.gov/nwis

Data are downloaded directly from the NWIS website to a DSS file using the import feature of *HEC-DSSVue Version 3*. The NWIS import feature no longer functions in *Version 2* of *HEC-DSSVue* due to changes made by the USGS to the NWIS website. However, the data import capability has been updated by the USACE HEC to work fine in Version 3 of *HEC-DSSVue*.

Daily means of observed flow rates in cubic feet per second (cfs) at the three gage sites listed in Tables 6.1 and 6.2 are plotted as Figures 6.5, 6.6, and 6.7. Mean annual flows in cfs at the three sites are compared in Figure 6.8. The three sites are included in the 45 primary control points listed in Table 2.1 of Chapter 2 with locations shown in Figures 2.1 and 2.2.

Table 6.1
Selected WAM Control Points at USGS Gage Sites on the Colorado River

Control Point	USGS Gage	Location	Watershed Area	Gage Period of Record
			(square miles)	
F10000	08147000	Colorado River near San Saba	19,830	1915-present
I10000	08158000	Colorado River at Austin	27,611	1898-present
K20000	08162000	Colorado River at Wharton	30,601	1938-present

Table 6.2
Means of Observed Flows at Selected USGS Gages on the Colorado River

Control	USGS		Mean Flow (cfs)		
Point	Gage	Location	Record	1940-2016	2017-2021
F10000	08147000	Colorado River near San Saba	956	778	382
I10000	08158000	Colorado River at Austin	2.067	1,769	1,129
K20000	08162000	Colorado River at Wharton	2,636	2,670	2,386

The USGS gage periods of record at WAM control points F10000, I10000, and K20000 extend from November 1, 1915, January 1, 1900, and October 1, 1938, respectively, to the present. The hydrographs plotted as Figures 6.5, 6.6, and 6.7 extend from the beginning of the period-of-record to January 4, 2022. Means are tabulated in the last three columns of Table 6.2 for the following alternative time periods: gage period-of-record; January 1940 through December 2016; and January 2017 through December 2021.

Initial impoundment of Lake Travis began in 1940. The effects of Lake Travis on the daily flows of the Colorado River at Austin are evident in Figure 6.6. Other major reservoirs with initial impoundment dates shown in Table 2.3 of Chapter 2 have also significantly affected river flows at the three gage sites. The annual mean flow rates plotted in Figure 6.8 exhibit much lesser degrees of non-stationarity than the daily mean flow rates plotted in Figures 6.5 and 6.6. Reservoir flood control operations greatly attenuate daily (and instantaneous) flow rates during and shortly after flood events with only minimal effects on annual mean flow rates. The effects of flood control operations also diminish with distance downstream of the dams.

Stream flow is extremely variable. Variability patterns and characteristics vary greatly between daily, monthly, and annual flows. The effects of water resources development and use on stream flow stationarity (or lack thereof) are also reflected differently in daily versus monthly versus annual flows.

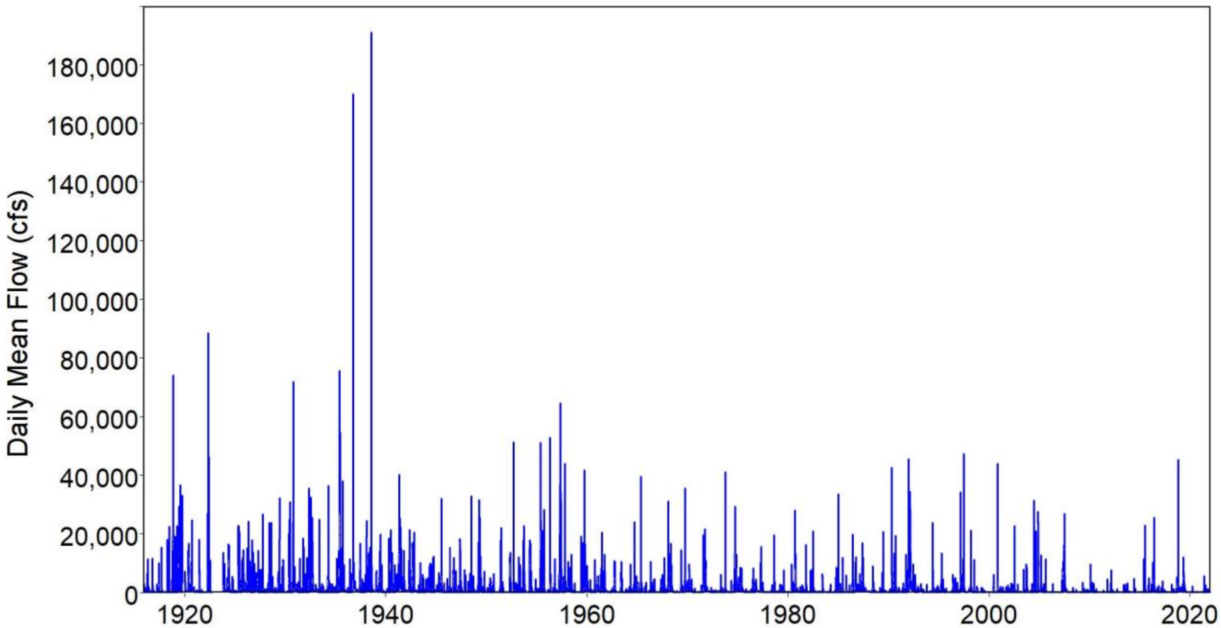

Figure 6.5 Observed Daily Flows of the Colorado River near San Saba (Control Point F10000)

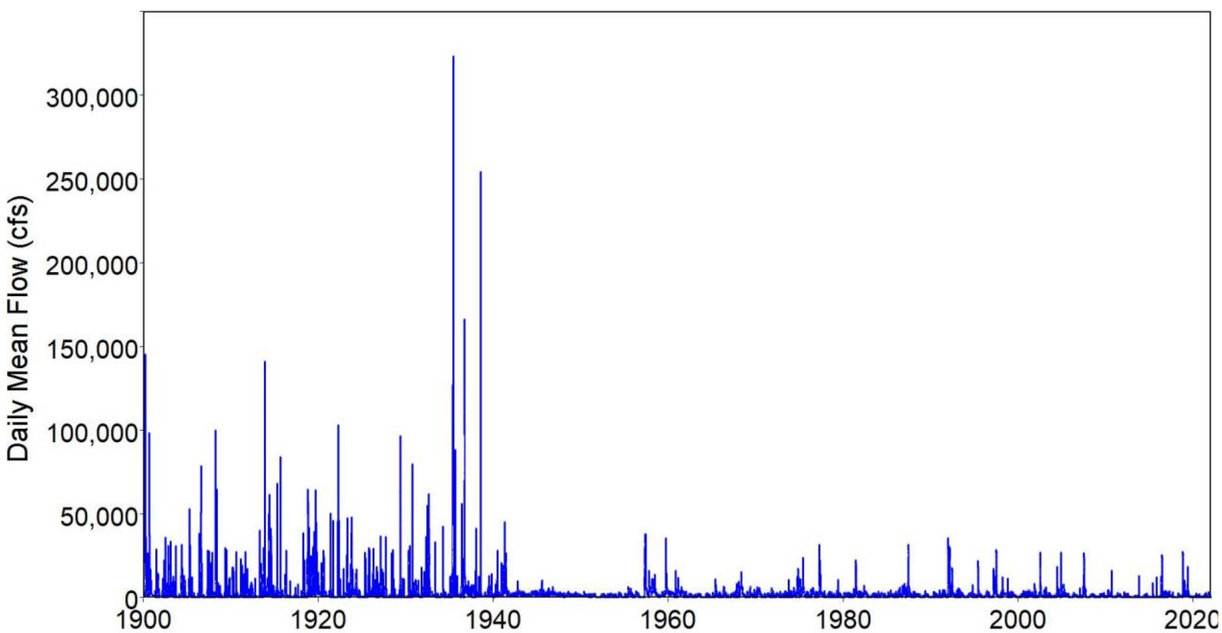

Figure 6.6 Observed Daily Flows of the Colorado River at Austin (Control Point I10000)

Naturalized Flows at Three Control Points on the Colorado River

Procedures for developing daily naturalized flows at the 45 primary control points are explained in Chapter 3. The daily flow hydrographs stored as *DF* records in the *SIMD* hydrology DSS input file are identically the same in all of the Colorado WAM simulations discussed in Chapters 7 and 8. Hydrologic period-of-analysis (1940-2016) naturalized daily flows at the three control points listed in Table 6.1 are plotted in Figures 6.9, 6.10, and 6.11.

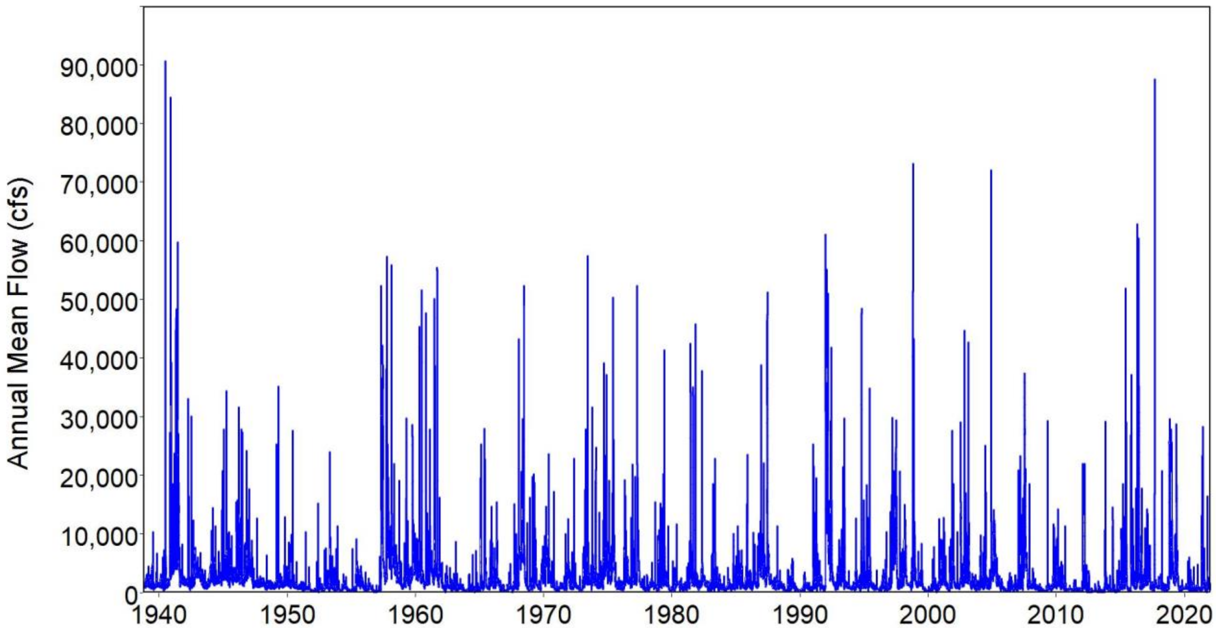

Figure 6.7 Observed Daily Flows of the Colorado River at Wharton (Control Point K20000)

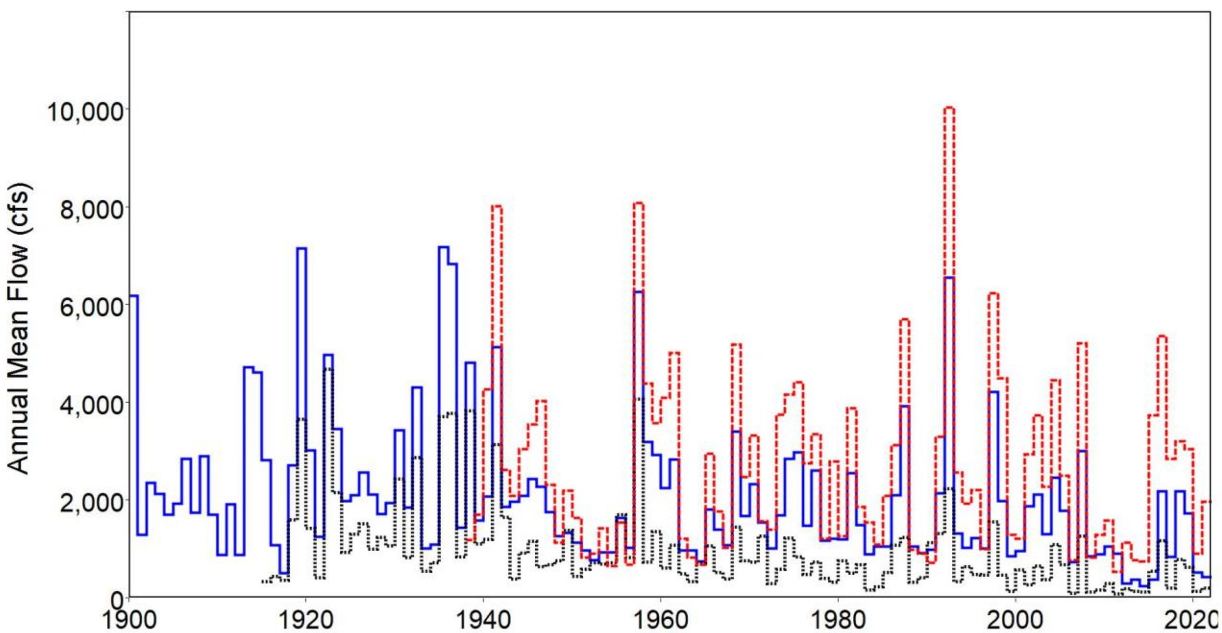

Figure 6.8 Annual Means of Observed Flows at Control Points F10000 (green dotted line), I10000 (blue solid line), and K20000 (red dashed)

Statistical frequency metrics developed with *HEC-DSSVue* for the 28,125 days of daily and 924 months of monthly naturalized flows spanning the 1940-2016 WAM hydrologic period-of-analysis are tabulated in Table 6.3. The naturalized flow are expressed as daily mean flow rates in cfs. Table 6.3 includes the mean and standard deviation and naturalized flow quantities that are exceeded specified percentages of the 28,125 days or 924 months of the 1940-2016 hydrologic period-of-analysis. Exceedance frequency is defined by the Weibull formula (Equation 6.1) where m is the relative rank and N is the sample size of 28,125 days or 924 months.

$$\text{Exceedance Frequency} = \frac{m}{N+1}(100\%) \qquad (6.1)$$

The statistics are computed with *HEC-DSSVue* using the option path: *Tools* - *Math Functions* - *Statistics* - *Basic* and *Duration Analysis*.

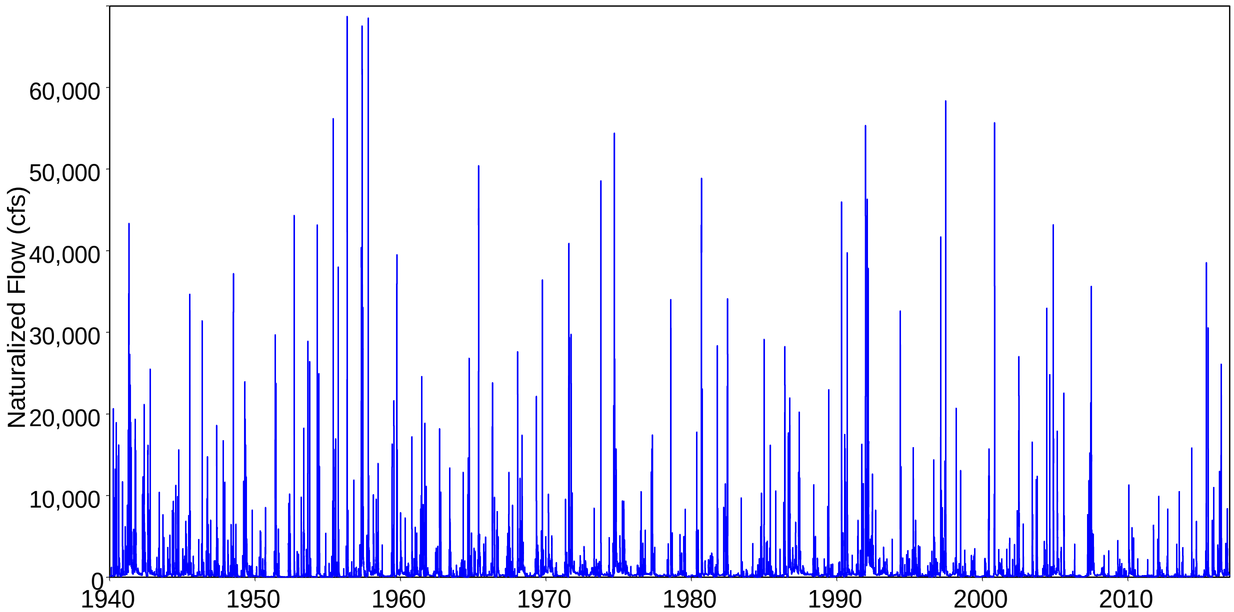

Figure 6.9 Daily Naturalized Flows of Colorado River near San Saba (F10000)

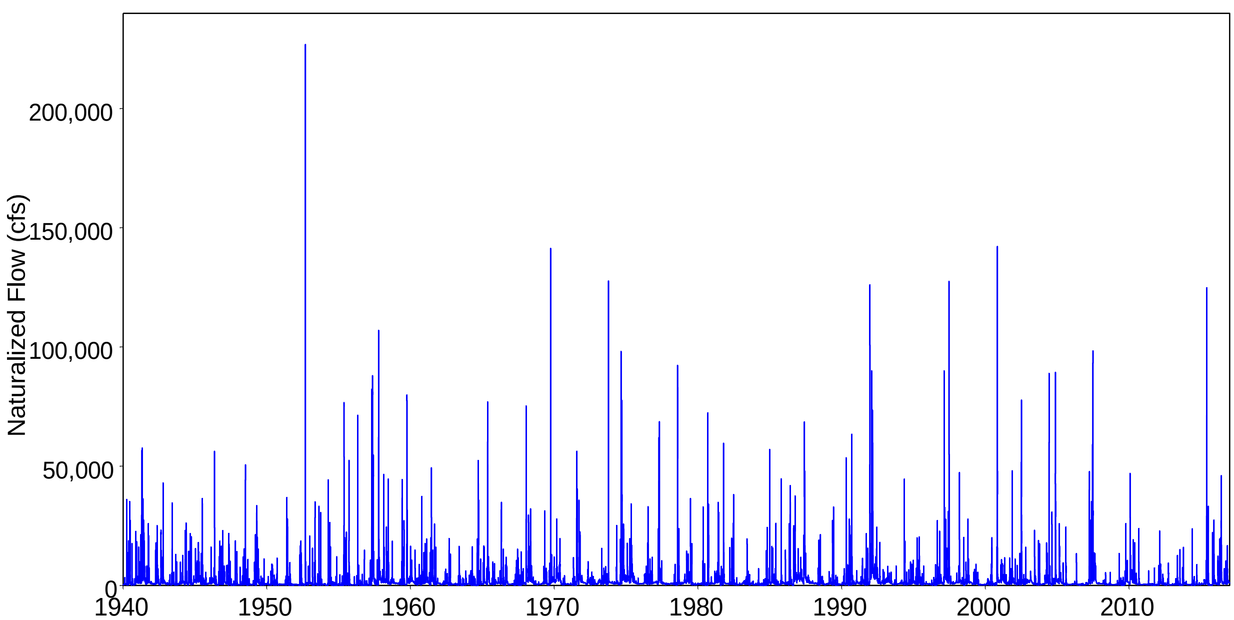

Figure 6.10 Daily Naturalized Flows of Colorado River at Austin (I10000)

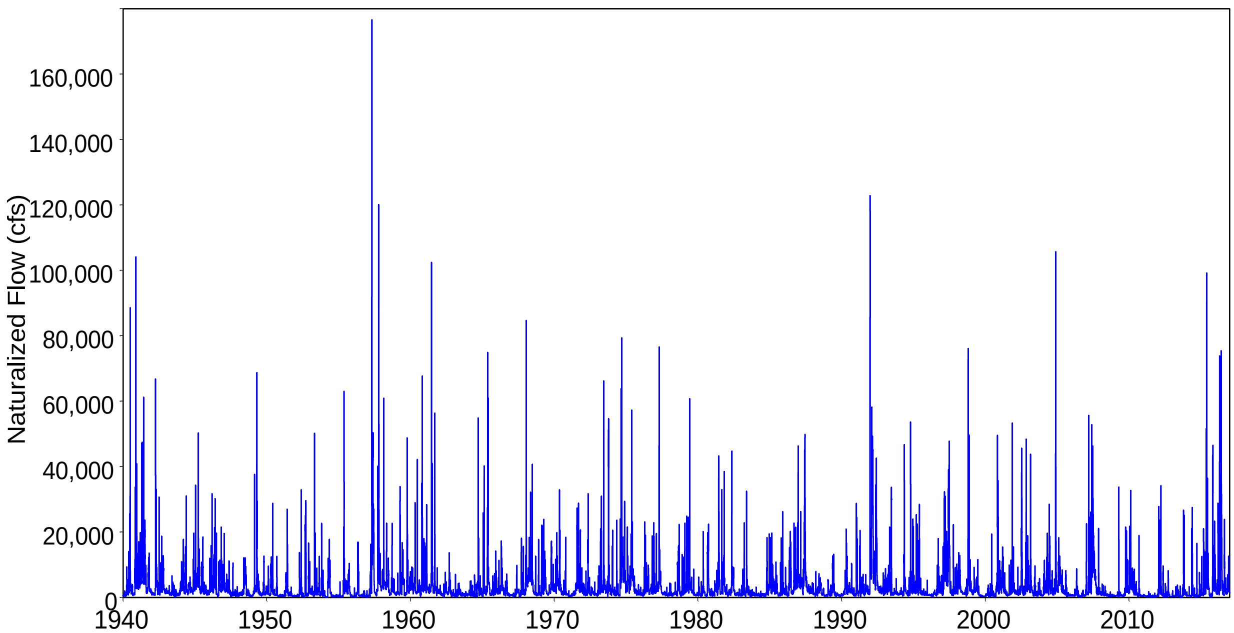

Figure 6.11 Daily Naturalized Flows of Colorado River at Wharton (K20000)

Table 6.3
Frequency Metrics for Monthly and Daily Naturalized Flows in cfs

Control Point	F10000		I10000		K20000	
	Daily	Monthly	Daily	Monthly	Daily	Monthly
Mean (cfs)	996.5	996.5	2,197	2,197	3,369	3,369
Stand Dev	3,396	1,826	6,356	3,186	6,669	4,277
Frequency	Flows (cfs) for Specified Exceedance Frequencies (Equation 6.1)					
0.1%	45,061	-	84,088	-	77,918	-
0.2%	37,315	15,466	68,585	27,627	61,763	33,598
0.5%	24,579	11,508	43,863	20,477	45,070	27,587
1%	16,162	9,136	28,350	17,257	34,166	23,446
2%	9,110	6,708	17,322	12,818	22,177	17,740
5%	3,581	4,044	7,545	8,131	12,028	11,521
10%	1,709	2,659	3,927	5,101	6,906	7,920
15%	1,071	1,734	2,685	3,622	4,907	5,858
20%	768.6	1,199	2,027	2,881	3,922	4,790
30%	473.7	764.4	1,337	1,954	2,669	3,422
40%	325.4	522.1	1,001	1,485	1,963	2,505
50%	246.9	359.1	774.4	1,149	1,501	1,845
60%	190.0	273.3	617.7	850.1	1,166	1,338
70%	147.0	205.8	481.1	699.8	914.9	1048
80%	109.2	148.7	357.2	544.6	690.7	825.7
85%	89.9	127.8	300.5	465.3	585.7	689.4
90%	70.0	103.2	231.5	382.6	483.1	569.7
95%	45.6	68.8	146.9	301.6	367.8	434.4
98%	24.4	45.6	76.6	223.5	257.9	319.0
99%	16.0	29.7	39.1	189.3	202.5	255.1
99.5%	5.0	25.7	15.4	149.5	156.1	204.0
99.8%	0.4	20.5	1.2	106.8	97.5	120.2

Historical Observed Reservoir Storage Contents

The major reservoirs in the Colorado WAM with authorized storage capacities exceeding 5,000 acre-feet are listed in Table 2.3 of Chapter 2. Historical storage contents in acre-feet of the five largest reservoirs are plotted in Figures 6.12 (Ivie), 6.23 (Spence), 6.14 (Thomas), 6.15 (Buchanan), and 6.16 (Travis). Similar plots of storage contents of the four reservoirs with flood control pools are presented as Figures 4.1 (Travis), 4.2 (Twin Buttes), 4.3 (Fischer), and 4.4 (Hords Creek) of Chapter 4. The five largest reservoirs of Figures 6.12-6.16 account for 64.8 percent of the total authorized storage capacity of the 484 reservoirs in the Colorado WAM. The historical storage contents plots of Figures 4.1-4.4 and 6.12-6.16 were obtained from the following Texas Water Development Board (TWDB) website.

https://www.twdb.texas.gov/surfacewater/rivers/index.asp

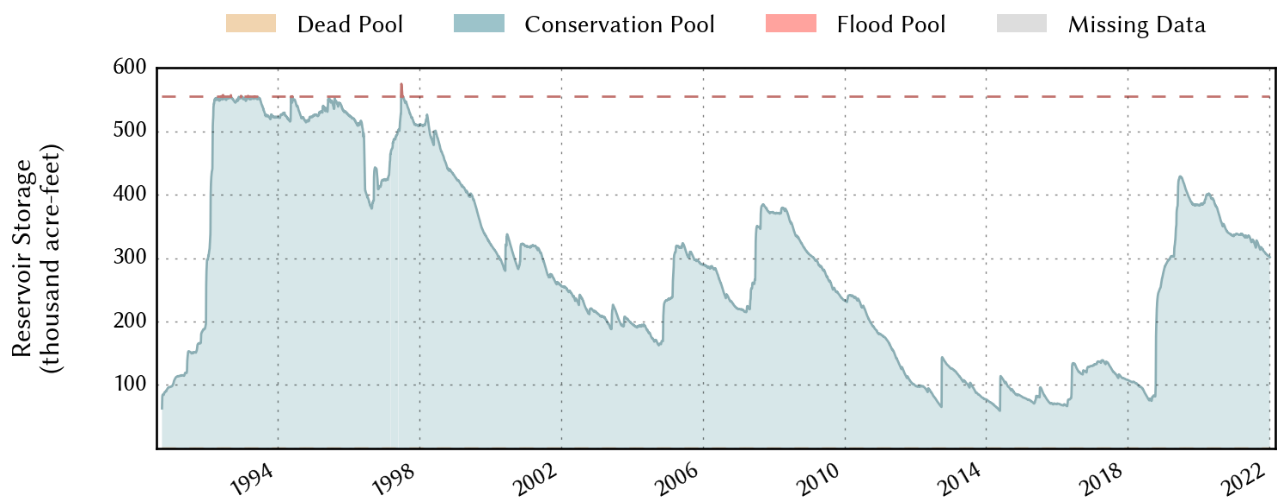

Figure 6.12 Historical Storage Contents of O. H. Ivie Reservoir (TWDB)

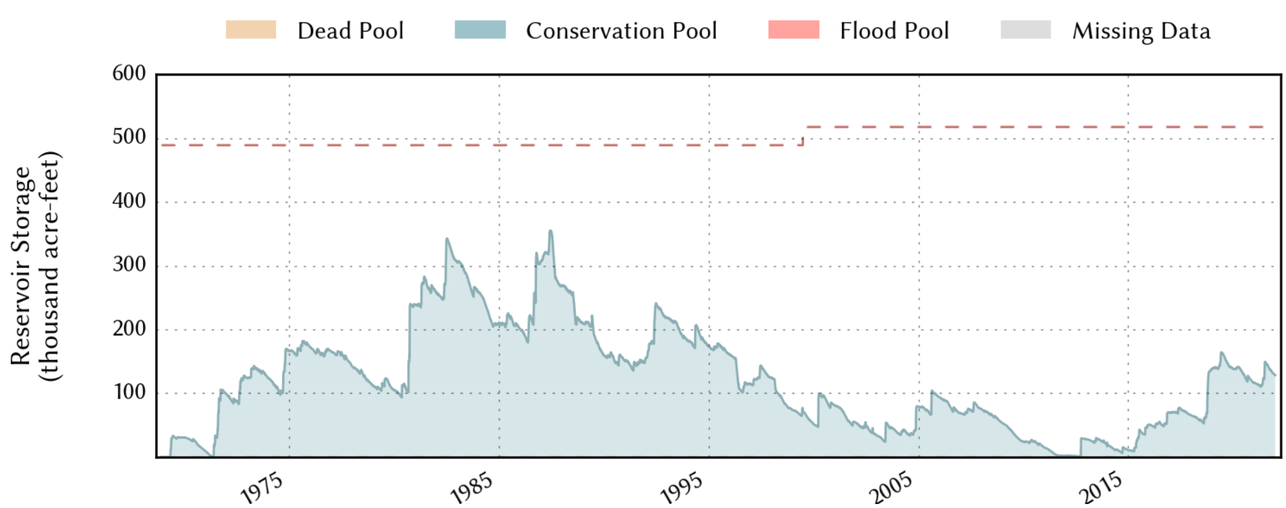

Figure 6.13 Historical Storage Contents of E. V. Spence Reservoir (TWDB)

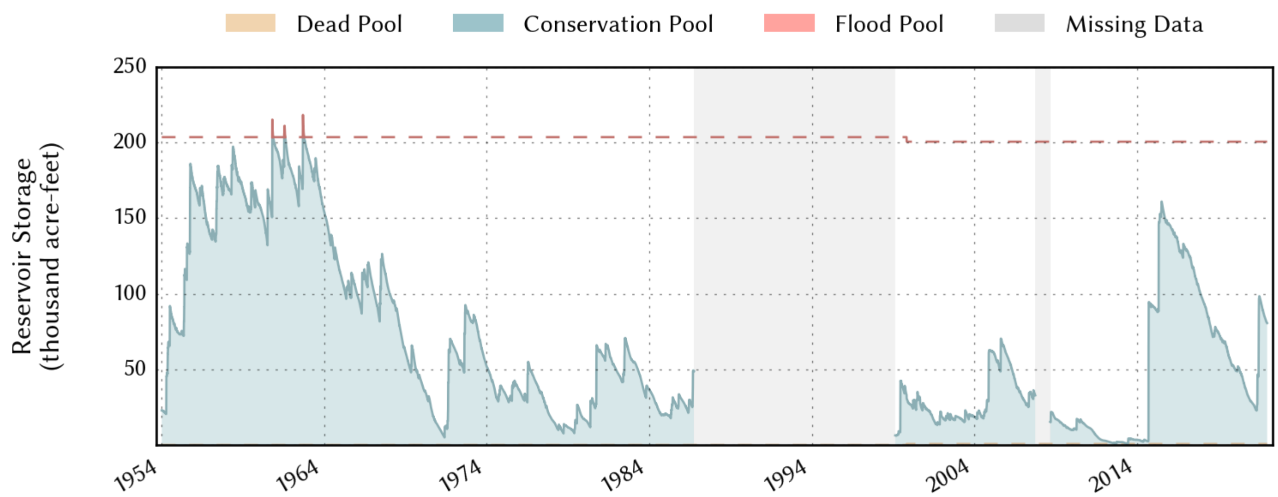

Figure 6.14 Historical Storage Contents of J. B. Thomas Reservoir (TWDB)

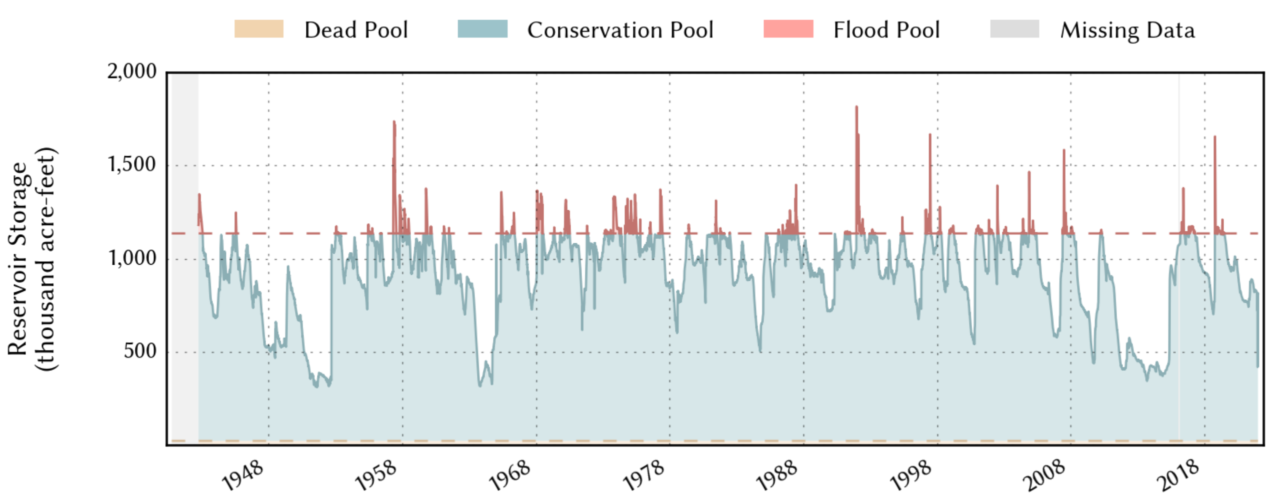

Figure 6.15 Historical Storage Contents of Lake Buchanan (TWDB)

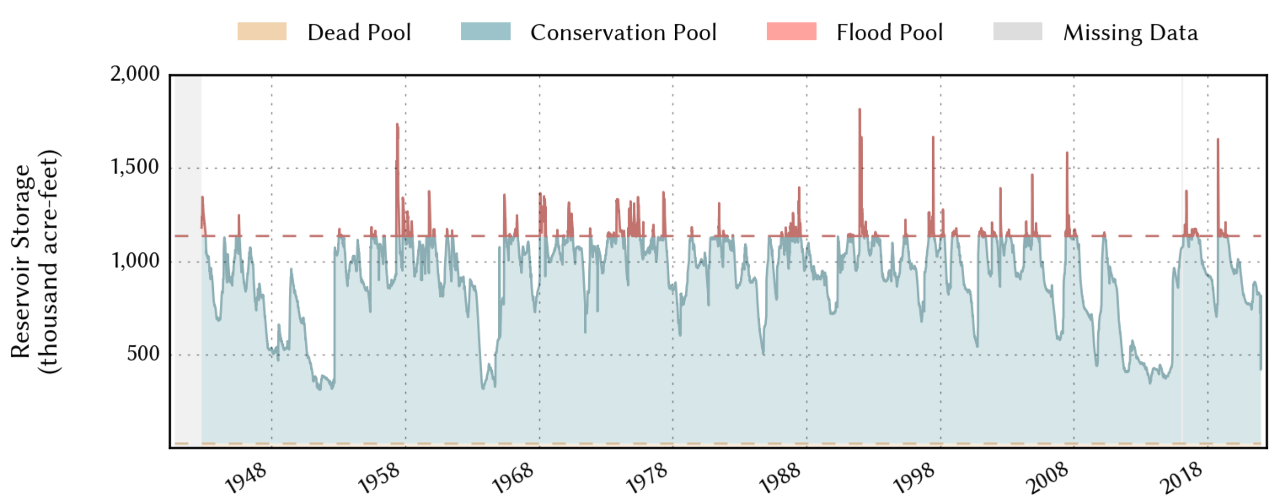

Figure 6.16 Historical Storage Contents of Lake Travis (TWDB)

CHAPTER 7
DAILY SIMULATION STUDY

The effects on simulation results of different modeling options and components of the daily WAM input dataset are explored in Chapter 7. The final version of the daily WAM adopted in Chapter 7 is employed to model SB3 EFS in Chapter 8. The alternative simulations in Chapters 7 and 8 progress through the model building process described in Chapters 2 through 5.

1. The conversion of the monthly WAM to daily including disaggregation of monthly naturalized flows to daily explained in Chapter 3 is further investigated in Chapter 7.
2. Routing and forecasting are explained in Chapter 3 and applied in Chapter 7.
3. Flood control operations of the four reservoirs with flood control pools are explained in Chapter 4 and added to the daily WAM in Chapter 7.
4. Addition of the Senate Bill 3 (SB3) environmental flow standards (EFS) described in Chapter 5 to the daily WAM adopted in Chapter 7 is covered in Chapter 8.
5. Computation of monthly instream flow targets for the SB3 EFS by summing daily targets within the daily *SIMD* simulation is also covered in Chapter 8.

Daily *SIMD* simulations are performed with and without routing, forecasting, flood control operations, SB3 EFS, and other modeling features. Comparative analyses in Chapter 7 focus on reservoir storage and naturalized, regulated, and unappropriated stream flows. Chapter 8 presents SB3 EFS flow targets and shortages. Time series plots and frequency analysis statistics are developed from *SIMD* and *SIM* simulation results using the program *HEC-DSSVue*.

Organization of the Simulation Study

The objectives of the WRAP/WAM simulation study are to:

- test, explore, refine, and demonstrate daily modeling capabilities
- analyze sensitivities of simulation results to various aspects of the modeling system
- expand the experience base for selecting between modeling options
- expand capabilities for incorporating SB3 EFS in water availability modeling
- develop an expanded understanding of water availability in the Colorado River Basin

The daily Colorado WAM data files are described on pages 7 and 8 of Chapter 1. Various components of the WAM dataset are explained in Chapters 2 through 5. Many simulations with various alterations to the monthly *SIM* and daily *SIMD* input datasets were performed. Results from selected simulations are presented in Chapters 7 and 8 to illustrate key concepts.

Alternative Simulations

Results from variations of the full authorization scenario Colorado WAM defined in Tables 7.1 and 7.2 and compared later in Tables 7.4-7.9 and 7.11-7.23 are used to investigate the effects of various modeling options on simulation results. These variations of the Colorado WAM are valid and appropriate models reflecting premises, approximations, and inaccuracies but generating meaningful information. Assessment of the relative accuracy of alternative variations is difficult and largely judgmental. The final version of the daily Colorado WAM labeled C3D is employed in modeling and analysis of the SB3 EFS described in Chapter 5 as reported in Chapter 8.

Table 7.1
WAM Variations with Simulation Results Compared in Tables 7.4-7.9 and 7.11-7.13

MC - The WAM version labeled MC is the full authorization scenario monthly Colorado WAM last updated by the TCEQ in February 2020 with modifications described in Chapter 2 that do not affect simulation results. This monthly WAM was converted to daily in Chapter 3.

M1 - The only difference between variations M1 and MC of the *SIM* input dataset that affects simulation results is the switch from negative incremental flow adjustment ADJINC option 5 in MC to option 4 in M1. A monthly simulation generating M1 results can be performed by executing the daily D1 input dataset with *SIM*. *SIM* ignores daily-only input records.

D1 - The version labeled D1 reflects the daily WAM dataset described in Chapter 3 with monthly-to-daily naturalized flow disaggregation implemented. Version D1 does not include routing, forecasting, flood control, and SB3 EFS.

D2 - WAM variation D2 is identical to variation D1 except the beginning-of-simulation storage contents for each reservoir is set equal to its end-of-simulation storage contents.

D3 - The variation labeled D3 is identical to WAM version D1 except the DIF file *RT* record routing parameters for the 30 control points in Table 3.6 are activated.

D4 - WAM variation D4 is identical to D3 except only the *RT* record routing parameters for the six control points located on the Colorado River below Lake Travis are employed.

D5 The *SIMD* input dataset labeled D5 was created by adding a 3-day forecast to dataset D3.

D6 The *SIMD* input dataset labeled D6 was created by adding a 7-day forecast to dataset D3.

D7 - WAM version D7 is identical to D3 except flood control operations are added for the four reservoirs with designated flood control pools (Tables 4.4, 4.5, 4.6, and 4.7).

C3D - The final Colorado daily WAM labeled C3D is identical to version D7 except SB3 environmental flow standards described in Chapter 5 are added as explained in Chapter 8.

Table 7.2
Features of Alternative Monthly *SIM* and Daily *SIMD* Datasets

Dataset Variation	Time Interval	ADJINC Option	Begin Storage	Lag Routing	Flow Forecast	Flood Control	SB3 EFS	Run Time (minutes)
MC	month	5	full	no	no	no	no	0.317
M1	month	4	full	no	no	no	no	0.450
D1	day	4	full	no	no	no	no	15.7
D2	day	4	ending	no	no	no	no	15.8
D3	day	4	full	30 cps	no	no	no	16.8
D4	day	4	full	6 cps	no	no	no	16.0
D5	day	7	full	30 cps	3 days	no	no	67.9
D6	day	7	full	30 cps	7 days	no	no	349
D7	day	7	full	30 cps	3 days	yes	no	69.8
C3D	day	7	full	30 cps	3 days	yes	yes	76.8

Computer Execution Times

The execution times for simulations performed on the same desktop computer are listed in the last column of Table 7.2. These run times provide insight regarding the computations added in the alternative simulations. The simulation computations are repeated 924 and 28,125 times, respectively, in the monthly and daily simulations. The run times for monthly simulation M1 and daily simulation D1 are 0.45 and 15.7 minutes, respectively. The routing computations added in simulations D3 and D4 require relatively minimum additional execution time. Forecasting greatly increases run times. Forecast periods of three days (D5) and seven days (D6) increase execution time to 67.9 and 349 minutes. Increases from adding flood control and SB3 EFS are small.

Data Files Accompanying this Report

A summary of data files referenced in Chapters 7 and 8 is presented in Chapter 9. Data files accompanying this report include *SIMD* and *SIM* input files and DSS files containing selected simulation results. Most of the tables and time series plots presented in Chapters 7 and 8 are from simulation results contained in auxiliary DSS files that also available with this report. The presentations of Chapters 7 and 8 can be conveniently supplemented by further graphical, tabular, and/or statistical analyses of the data in the accompanying DSS files using *HEC-DSSVue*. Chapter 6 of the WRAP *Users Manual* [2] describes WRAP use of DSS files and *HEC-DSSVue*.

Alternative Negative Incremental Flow Adjustment Options

Negative incremental flows and associated adjustments are explained in Chapter 3 of the *Reference Manual* [1] and Chapter 3 of the *Daily Manual* [4]. The Brazos Daily WAM Report [8] includes comparative analyses of monthly and daily simulation results employing alternative negative incremental flow options.

The term *negative incremental flow* refers to situations with naturalized flow at a site in a particular time period being smaller than the corresponding upstream naturalized flow. 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 flow adjustment options are specified by input parameter ADJINC in *JD* record field 8 [2]. ADJINC option 5 is employed in the official TCEQ monthly Colorado WAM and WAMs for several other river basins. *SIMD* does not allow option 5 for daily simulations. 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 the standard recommended 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 considers flows in each future time period of the forecast simulation as well as in the current simulation time interval but less accurately. ADJINC option 7 methodology for dealing with future negative incremental flows during the forecast simulation are relevant only if forecasting is activated.

The following negative incremental flow adjustment ADJINC options are activated in the WAM simulations (Table 7.2 third column). ADJINC option 5 is activated in the original monthly TCEQ WAM. *SIMD* does not allow option 5 for daily simulations. Option 4 is employed in daily simulations that do not include forecasting. Option 7 is used in daily simulations with forecasting.

SIM and *SIMD* Water Accounting Procedures

Comparative analyses of differences between simulation results for the monthly versus daily WAMs and between results for alternative variations of the monthly and daily WAMs are presented in Chapters 7 and 8. The following discussion outlines certain aspects of the simulation computations that are fundamental to comparisons of simulation results.

Stream flow and other relevant quantities vary continuously in reality. However, a fixed computational time step is required for models. Daily is closer to continuous (or instantaneous) than monthly. However, approximations and simplifications are inherent in both daily and monthly models. Either daily or monthly WAMs or variations thereof may be more accurate or more appropriate depending on circumstances and particular applications. The tradeoffs between various interrelated modeling options are complex. The following discussion highlights basic concepts essential to understanding effects of alternative modeling options.

In a daily simulation, refilling reservoir storage and supplying diversion targets in each day depends on the volume of stream flow available in that day. A monthly simulation averages streamflow availability over the month. Attenuating or averaging out the daily variations in stream flow over each month generally results in more stream flow being available for refilling reservoir storage and supplying diversion targets. However, the complexities noted in the following paragraphs also significantly affect relative accuracies of daily versus monthly computations.

Differences between monthly and daily simulation results are viewed within the framework of the *SIM/SIMD* water accounting computational algorithms. The simulation steps through time. At each time step, computations are performed for each water right in priority order. With either a daily or monthly simulation, as each set of water management and use requirements (water right) is considered in the water right priority sequence, the tasks described in Table 7.3 are performed [1, 4]. Flow forecasting with reverse routing, if activated, is performed in conjunction with Task 1. Routing of flow adjustments, if employed, is performed in conjunction with Task 4.

Differences between monthly and daily simulation results are related significantly to the stream flow availability computations of Task 1 in Table 7.3. The algorithm considers flows at downstream control points in computing stream water available to each water right in order to protect downstream senior rights. The following considerations are important to this discussion: (1) curtailing diversions and passing inflows through reservoirs to protect downstream senior rights, (2) negative incremental naturalized flows; and (3) within-month stream flow availability. These concerns are relevant from the perspective of considering stream flows at downstream control points in the determination of the amount of stream flow available in a particular month (*SIM*) or day (*SIMD*) for refilling reservoir storage and supplying diversion targets.

Table 7.3
Computations Repeated for Each Water Right at Each Time Step [4]

Task 1: _Stream Flow Availability Determination_. – The amount of stream flow available to the water right is the minimum of the control point flow *CPFLOW* array available flows at the control point of the water right and at all relevant control points located downstream, optionally adjusted for channel losses and/or routing. In simulating flood control operations, the amount of channel flood flow capacity below maximum allowable non-damaging limits is determined considering the control point of the flood control dam and pertinent downstream control points.

Task 2: _Target Set_. – The water supply diversion target, hydroelectric power generation target, minimum instream flow limit, or non-damaging flood flow limit is set.

Task 3: _Water Right Simulation_. – For the water right being considered, decisions are made regarding reservoir storage and releases, water supply diversions, and other water management/use requirements, and appropriate actions are taken. Net evaporation volumes are determined. Water balance accounting computations are performed.

Task 4: _Flow Adjustment_. – The *CPFLOW* array used to determine stream flow availability and remaining flood flow capacity in Task 1 is adjusted for the effects of the Task 3 water management and use actions associated with that particular water right.

Dealing with the downstream propagation of flow alterations in the computations of Tasks 1 and 4 of Table 7.3 is fundamental to both daily and monthly simulations. However, daily simulations are characterized by more complexity and greater opportunities for inaccuracies. Actual real-world alterations to stream flow resulting from refilling reservoir storage, reservoir net evaporation and releases, diversions, and return flows may require several days to reach various downstream locations. The flow changes are assumed to propagate to the basin outlet in the same month in a monthly simulation. *SIMD* includes routing to address this time lag issue. As discussed in Chapter 4, routing is very approximate. Routing also introduces the issue of forecasting.

Inaccuracies associated with routing and forecasting are significant issues either without or with negative incremental flows. Likewise, negative incremental flows significantly add to complexities and inaccuracies either without or with routing and forecasting. Daily simulations typically have many more negative incremental flows than the corresponding monthly simulations.

Naturalized, regulated, and unappropriated flow volumes, and *SIM/SIMD* algorithms are all based on cumulated total flows at each control point, rather than incremental local flows between control points. However, with no routing, the term *negative incremental flow* is applied to describe situations in which the naturalized flow volume for a particular time step at a control point is less than concurrent flows at control points located upstream. Without routing, by definition, negative incremental flows do not exist in a naturalized flow dataset if flows in each time step always increase going downstream. A daily simulation is complicated by routing which extends the concept of negative incremental flows across multiple time steps. Negative incremental flow adjustment options employed in this simulation study are described in the preceding section.

Artificial Control Points, Reservoirs, and Water Rights

The designation of artificial control points, reservoirs, and water rights described in Chapter 2 facilitates developing Chapter 7 frequency statistics and time series plots of total storage contents of the 484 actual reservoirs in the WAM while excluding the 42 artificial reservoirs. However, determining basin-wide totals of water supply diversions and diversion shortages is complicated by the Lower Colorado River Authority (LCRA) Water Management Plan (WMP), which is modeled employing an array of computational accounting water rights. Control point I20000, which is central to the scheme for modeling the LCRA WMP, is not included with the selected group of designated artificial control points.

Units and Statistics for Flow Rates and Reservoir Storage Volumes

SIMD performs a simulation using a daily computational time step. The 43 time series output variables selected with the *OF* record [2], along with other variables, are computed for each of the 28,125 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 1940-2016 hydrologic period-of-analysis contains leap years 1940 and every fourth year thereafter in both reality and *SIMD* simulations. 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 924 monthly values is slightly different than the mean of 28,125 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 acre-feet per month = 0.0165640 cfs assuming 30.4375 days per month
1.0 acre-foot = 43,560 cubic feet (ft^3)
1940-2016 contains 77 years = 924 months = 28,125 days

The 1940-2016 time series of simulated reservoir storage content volumes consist of either 28,125 end-of-day volumes or 924 end-of-month volumes. The 924 end-of-month storage volumes are a subset of the 28,125 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 924 end-of-month volumes and the corresponding 28,125 end-of-day volumes are typically not visually noticeable.

Statistical frequency statistics presented in the tables of Chapter 7 include the mean and standard deviation and exceedance frequency quantities for the 28,125 days or 924 months of the 1940-2016 hydrologic period-of-analysis computed with *HEC-DSSVue* using the option path:

Tools - Math Functions - Statistics - Basic and *Duration Analysis*. Similar statistical analysis capabilities are provided in the WRAP program *TABLES*. The computations are essentially the same but results are recorded differently with *TABLES* versus *HEC-DSSVue*. Both include additional other optional statistical analysis methods not employed in this report.

Exceedance frequency quantities are computed based on the Weibull formula (Equation 7.1) where m is the relative rank and N is the sample size of 28,125 days or 924 months.

$$\text{Exceedance Frequency} = \frac{\text{m}}{\text{N} + 1}(100\%) \tag{7.1}$$

Exceedance frequency represents the percentage of time (duration) that a quantity is equaled or exceeded and/or the probability that a quantity will be equaled or exceeded in any randomly selected day or month.

Statistical Analyses of Simulated River Flows and Reservoir Storage

All of the simulations employ the same hydrology input DSS file with the filename C3HYD.DSS. Naturalized flows are identically the same in all simulations. Statistical frequency metrics for daily naturalized flows at the three control points (F10000, I10000, K20000) listed in Table 6.1 are tabulated in Table 6.3 of Chapter 6.

Naturalized flows are converted to regulated and unappropriated flows during a *SIM* or *SIMD* simulation. Frequency metrics for the regulated and unappropriated stream flows at control points F10000, I10000, K20000 (Table 6.1) computed in the alternative simulations defined in Tables 7.1 and 7.2 are tabulated in Tables 7.4, 7.5, 7.6, 7.7, 7.8 and 7.9. Monthly mean flow rates in cfs exhibit less variability than daily mean flow rates in cfs.

The discussions of simulation results in this chapter focus on naturalized, regulated, and unappropriated stream flows at three selected control points on the Colorado River (Table 6.1) and storage contents of three groups of major reservoirs (Table 7.10). Chapter 8 presents analyses of SB3 EFS instream flow targets and shortages.

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. Regulated flows are particularly relevant in simulating SB3 EFS. Although many other simulations were included in the comparative analyses, the discussions in Chapter 7 focus on simulation results for the simulations defined in Tables 7.1 and 7.2.

The summary tables of frequency statistics for monthly or daily means of stream flows presented in Tables 7.4-7.9 and end-of-period reservoir storage volumes presented in Tables 7.11-7.13 are relevant to the discussions that follow later throughout this chapter. The frequency metric tables include the mean and standard deviation and quantities that are equaled or exceeded specified percentages of the 924 months or 28,125 days of the 1940-2016 hydrologic period-of-analysis. Exceedance frequency quantities are determined in *HEC-DSSVue* based on Equation 7.1.

Table 7.4
Frequency Metrics for Regulated Flows of Colorado River near San Saba (F10000)

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (cfs)	701.9	695.2	858.3	866.9	796.3	831.7	660.7	884.0	657.9	657.9
Stand Dev	1,176	1,156	3,173	3,208	2,922	2,994	2,675	68,470	2,660	2,660
Frequency	Regulated Flow (cfs) Corresponding to Exceedance Frequencies in First Column									
0.1%	-	-	44,238	44,238	41,113	42,264	37,285	43,616	37,114	37,114
0.2%	10,087	10,087	35,646	36,074	32,163	32,659	29,566	35,193	29,237	29,237
0.5%	8,179	7,742	22,524	23,121	20,869	20,699	18,602	22,953	18,577	18,577
1%	6,717	6,529	14,772	14,847	13,484	14,167	12,400	15,129	12,310	12,310
2%	4,656	4,661	7,919	8,087	7,397	7,658	6,666	8,183	6,613	6,613
5%	2,838	2,839	2,879	2,931	2,722	2,970	2,213	3,013	2,195	2,195
10%	1,704	1,656	1,323	1,326	1,270	1,428	931	1,389	928	928.4
15%	1,120	1,120	825	828	801	893	551	870	552	552
20%	847	847	602	603	574	633	394	637	393	393.
30%	533	533	383	383	365	385	248	410	248	248
40%	386	385	282	283	266	272	178	300	179	179
50%	296	295	218	218	201	198	137	232	137	137
60%	239	237	168	168	154	145	108	178	108	108
70%	192	191	129	129	116	105	82	135	82.1	82.1
80%	148	147	93.0	93.0	80.0	67.0	57.0	96.0	56.8	56.8
85%	125	124	75.0	75.0	61.0	45.0	44.0	78.0	44.1	44.1
90%	102	100	53.0	53.0	40.0	14.0	29.0	60.0	29.4	29.4
95%	82	81	1.0	1.0	6.0	0.0	11.0	37.0	11.4	11.4
98%	64	64	0.0	0.0	0.0	0.0	2.0	18.0	2.3	2.3
99%	54	54	0.0	0.0	0.0	0.0	0.0	11.0	0.0	0.0
99.5%	47	47	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0
99.8%	40	42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7.5
Frequency Metrics for Unappropriated Flows of Colorado River near San Saba (F10000)

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (cfs)	106.7	107.3	28.72	21.1	48.14	25.22	69.35	119.0	113.5	97.61
Stand Dev	651.0	646.4	419	350.5	511.1	353.5	814.5	927.3	1,157	1,027
Frequency	Unappropriated Flow (cfs) Corresponding to Exceedance Frequencies in First Column									
0.1%	-	-	6,732	4,653	8,294	5,751	12,066	13,350	17,883	12,884
0.2%	7,371	7,247	3,115	2,138	4,424	2,853	7,006	8,289	10,456	8,201
0.5%	6,104	5,707	1,324	999	2,064	1,078	3,137	4,790	5,012	4,050
1%	3,451	3,469	594	392	985	372	1,319	2,662	2,281	2,048
2%	1,494	1,701	17.1	0.0	374.6	124.4	563.0	1,319	984	912
5%	380	383	0.0	0.0	96.7	4.1	26.0	401.0	269	240
10%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	64.0	3.0	2.0
15%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
20%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 7.6
Frequency Metrics for Regulated Flows of Colorado River at Austin (Control Point I10000)

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (cfs)	1,212	1,204	1,440	1,427	1,463	1,525	1,271	1,486	1,304	1,304
Stand Dev	1,790	1,794	5,268	5,243	4,943	4,832	4,754	5,013	3,883	3,883
Frequency	Regulated Flow (cfs) Corresponding to Exceedance Frequencies in First Column									
0.1%	-	-	71,128	71,128	65,297	65,432	59,495	66,241	45,898	45,898
0.2%	19,327	19,327	56,807	56,807	48,798	47,491	48,913	51,296	34,023	34,023
0.5%	13,424	13,417	35,073	34,452	31,511	31,501	30,519	31,829	21,861	21,861
1%	10,281	10,099	22,613	22,425	21,149	20,784	20,432	22,017	15,363	15,363
2%	6,162	6,207	13,313	13,119	12,674	12,441	12,055	12,860	9,376	9,376
5%	3,482	3,482	4,754	4,675	4,819	5,385	4,398	4,948	6,854	6,854
10%	2,323	2,319	2,082	2,060	2,333	2,828	1,844	2,233	2,770	2,769
15%	1,845	1,833	1,378	1,366	1,537	1,863	1,064	1,440	1,409	1,407
20%	1,562	1,563	1,071	1,062	1,189	1,385	750	1,101	916	916
30%	1,227	1,229	763	757	832	916	509	804	551	553
40%	973	968	581	576	627	661	421	631	438	438
50%	731	730	448	445	491	491	362	509	375	375
60%	557	551	354	351	389	363	316	412	327	327
70%	428	415	270	268	311	276	279	336	290	290
80%	328	321	183	181	237	195	236	268	252	252
85%	294	280	116	113	195	144	212	234	232	231
90%	251	235	18.0	15.0	143	80.0	185	196	209	209
95%	206	175	0.0	0.0	54.0	0.0	132	140	178	178
98%	150	105	0.0	0.0	0.0	0.0	23.0	71.0	136	135
99%	123	57.6	0.0	0.0	0.0	0.0	0.0	27.0	109	109
99.5%	83.2	49.3	0.0	0.0	0.0	0.0	0.0	1.0	68.5	68.4
99.8%	55.7	3.5	0.0	0.0	0.0	0.0	0.0	0.0	51.0	51.0

Table 7.7
Frequency Metrics for Unappropriated Flows of Colorado River at Austin (I10000)

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (cfs)	249.8	249.7	55.17	44.05	96.35	79.96	298.8	117.0	473.8	441.2
Stand Dev	1,429	1,423	616.6	556.7	742.7	623.9	1,682	991.9	1,737	1,707
0.1%	-	-	10,766	10,324	11,587	9,101	25,591	16,371	17,730	17,655
0.2%	16,798	16,799	6,197	5,183	7,687	6,084	18,167	9,697	12,445	12,445
0.5%	10,313	10,160	2,966	2,433	4,100	3,541	8,301	5,000	8,008	7,842
1%	7,637	7,637	1,594	1,206	2,358	1,924	5,108	2,845	7,250	7,201
2%	3,686	3,684	239.1	11.0	1,032	916.6	3,005	1,343	6,799	6,714
5%	1,099	1,091	0.0	0.0	270.2	237.7	1,059	240.5	3,018	2,753
10%	0.0	0.0	0.0	0.0	50.6	13.5	350.3	0.8	737	632
15%	0.0	0.0	0.0	0.0	0.0	0.0	225.3	0.0	289	250
20%	0.0	0.0	0.0	0.0	0.0	0.0	167	0.0	198	168
30%	0.0	0.0	0.0	0.0	0.0	0.0	100.7	0.0	115	85.3
40%	0.0	0.0	0.0	0.0	0.0	0.0	56.7	0.0	65.0	28.3
50%	0.0	0.0	0.0	0.0	0.0	0.0	17.4	0.0	23.0	0.1
60%	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.4	0.0
70%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7.8
Frequency Metrics for Regulated Flows of Colorado River at Wharton (Control Point K20000)

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (cfs)	1,547	1,540	1,530	1,512	1,710	1,793	1,552	1,637	1,545	1,545
Stand Dev	2,369	2,368	4,780	4,725	5,075	5,180	4,878	4,893	4,758	4,757
Frequency	Regulated Flow (cfs) Corresponding to Exceedance Frequencies in First Column									
0.1%	-	-	60,209	60,209	63,274	62,564	62,617	62,284	60,427	60,427
0.2%	25,313	25,346	47,285	47,073	50,019	49,931	48,212	47,294	46,034	46,034
0.5%	16,925	16,870	34,353	33,088	35,671	37,064	35,825	36,260	33,748	33,746
1%	11,229	11,255	23,333	23,093	25,227	26,367	23,570	23,692	22,598	22,598
2%	9,136	9,142	13,761	13,428	15,300	15,634	14,056	14,068	14,164	14,164
5%	5,001	5,008	5,919	5,870	7,010	7,249	6,081	6,278	6,853	6,853
10%	3,389	3,389	2,748	2,712	3,306	3,582	2,782	2,878	2,941	2,939
15%	2,595	2,566	1,713	1,691	2,116	2,304	1,731	1,886	1,726	1,727
20%	2,037	2,027	1,254	1,243	1,560	1,674	1,260	1,392	1,222	1,222
30%	1,478	1462	826.8	826.9	980.7	1029.5	808.4	918.3	765	764
40%	1,067	1,066	594	596	672	707	560	668	505	505
50%	810	804	443	445	459	488	385	499	333	333
60%	620	611	324	325	316	330	269	372	228	229
70%	472	465	240	241	212	210	196	276	187	187
80%	354	347	156	156	135	123	169	198	169	169
85%	309	304	100	98.8	80.0	57.5	169	169	169	169
90%	267	266	0.0	0.0	2.1	0.0	146	146	157	157
95%	223	216	0.0	0.0	0.0	0.0	113	109	133	133
98%	171	155	0.0	0.0	0.0	0.0	37.3	55.2	105	106
99%	110	110	0.0	0.0	0.0	0.0	1.0	7.9	87.7	87.8
99.5%	110	81.0	0.0	0.0	0.0	0.0	0.8	1.0	70.2	70.3
99.8%	97.8	0.0	0.0	0.0	0.0	0.0	0.5	0.7	34.2	36.0
99.9%	-	-	0.0	0.0	0.0	0.0	0.1	0.1	3.0	3.0

Table 7.9
Frequency Metrics for Unappropriated Flows of Colorado River at Wharton (K20000)

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (cfs)	399.7	399.9	185.4	166.7	400.2	441	253.4	126.7	312.6	283.8
Stand Dev	1,991	1,985	1,406	1,333	1,653	1,779	1,585	792.2	1,699	1,625
Frequency	Unappropriated Flow (cfs) Corresponding to Exceedance Frequencies in First Column									
0.1%	-	-	20,496	20,496	20,570	22,869	21,240	10,523	21,918	21,522
0.2%	21,438	21,470	17,000	16,121	16,895	17,783	17,967	9,186	18,128	16,736
0.5%	15,593	15,593	9,928	8,114	11,793	12,125	11,424	5,422	11,038	10,236
1%	9,786	9,755	4,790	4,447	7,746	8,259	6,308	3,123	7,274	6,974
2%	7,142	7,181	2,197	1,870	4,829	5,258	3,470	1,617	5,091	4,773
5%	2,366	2,317	388.3	322.4	2,249	2,516	954.5	481.5	1,379	1,124
10%	36.0	36.0	0.0	0.0	925.1	1036	56.2	54.1	118	0.4
15%	0.0	0.0	0.0	0.0	323.5	388.5	0.0	0.0	0.0	0.0
20%	0.0	0.0	0.0	0.0	5.6	64.2	0.0	0.0	0.0	0.0
30%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Statistics for Summations of End-of-Period Storage Contents of Groups of Reservoirs

Reservoir storage content plots and statistics provide meaningful water availability metrics for comparing the results of the alternative simulations. Storage frequency metrics for each of the alternative daily simulations are tabulated in Tables 7.11, 7.12, and 7.13 for the three groups of reservoirs defined in Table 7.10. The first group includes all of the actual reservoirs in the WAM. This does not include the computational accounting reservoirs designated as artificial as described in Chapter 2. The second group consists of the three largest reservoirs owned and operated by the Canadian River Municipal Water District (CRMWD). The six Highland Lakes operated by the Lower Colorado River Authority (LCRA) comprise the third group.

The end-of-month or end-of-day storage volumes in acre-feet for all of the reservoirs in a group were summed within *HEC-DSSVue* for each of the 924 months or 28,125 days of the simulation. The basic statistics and duration analysis features of *HEC-DSSVue* were applied to the totals to compute the metrics tabulated in Tables 7.11, 7.12, and 7.13.

The summations of end-of-day storage volumes exhibit significant variability. However, the storage contents of individual reservoirs tend to exhibit greater variability in general and in some cases much greater variability than the combined total storage since the timing of storage draw-downs and refilling vary between the multiple reservoirs in a group. Summing storage of multiple reservoirs has an averaging-out effect.

Table 7.10
Groups of Reservoirs

Reservoir	Stream	Reservoir Identifier	Control Point ID	Storage Capacity Conservation (acre-feet)	Storage Capacity Flood Control (acre-feet)	Storage Capacity Total (acre-feet)
All Reservoirs in the WAM						
Total Storage Capacity of 484 Reservoirs				5,263,900	1,546,890	6,810,790
Colorado River Municipal Water District (CRMWD) Reservoirs						
O. H. Ivie	Colorado River	OHIVIE	D20050	554,340	0	554,340
E. V. Spence	Colorado River	SPENCE	B10050	488,760	0	488,760
J. B. Thomas	Colorado River	THOMAS	A30060	204,000	0	204,000
Total Storage Capacity				1,247,100		1,247,100
Highland Lakes Operated by Lower Colorado River Authority (LCRA) Reservoirs						
Travis	Colorado River	TRAVIS	I20000	1,170,752	798,253	1,969,005
Buchanan	Colorado River	BUCHAN	I40000	992,475	0	992,475
LBJ	Colorado River	LAKLBJ	I21280	138,500	0	138,500
Austin	Colorado River	LKAUST	I10340	21,000	0	21,000
Roy Inks	Colorado River	ROYINK	I20820	17,545	0	17,545
Marble Falls	Colorado River	MARBLE	I20590	8,760	0	8,760
Total Storage Capacity				2,349,032	798,253	1,969,005

Table 7.11
Frequency Metrics for Storage Contents Summed for All Reservoirs in the WAM

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (af)	2,650,940	2,651,395	2,180,080	2,071,088	1,796,735	1,344,228	2,460,202	2,145,757	2,696,715	2,697,097
Stand Dev	907,613	897,911	956,793	807,839	975,853	985,611	981,345	952,014	875,422	877,074
Frequency	Storage Volumes (acre-feet) Associated with Exceedance Frequencies in First Column									
0.1%	-	-	5,188,258	3,764,489	5,187,147	5,222,117	5,190,409	5,190,122	5,411,680	5,411,680
0.2%	5,129,377	5,129,366	5,140,220	3,692,049	5,141,989	5,173,706	5,149,086	5,145,226	5,319,010	5,319,010
0.5%	5,092,458	5,092,448	4,933,176	3,571,921	4,918,990	5,017,379	4,962,747	4,927,442	5,131,894	5,131,894
1%	4,933,216	4,941,705	4,805,788	3,456,338	4,797,046	4,868,397	4,805,834	4,748,079	4,911,479	4,911,479
2%	4,746,240	4,742,178	4,604,937	3,347,053	4,527,244	4,577,181	4,622,468	4,509,397	4,656,717	4,657,024
5%	4,264,074	4,250,515	3,603,986	3,247,279	3,350,529	3,061,410	3,871,033	3,505,426	4,195,171	4,205,334
10%	3,829,990	3,809,729	3,236,242	3,103,513	2,991,106	2,577,167	3,573,147	3,192,516	3,720,699	3,726,741
15%	3,586,482	3,567,493	3,078,754	2,970,814	2,797,455	2,275,026	3,408,602	3,043,261	3,556,013	3,559,156
20%	3,379,505	3,363,559	2,954,476	2,854,416	2,592,090	2,076,260	3,272,492	2,913,955	3,374,738	3,374,818
30%	3,111,803	3,107,991	2,697,483	2,551,694	2,190,318	1,594,959	3,014,475	2,662,590	3,135,365	3,135,719
40%	2,847,565	2,855,514	2,368,000	2,308,834	1,903,386	1,265,813	2,750,514	2,404,251	2,917,339	2,918,008
50%	2,588,598	2,598,240	2,159,029	2,123,524	1,689,074	1,032,447	2,520,149	2,147,199	2,725,276	2,725,829
60%	2,384,329	2,385,556	1,969,787	1,951,273	1,493,281	844,209	2,291,788	1,958,849	2,512,004	2,512,564
70%	2,121,782	2,141,209	1,757,265	1,725,624	1,273,629	702,706	1,966,697	1,680,428	2,239,411	2,238,594
80%	1,865,959	1,882,650	1,423,046	1,414,780	834,044	552,892	1,670,741	1,367,264	1,947,076	1,947,535
85%	1,748,647	1,758,085	1,136,914	1,136,914	705,031	509,181	1,432,633	1,096,401	1,782,590	1,780,289
90%	1,581,243	1,599,759	827,549	827,533	548,814	447,893	987,921	813,402	1,543,810	1,539,844
95%	1,195,365	1,202,115	488,605	488,600	442,676	369,222	635,376	426,094	1,257,851	1,254,715
98%	736,676	747,987	388,067	388,066	365,723	311,674	505,958	353,638	861,824	860,805
99%	553,325	565,628	339,834	339,834	349,521	300,551	450,509	331,113	648,155	648,155
99.5%	471,590	484,420	322,018	322,018	344,972	291,457	422,197	318,133	519,079	519,079
99.8%	448,216	461,041	318,396	318,396	331,972	280,904	407,086	311,706	499,098	499,098
99.9%	-	-	316,667	316,667	324,181	279,419	402,959	305,842	486,296	486,296

Table 7.12
Frequency Metrics for Storage Contents of the Three Largest CRMWD Reservoirs

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (af)	171,385	164,365	72,620	10,509	87,861	83,356	198,325	63,890	196,956	189,118
Stand Dev	276,239	272,804	228,479	45,676	223,416	225,180	261,915	215,549	261,513	238,142
Frequency	Storage Volumes (acre-feet) Associated with Exceedance Frequencies in First Column									
0.1%	-	-	1,230,566	419,005	1,230,634	1,230,626	1,231,260	1,230,802	1,231,260	1,035,600
0.2%	1,247,100	1,247,100	1,218,047	394,362	1,216,172	1,216,005	1,220,266	1,216,435	1,220,266	1,030,240
0.5%	1,231,120	1,231,109	1,188,778	339,671	1,172,949	1,192,221	1,182,247	1,169,740	1,182,247	1,022,668
1%	1,190,270	1,192,788	1,155,175	290,043	1,136,909	1,143,675	1,160,952	1,118,819	1,160,952	999,098
2%	1,144,710	1,141,530	1,079,396	187,471	1,061,855	1,062,683	1,110,154	1,027,208	1,110,154	971,687
5%	844,217	830,524	595,455	46,901	574,471	585,949	747,978	514,571	748,513	728,571
10%	568,341	554,125	156,455	13,813	200,661	187,454	520,036	121,255	515,900	507,232
15%	400,612	377,857	47,966	3,424	134,256	102,452	417,151	33,589	410,592	408,358
20%	277,529	259,357	13,927	581	78,778	60,237	335,671	8,544	333,661	330,914
30%	146,290	133,127	252	0.0	36,054	30,981	217,769	0.0	214,551	213,237
40%	79,568	74,856	0.0	0.0	17,157	12,882	154,134	0.0	151,565	151,228
50%	46,705	42,685	0.0	0.0	7,477	3,642	105,707	0.0	104,798	104,357
60%	24,215	22,458	0.0	0.0	1,639	120	66,492	0.0	65,500	65,543
70%	9,288	8,755	0.0	0.0	0.0	0.0	24,180	0.0	23,852	23,794
80%	0.0	0.0	0.0	0.0	0.0	0.0	1,115	0.0	1,050	1,062
85%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02

Table 7.13
Frequency Metrics for Storage Contents of the Six Highland Lakes

WAM	MC	M1	D1	D2	D3	D4	D5	D6	D7	C3D
Mean (af)	1,879,466	1,885,494	1,585,589	1,562,802	1,240,334	736,097	1,676,232	1,574,876	1,911,913	1,911,313
Stand Dev	480,416	475,634	660,866	657,777	666,036	589,513	635,646	646,322	493,571	494,209
Frequency	Storage Volumes (acre-feet) Associated with Exceedance Frequencies in First Column									
0.1%	-	-	2,349,032	2,349,032	2,349,031	2,349,032	2,349,032	2,349,032	3,147,278	3,147,278
0.2%	2,349,032	2,349,032	2,349,032	2,349,032	2,348,943	2,349,014	2,349,032	2,349,032	3,085,383	3,085,383
0.5%	2,349,032	2,349,032	2,349,032	2,349,032	2,345,638	2,343,698	2,349,032	2,349,032	2,950,110	2,950,110
1%	2,349,032	2,349,032	2,349,032	2,349,021	2,335,018	2,308,132	2,349,032	2,349,032	2,836,360	2,836,040
2%	2,349,032	2,349,032	2,348,977	2,348,922	2,305,005	2,252,534	2,348,992	2,348,919	2,622,101	2,618,834
5%	2,349,032	2,349,032	2,348,389	2,348,046	2,224,616	1,848,038	2,347,439	2,344,174	2,351,787	2,351,736
10%	2,349,031	2,349,031	2,317,422	2,303,666	2,133,913	1,638,989	2,312,124	2,286,920	2,346,428	2,346,420
15%	2,336,858	2,338,883	2,260,003	2,240,137	2,016,192	1,480,562	2,256,851	2,221,661	2,320,432	2,320,432
20%	2,306,587	2,307,165	2,207,472	2,188,942	1,893,672	1,291,850	2,219,615	2,160,858	2,288,272	2,288,278
30%	2,230,299	2,232,252	2,037,327	2,004,378	1,707,752	935,228	2,116,857	2,015,038	2,245,615	2,245,595
40%	2,146,164	2,145,870	1,879,516	1,860,989	1,468,056	718,022	2,018,696	1,869,758	2,168,674	2,168,685
50%	2,030,320	2,032,639	1,743,637	1,716,630	1,276,969	547,257	1,890,389	1,732,150	2,063,885	2,063,886
60%	1,894,441	1,896,043	1,608,019	1,572,017	1,113,835	396,464	1,739,238	1,588,697	1,944,920	1,944,628
70%	1,710,217	1,726,785	1,379,837	1,339,051	880,950	257,769	1,502,767	1,368,081	1,774,465	1,774,248
80%	1,503,260	1,516,271	1,017,995	970,785	487,035	183,949	1,196,429	1,043,457	1,543,684	1,543,753
85%	1,381,053	1,401,753	812,360	812,360	308,927	178,531	1,055,216	825,961	1,381,902	1,380,276
90%	1,217,445	1,230,818	320,209	320,209	203,577	169,064	437,300	342,243	1,191,411	1,187,265
95%	856,922	864,283	174,597	174,597	177,936	157,851	210,102	180,375	834,024	833,028
98%	478,293	489,857	159,256	159,256	169,117	146,134	172,084	171,526	592,729	591,620
99%	298,430	314,023	150,316	150,316	162,282	137,435	165,552	166,368	397,932	397,932
99.5%	193,759	206,625	145,911	145,911	160,746	134,389	163,398	164,341	270,750	270,750
99.8%	189,518	202,375	142,970	142,970	159,770	131,156	160,713	162,909	238,951	238,952
99.9%	-	-	142,241	142,241	158,380	130,870	160,445	161,290	227,844	227,844

Basic WAM Concepts Explored with Simulations MC, M1, and D1

The monthly full authorization scenario Colorado WAM dataset from the TCEQ WAM System last updated by the TCEQ in February 2020 is described in Chapter 2. This WAM dataset consists of *SIM* input files with filename root C3. Chapter 2 describes the following two modifications added to this WAM dataset that do not affect computed values in simulation results.

1. designation of artificial control points, reservoirs, and water rights
2. consolidation of multiple time series input data files into a single DSS file

The label MC is adopted in Chapter 7 to refer to this initial enhanced version of the monthly WAM. Simulation results would be identical with M1 and MC except the negative incremental flow adjustment methodology is changed from ADJINC option 5 in MC to ADJINC option 4 in M1.

The version of the WAM labeled D1 in Tables 7.1 and 7.2 is the daily version of the monthly M1 dataset with the following additional modification. Monthly naturalized flows are disaggregated to daily as explained in Chapter 3.

Version D1 is the initial daily simulation model developed as described in Chapters 2 and 3. Disaggregation of monthly naturalized flows are included in the daily WAM variation D1.

However, routing, forecasting, flood control, and SB3 EFS are not included. The negative incremental flow option selected by *ADJINC* on the *JD* record is changed from option 5 in version MC to option 4 in variations M1 and D1. *SIMD* does not allow use of option 5 in a daily simulation.

Simulation results from monthly *SIM* input dataset M1 are exactly replicated by executing the *SIMD* daily D1 input dataset with the monthly *SIM* rather than with *SIMD*. *SIM* ignores all daily-only input data.

The *SIMD* message MSS file includes the counts of WAM components replicated as Table 7.14 for a simulation with the Colorado WAM dataset labeled D1. These counts are descriptive of the size and complexity of the WAM dataset.

Table 7.14
SIMD Message File Counts of Components for *SIMD* Input Dataset D1

```
*******************************************************
  System components counted from input file:
    2457 control points (CP records)
      45 primary control points (INMETHOD=1)
      48 control points with evap input (CPEV=blank)
     156 artificial control points (ARTIF on CO record)
     526 reservoirs
      42 artificial reservoirs
     120 instream flow IF records
    2167 water right WR records
     446 system water rights
     488 artificial water rights
     103 sets of water use coefficients (UC records)
      29 storage-area tables (SV/SA records)
      21 drought indices (DI records)
     154 flow switch FS and cumulative volume CV records
       7 dual simulation rights
    2240 FD records in the DIS file
       5 maximum upstream gaged cpts on FD records
 *******************************************************
  Daily simulation information:
     484 control points form the longest flow path to the outlet.
       0 control points have routing coefficients in the DIF file.
         Routing is deactivated by NORT on JU record.
       0 control points form the longest routing chain to the outlet.
        --- Forecasting is not performed. ---
 *******************************************************
```

WAM version D1 includes monthly-to-daily naturalized flow disaggregation but is not complicated by other model components discussed later in this chapter. Modeling within-month stream flow variability is generally the most important aspect of converting from a monthly to daily WAM. Streamflow is extremely variable. The plots and frequency metrics of observed, naturalized, and simulated regulated and unappropriated flows presented in Chapters 6 and 7 illustrate the continual high variability and occasional extreme fluctuations that are characteristic of river flows throughout the Colorado River Basin and throughout Texas.

Stream Flow Comparisons

Daily naturalized flows in cfs of the Colorado River at or near San Saba, Austin, and Wharton (WAM control points F10000, I10000, and K20000) are plotted in Figures 6.9, 6.10, and 6.11 of Chapter 6. Exceedance frequency statistics for daily mean and monthly mean naturalized flow rates at these three sites are tabulated in Table 6.3. The mean flow rates of 996.5 cfs, 2,197 cfs, and 3,369 cfs at control points F10000, I10000, and K20000, respectively, are the same for daily flows, monthly flows, annual flows, or 1940-2016 flows. Means flow rates in cfs are not dependent on the averaging time interval. However, the standard deviation and exceedance frequency quantities in Table 6.3 for daily versus monthly mean flow rates are very different. Means averaged within each day are much more variable than means averaged within each month.

The only difference in input data between monthly simulations MC and M1 is use of negative incremental flow adjustment ADJINC option 5 versus option 4. Computer execution times of 0.317 and 0.450 minute for options 5 and 4, respectively, in Table 6.2 indicate that option 4 requires more computations than option 5. Simulated regulated and unappropriated flows from the two monthly and eight daily variations of the Colorado WAM are compared in Tables 7.4-7.9. The flow statistics for simulations MC and M1, though not identical, are almost the same.

Table 7.15 provides a concise comparison of the results of simulations M1 and D1. The 1940-2016 average total simulated reservoir storage contents in all reservoirs in the WAM and naturalized, regulated, and unappropriated stream flows at selected control points are compared. Means of naturalized flows are the same in monthly and daily simulations. Regulated flows are important in modeling instream flow requirements and flood control operations. The average regulated flows are relatively close between simulations M1 and D1. The means of the unappropriated flows differ greatly between simulations M1 and D1. Tables 7.4 through 7.12 provide more detailed statistical comparisons that include variability metrics as well as means.

Table 7.15
Comparison of Means of Selected Quantities from Simulations M1 and D1

Location	Variable	M1	D1
CRMWD	reservoir storage (acre-feet)	164,365	72,620
Highland Lakes	reservoir storage (acre-feet)	1,885,494	1,585,589
Entire WAM	reservoir storage (acre-feet)	2,651,395	2,180,080
F10000	naturalized flow (cfs)	997	997
Colorado River	regulated flow (cfs)	695	858
near San Saba	unappropriated flow (cfs)	107	28.7
I0000	naturalized flow (cfs)	2,197	2,197
Colorado River	regulated flow (cfs)	1,204	1,440
at Austin	unappropriated flow (cfs)	250	55.2
K20000	naturalized flow (cfs)	3,369	3,369
Colorado River	regulated flow (cfs)	1,540	1,530
at Wharton	unappropriated flow (cfs)	400	185
K10000	naturalized flow (cfs)	3,582	3,582
Colorado River	regulated flow (cfs)	1,425	1,456
at Bay City	unappropriated flow (cfs)	496	306

Comparison of Reservoir Storage Contents from Monthly versus Daily Simulations

Reservoir storage contents computed in simulations M1 and D1 are compared in Figures 7.1, 7.2, and 7.3. The three groups of reservoirs reflected in Figures 7.1, 7.2, and 7.3 are defined in Table 7.10. End-of-period (28,125 days or 924 months) storage contents are summed for: (1) the 484 reservoirs in the WAM, (2) the six Highland Lakes reservoirs operated by the LCRA, and (3) the three largest reservoirs owned and operated by the CRMWD. The reservoir storage volumes in acre-feet are added and plotted within *HEC-DSSVue*.

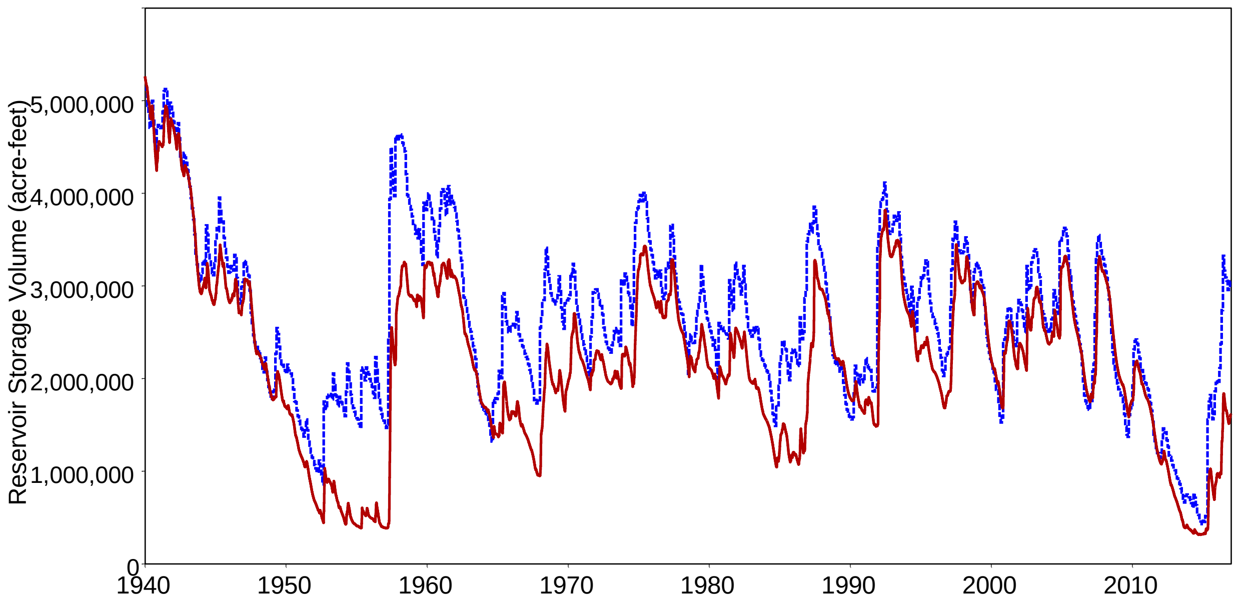

Figure 7.1 Summation of Storage in All Reservoirs for Simulations M1 (blue dashed line) and D1 (red solid line)

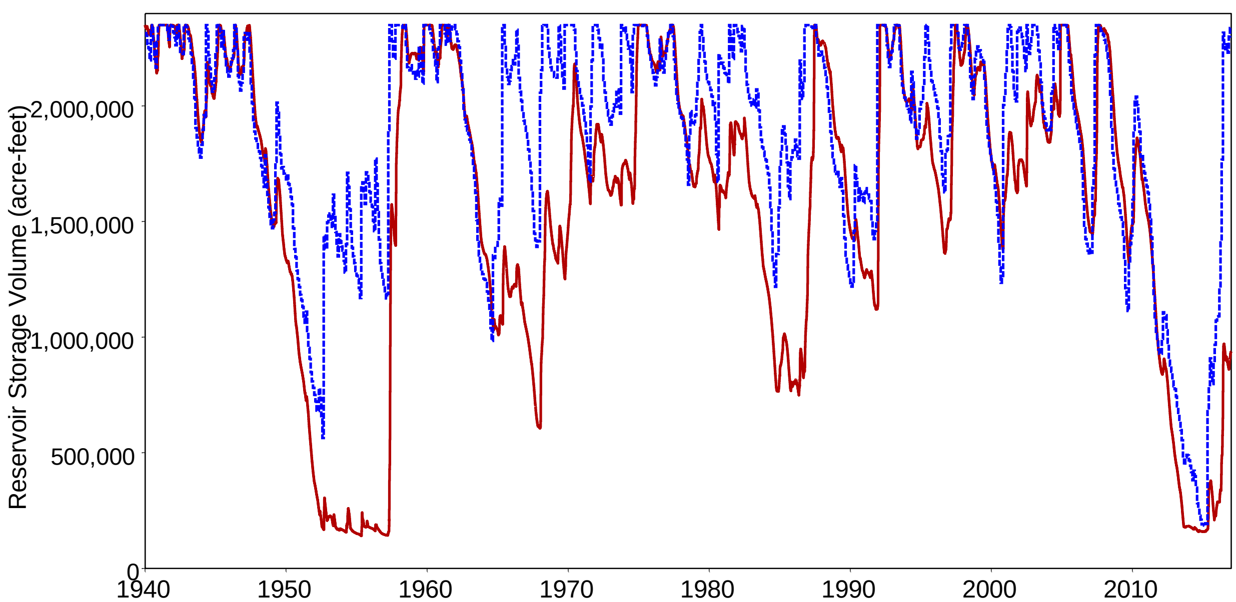

Figure 7.2 Summation of Storage in Six Highland Lakes for Simulations M1 (blue dashed line) and D1 (red solid line)

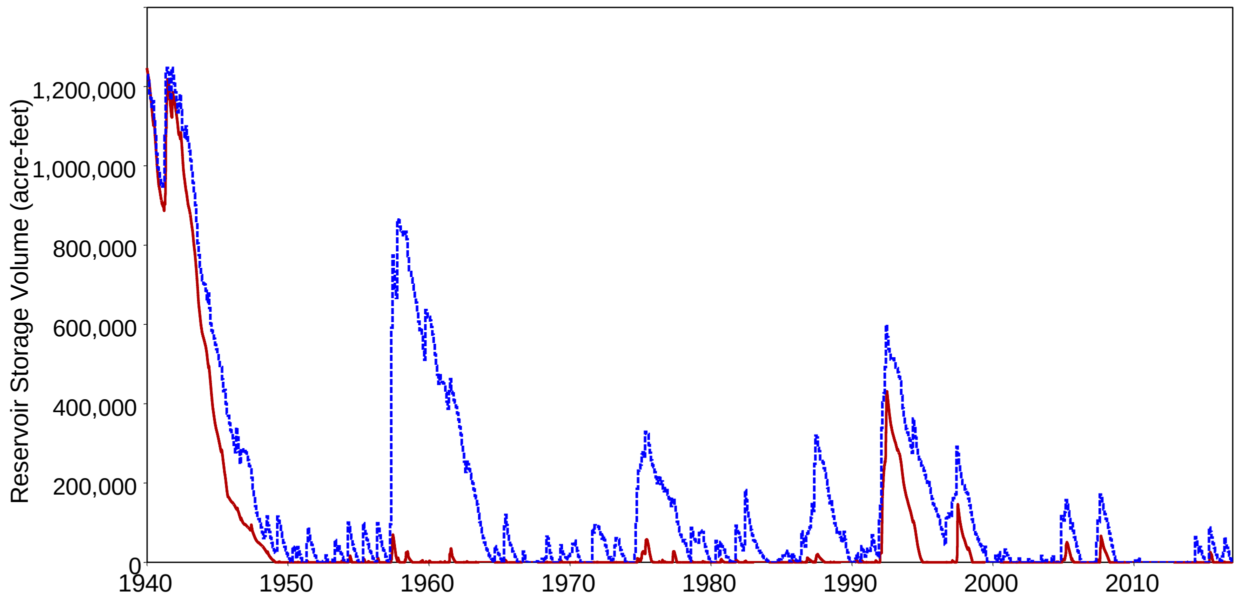

Figure 7.3 Summation of Storage in Three CRMWD Reservoirs for Simulations M1 (blue dashed line) and D1 (red solid line)

The dashed blue lines in the figures are plots of end-of-month storage summations for the 924 months of the monthly *SIM* simulation with the M1 dataset. The solid red lines are plots of end-of-day storage summations for the 28,125 days of the *SIMD* simulation with the D1 WAM.

Simulated reservoir storage contents are significantly lower in the daily D1 simulation than in the monthly M1 simulation. This is consistent with previous analyses with the Brazos, Trinity, and Neches monthly and daily WAMs [8, 9, 10]. Key factors contributing to the differences are noted in the following paragraphs.

The primary reason for converting from a monthly to a daily WAM is to capture within-month stream flow variability. Although other relevant variables also vary within the month, stream flow variability is the most significant. Daily variability of simulated regulated flows are particularly important is modeling instream flow requirements and flood control operations.

A monthly simulation averages over the month the amount of stream flow available to fill reservoir storage and supply diversion targets. Attenuating or averaging out the daily variations in stream flow over each month generally results in more stream flow being available for reservoir storage and supply diversions. However, the previously discussed complexities of the simulation computations outlined in Table 7.3 are primary drivers of the relative accuracies of daily versus monthly computations. The computational procedures are complicated by requirements to curtail refilling reservoir storage and supplying diversion targets by junior water rights in the simulation as necessary to protect more senior water rights located downstream.

As previously noted, the following negative incremental flow adjustment ADJINC options are activated in the Colorado WAM simulations of this report. ADJINC option 5 is activated in the original monthly TCEQ WAM. *SIMD* does not allow option 5 for daily simulations. Option 4 is employed in daily simulations that do not include routing. Option 7 is used in daily simulations with routing. The monthly simulation M1 discussed in this section employs ADJINC option 4 for consistency in comparisons with simulation D1.

ADJINC option 8 is designed for experimentation rather than for final simulations [1, 2, 4]. With ADJINC option 8, the procedure outlined in Table 7.3 is revised to not consider downstream control points in the determination of the amount of stream flow available to fill reservoir storage and/or supply diversion targets. Only stream flow at the site of the water right is considered. Downstream senior water rights are not considered or protected. Negative incremental flows are no longer relevant. Flow may be over-appropriated. Simulation results with ADJINC option 8 activated, though incorrect, provide insight regarding causes of the differences in storage contents between monthly and daily simulations. Simulation results with ADJINC option 8 activated are included in Figures 7.4, 7.5, and 7.6.

Figures 7.4, 7.5, and 7.6 contain storage plots from the results of four alternative simulations. The simulations labeled M1 and D1 are the same simulations reflected in Figures 7.1, 7.2, and 7.3. The M1 and D1 storage plots in Figures 7.4, 7.5, and 7.6, respectively, are exactly replicate the M1 and D1 storage plots in Figures 7.4, 7.5, and 7.6. The other two alternative simulations reflect a single modification to the M1 and D1 simulations. ADJINC is changed from option 4 to option 8. Figures 7.4, 7.5, and 7.6 demonstrate the effects of ignoring downstream control points in the performance of Task 1of Table 7.3. The effects are very significant.

The storage contents resulting from the two versions of the monthly simulation M1 are plotted as dashed blue lines in Figures 7.4, 7.5, and 7.6. Green circles are added to the dashed blue lines for the alternative month simulation with ADJINC changed to option 8. Likewise, reservoir storage results from daily simulation D1 are plotted as solid red lines. Green circles signify that ADJINC option 8 is in effect.

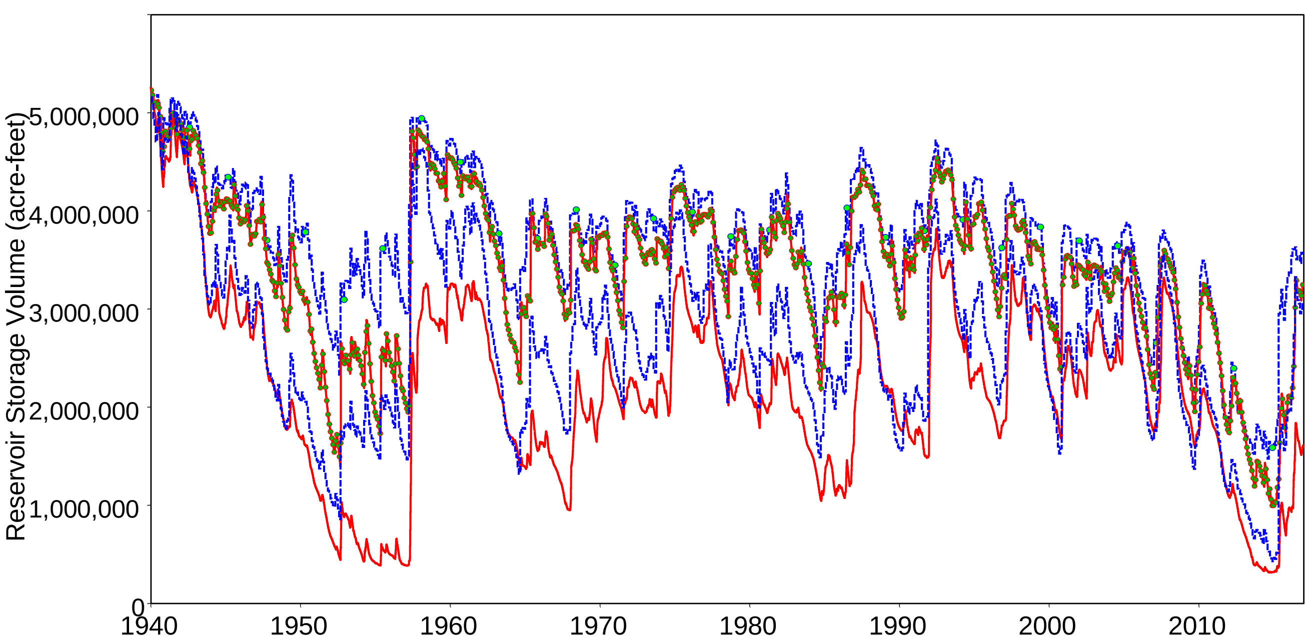

Figure 7.4 All Reservoirs for Simulations M1 (blue dashed line) and D1 (red solid line)
(Green Circles for ADJINC Option 8)

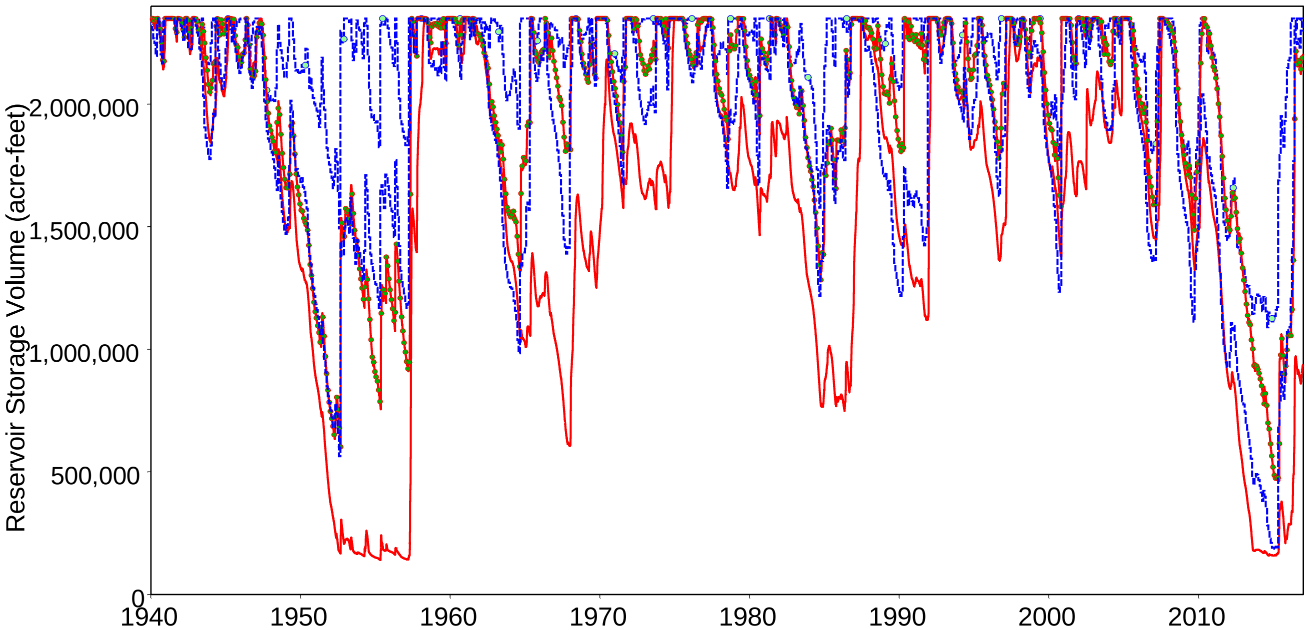

Figure 7.5 Highland Lakes for Simulations M1 (blue dashed line) and D1 (red solid line) (Green Circles for ADJINC Option 8)

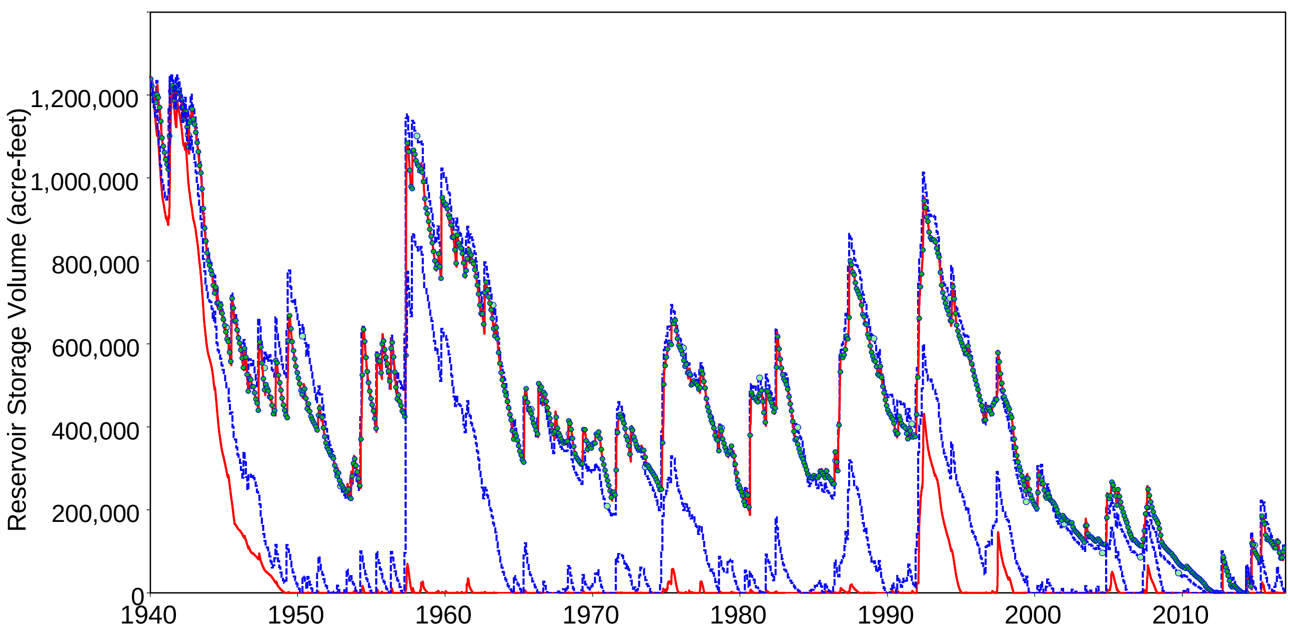

Figure 7.6 CRMWD Reservoirs for Simulations M1 (blue dashed line) and D1 (red solid line) (Green Circles for ADJINC Option 8)

Figures 7.1, 7.2, and 7.3 indicate that converting from the monthly M1 to daily D1 simulation significantly decreases the volume of water stored in the reservoirs. Figures 7.4, 7.5, and 7.6 indicate that ignoring effects of downstream senior water rights and negative incremental flows greatly increases the volume of water stored in the reservoirs. Complex approximations are inherent in both the monthly and daily models. The general overall effect of tradeoffs in accuracies/inaccuracies of monthly versus daily models are difficult to access.

Canadian River Municipal Water District (CRMWD) Reservoirs

Storage levels in O. H. Ivie, E. V. Spence, and J. B. Thomas Reservoirs are notably low throughout the 1940-2016 hydrologic period-of-analysis. The actual historical storage contents of these three CRMWD reservoirs are plotted in Figures 6.12, 6.13, and 6.14 of Chapter 6. E. V. Spence Reservoir (Figure 6.12), with impoundment beginning in 1968, has never reached 80 percent of capacity, and storage contents have been well below 40 percent of capacity during most of its project life. O. H. Ivie Reservoir (Figure 6.13), with initial impoundment in 1990, filled to capacity during the 1990s but has been severely drawn down continuously since 1998. The storage contents of J. B. Thomas Reservoir (Figure 6.14) reached capacity during the late 1950s but has been dramatically depleted continuously since the early 1960s.

The summation of the full authorization scenario M1 and D1 simulation storage contents of O. H. Ivie, E. V. Spence, and J. B. Thomas Reservoirs are plotted in Figure 7.3. Simulated storage contents computed in the daily D1 simulation are dramatically lower than storage levels from the monthly M1 simulation. Full authorization scenario M1 simulated storage levels are much lower than actual historical storage levels. The plots of Figure 7.6 show that dramatic increases in storage levels result from activation of ADJINC option 8. This means that storage levels in the model are greatly affected by downstream stream flow availability conditions. The monthly and daily simulation results in Figure 7.6 are almost the same with ADJINC option 8 activated.

Most Hydrologically Severe Droughts Since 1940

All simulations discussed in this report are based on combining the full authorization scenario (as defined by the TCEQ for the Texas WAM System) with natural river system hydrology. The 1940-2016 time series of storage contents, regulated flows, and unappropriated presented in this chapter are WRAP/WAM simulated, not actual historical observed quantities.

Using the full authorization scenario storage plots as a basin-wide drought index, the two most severe droughts in the Colorado River Basin occurred during 1950-1957 and 2008-2015. The 1950s drought begin gradually in 1950 and ended with a major flood in May-April 1957. The 2008-2015 drought began in 2008 and ended with extremely high annual rainfall during 2015.

Storage in all reservoirs and the six Highland Lakes are plotted in Figures 7.1 and 7.2 for simulations M1 and D1. Storage depletions during the 1950s drought are significantly greater in simulation D1 than M1 in both Figures 7.1 and 7.2. However, the six Highland Lakes (Figure 7.2) are completely refilled by the April-May 1957 flood. The storage summation for all reservoirs never totally refills to capacity allowing the severe storage deletion during the 1950s drought to affect storage in future years. This effect is more pronounced in simulation D1 than M1.

The storage plots for M1 and D1 in Figures 7.1 and 7.2 are further examined as follows. The minimum storage volumes during 1940-1960 and 1961-2016 are shown in Table 7.6 as a percentage of the storage capacities of 5,263,900 acre-feet and 2,349,032 acre-feet (Table 7.10), for all 484 reservoirs in the WAM and the six Highland Lakes operated by the LCRA. The dates at which the minimum storage contents occur are also shown in Table 7.16. In the daily simulation D1, the minimum storage contents of the six LCRA reservoirs of 5.97 percent of capacity during the 1950-1957 drought is lower than the minimum of 6.73 percent of capacity during the 2008-

2015 drought. Minimum storages levels occurred during the 2008-2015 drought in the other cases shown in Table 7.16.

Table 7.16
Minimum Storage Contents as Percentage of Authorized Storage Capacity

Simulation	Reservoirs	1940-1960 Minimum		1961-2016 Minimum	
M1	All 484 Reservoirs	16.5%	31 Aug 1952	8.38%	31 Dec 2014
D1	All 484 Reservoirs	7.25%	6 Feb 1957	5.97%	4 Nov 2014
M1	6 Highland Lakes	24.5%	31 Aug 1952	8.42%	28 Feb 2015
D1	6 Highland Lakes	5.97%	11 May 1955	6.73%	19 Sep 2014

Reservoirs storage is still severely depleted at the end of the 1940-2016 hydrologic period-of-analysis due to 2010-2015 drought conditions. Maximum storage levels of the 484 reservoirs occurring after the 2014-2015 maximum draw-downs (minimum storage contents) for simulations M1 and D1 are 63.5% and 34.9% of capacity on 31 June 2016 and 23 June 2016. The summation of storage volume in the 484 reservoirs at the end of the 1940-2016 simulation in simulations M1 and M2 are 3,070,908 acre-feet (58.3% of capacity) and 1,608,193 acre-feet (30.6% of capacity).

Information in Chapter 6 indicates relatively normal hydrologic conditions following 2016. For example, the 2017-2020 basin-wide mean precipitation of 26.9 inches/year is close to the 2017-2020 mean of 26.3 inches/year. Plots of actual observed storage contents in the five largest reservoirs in the basin presented in Figures 6.12-6.16 show significant refilling of storage during 2017 to near the present.

In the monthly simulation M1, the two highest values of the summation of end-of-month storage volumes of the 484 reservoirs during 1941-2016 were 5,124,846 acre-feet (97.4% of capacity) and 4,612,730 acre-feet (87.6% of capacity) on June 1941 and February 1958. Storage contents are dramatically depleted during the 1950s drought, even more so in D1 than M1. The total storage content plotted in Figure 7.1 never fully recovers to capacity after the 1950s drought.

The WAMs incorporate the premise that all reservoirs are full to capacity at the beginning of the simulation. In a full authorization scenario all reservoirs are seldom if ever full at the same time. An interesting issue addressed in the next section is whether switching the beginning-of-simulation storage contents from the D1 to the D2 strategy described below affects the critical draw-down during the 1940s-1950s drought. Full authorization scenario simulated storage levels were found to be essentially the same throughout the 1950s for simulations D1 versus D2.

Beginning-of-Simulation Storage Contents in Simulations D1 and D2

The storage content of each of the reservoirs at the beginning of the simulation is a fundamental modeling issue. The full authorization scenario simulated storage plots of Figures 7.1, 7.2, and 7.3 show storage levels significantly below capacity much of the time. The simulation begins with all reservoirs full to their authorized storage capacity.

All of the WAMs in the TCEQ WAM System for all of the river basins of Texas reflect the premise that all reservoirs are full to their authorized storage capacities at the beginning of the hydrologic period-of-analysis, which for most of the WAMs is January 1940. The reservoirs beginning full premise is partially justified by the late 1930's and early 1940s being relatively wet years. The plots of observed flows in Figures 6.5-6.7 of the preceding chapter show high flows including major floods during the late 1930's and early 1940s. The famous dust bowl drought of the 1930s was generally most severe during 1930-1936 and ended largely by record high rains in 1941. The 1930s drought centered in the panhandles of Texas and Oklahoma but significantly affected adjacent areas of western Texas, eastern New Mexico, and western Kansas.

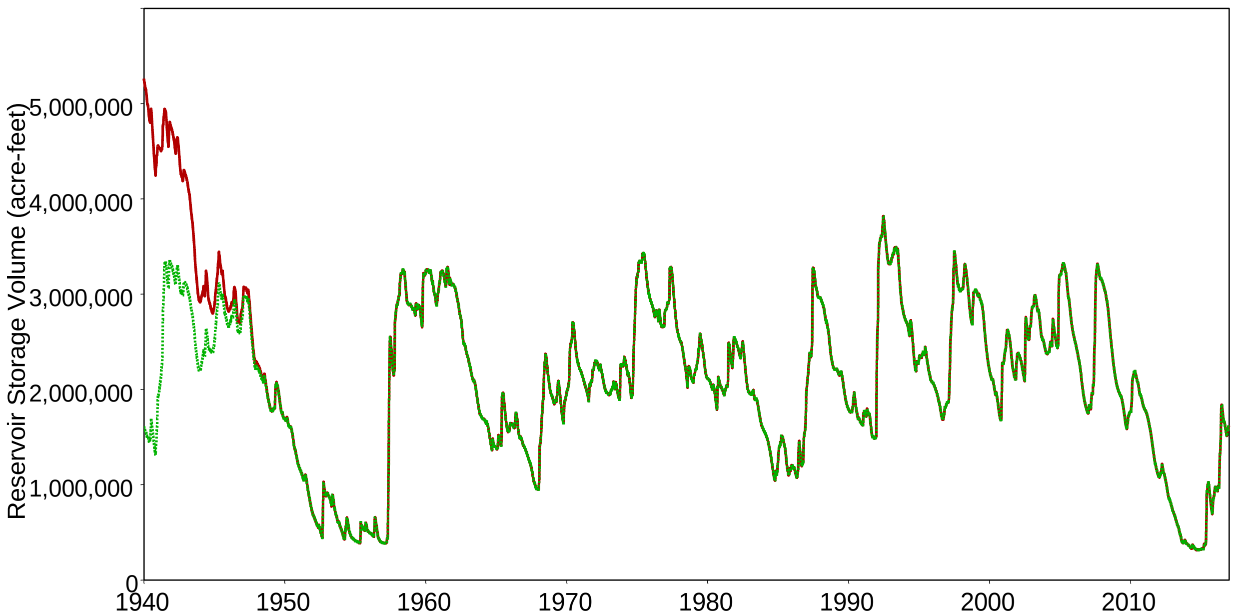

Figure 7.7 Summation of Daily Storage in All Reservoirs for Simulations D1 (red solid line) and D2 (green dotted line)

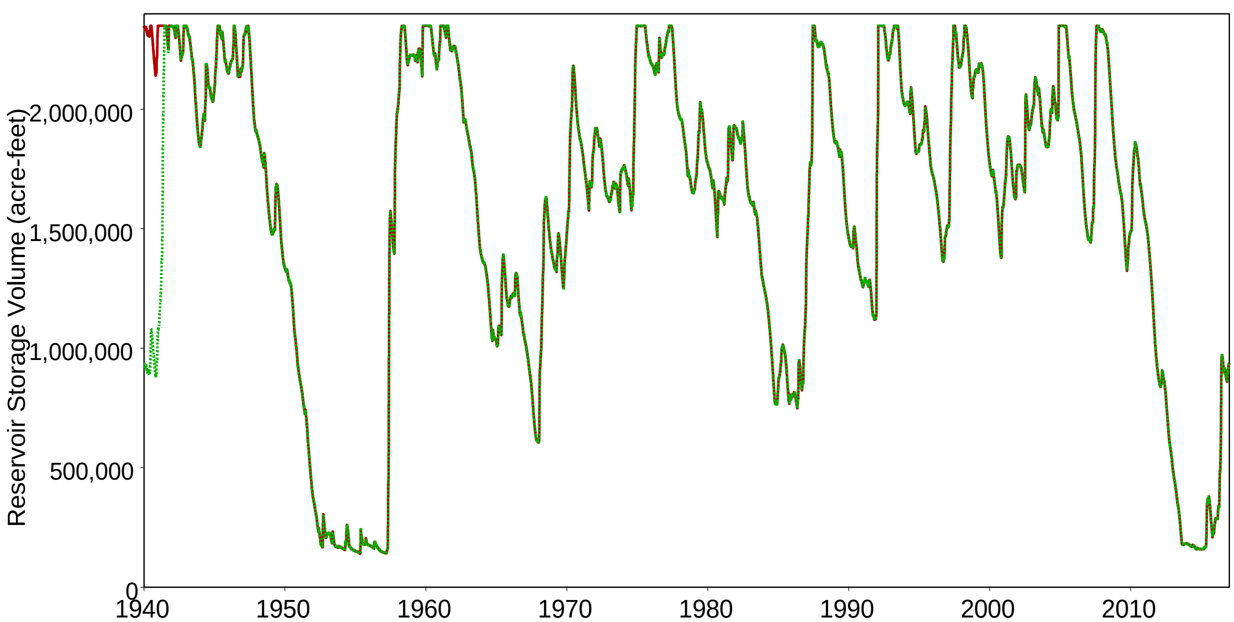

Figure 7.8 Summation of Daily Storage in Six Highland Lakes for Simulations D1 (red solid line) and D2 (green dotted line)

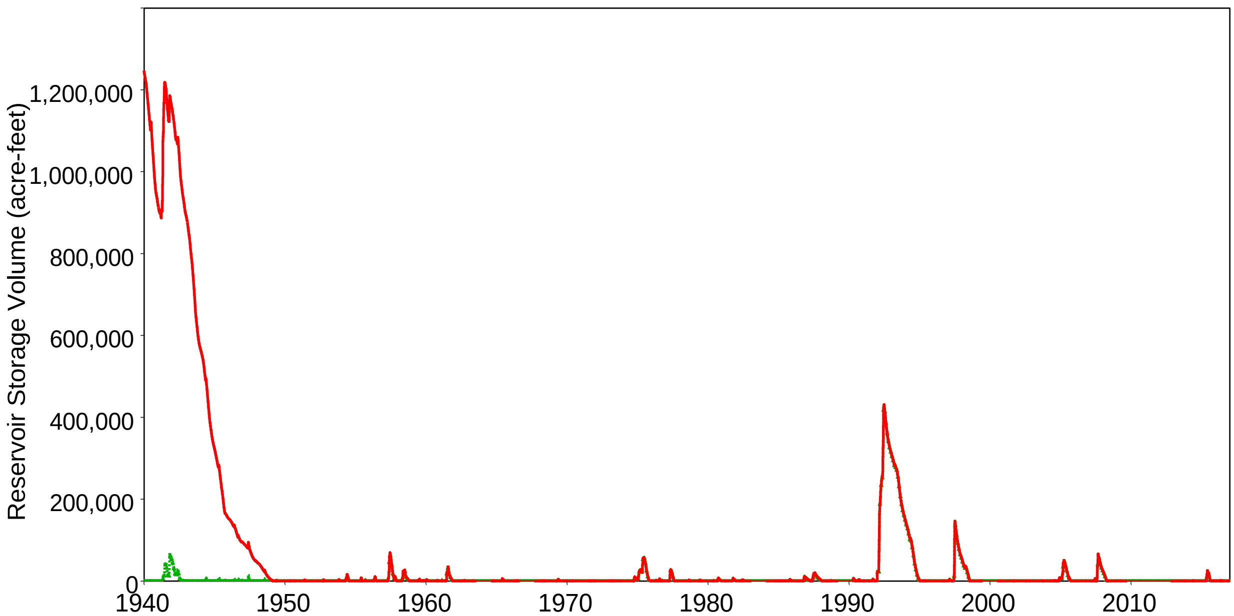

Figure 7.9 Daily Storage in Three CRMWD Reservoirs for D1 (red solid) and D2 (green dots)

The WRAP simulation models *SIM* and *SIMD* include a beginning-ending-storage (BES) option controlled by input parameter BES on the *JO* record that sets the storage contents of each reservoir at the beginning of the simulation equal to its storage at the end of the simulation. This WRAP option is equivalent to the concept of cycling found in the literature meaning a finite fixed-length simulation period is repeated infinitely by setting conditions at the beginning of the fixed length simulation equal to conditions at the end.

As indicated in Tables 7.1 and 7.2, the only difference between the D1 and D2 variations of the daily WAM is the beginning-of-simulation storage contents of each of the reservoirs. In a D1 simulation, all reservoirs are full to their authorized storage capacities at the beginning of January 1940 of the hydrologic period-of-analysis. In a D2 simulation, the storage content of each reservoir at the beginning of January 1940 is set at its storage content at the end of December 2016 determined in a preceding simulation.

The storage contents of the reservoirs at the beginning of the D1 and D2 simulations are shown in the second and third columns of Table 7.15. The reservoir storage in both simulation D1 and D2 are at the level tabulated in the fourth column of Table 7.15 at the date shown in the last column. The storage volumes are the same for simulations D1 and D2 continuously after this date.

Table 7.15
Periods of Different Storage for Simulations D1 and D2

Groups of Reservoirs	January 1, 1940 Storage (ac-ft) Simulation D1	Simulation D2	Same Storage (acre-feet)	Date for Initial Same Storage
All Reservoirs	5,263,900	1,606,860	1,214,062	August 11, 1961
Highland Lakes	2,349,032	936,340	2,348,389	April 12, 1942
CRMWD	1,247,100	0	0	February 17, 1949

Routing in Simulations D3 and D4

Routing in a daily *SIMD* simulation accounts for the time lag and attenuation that occur in the downstream propagation of stream flow alterations (changes) due to filling reservoir storage, releasing flows from reservoirs, and water supply diversions and return flows [4]. The term "*routing*" is used in WRAP/WAM simulation modeling to refer to propagation of flow alterations through free-flowing river reaches. Reservoir operations are simulated separately by reservoir volume balance computations that include inflows and outflows as well storage refilling, net evaporation, and diversions from storage. Routing is controlled by *RT* records in the DIF file.

Routing algorithms modeling lag and attenuation are not employed in a monthly simulation. Stream flow changes resulting from each water right propagate through all downstream control points to the outlet in the same month. Routing is not required in a daily simulation. Without routing, stream flow alterations resulting from each water right in each day propagate through all downstream control points to the outlet in the same day.

WAM variations D1 and D2 do not include routing. WAM variations D3 and D4 are identical to variation D1 except routing is added.

- D3 is identical to simulation D1 except the *RT* record routing parameters for the 30 control points in Table 3.6 of Chapter 3 are activated.
- D4 is identical to D1 except only the *RT* record routing parameters for six control points on the Colorado River below Lake Travis are activated.

Time series plots of storage volumes the three groups of reservoirs defined in Table 7.10 for simulations M1, D1, D3, and D4 are compared in Figures 7.10, 7.11, and 7.12. Storage frequency metrics are compared in Tables 7.11, 7.12, and 7.13. Frequency statistics for regulated and unappropriated flows at three sites are compared in Tables 7.4 through 7.9.

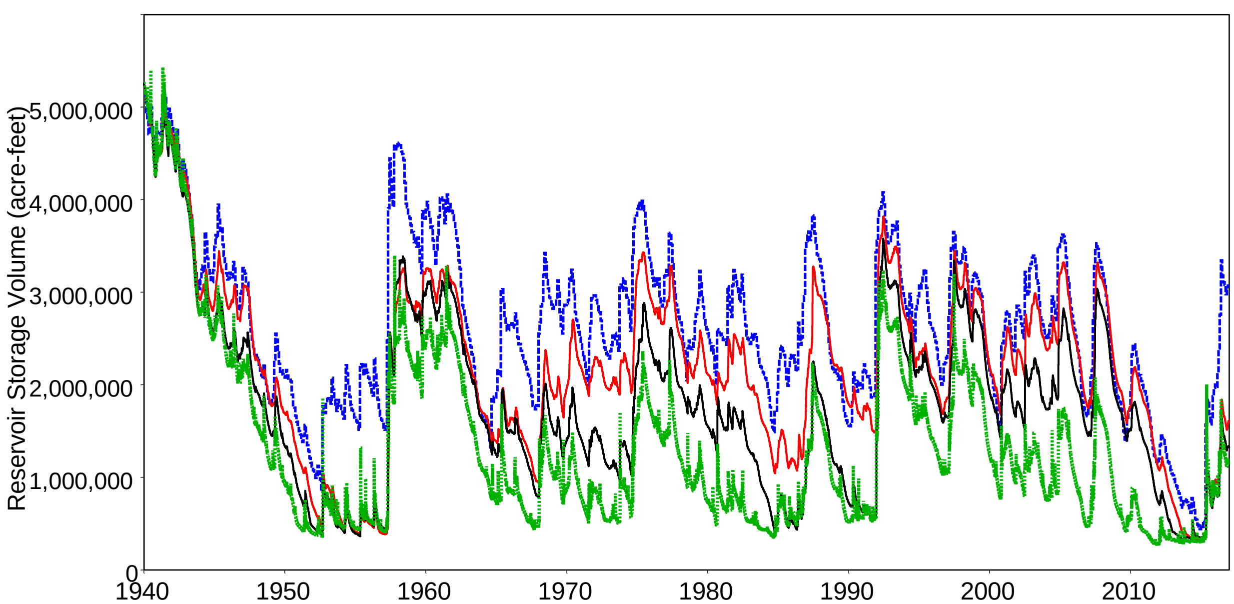

Figure 7.10 Summation of Storage in All Reservoirs for Simulations M1, D1, D3, and D4
(Legend is on the next page.)

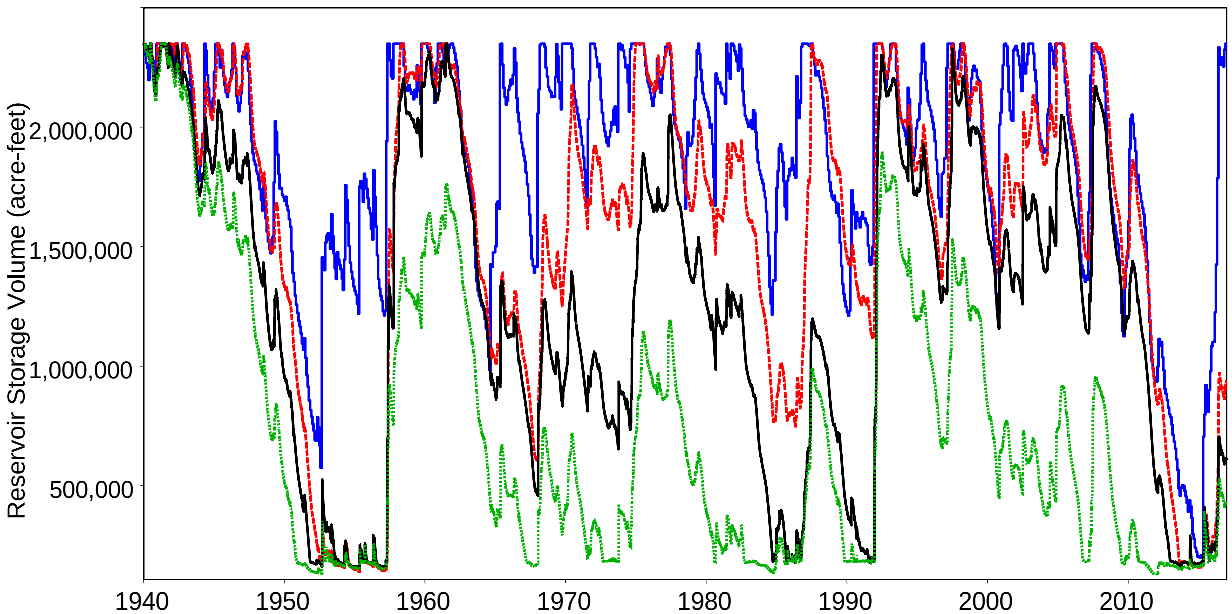

Figure 7.11 Summation of Storage in Six Highland Lakes for
Simulations M1, D1, D3, and D4 (Legend below.)

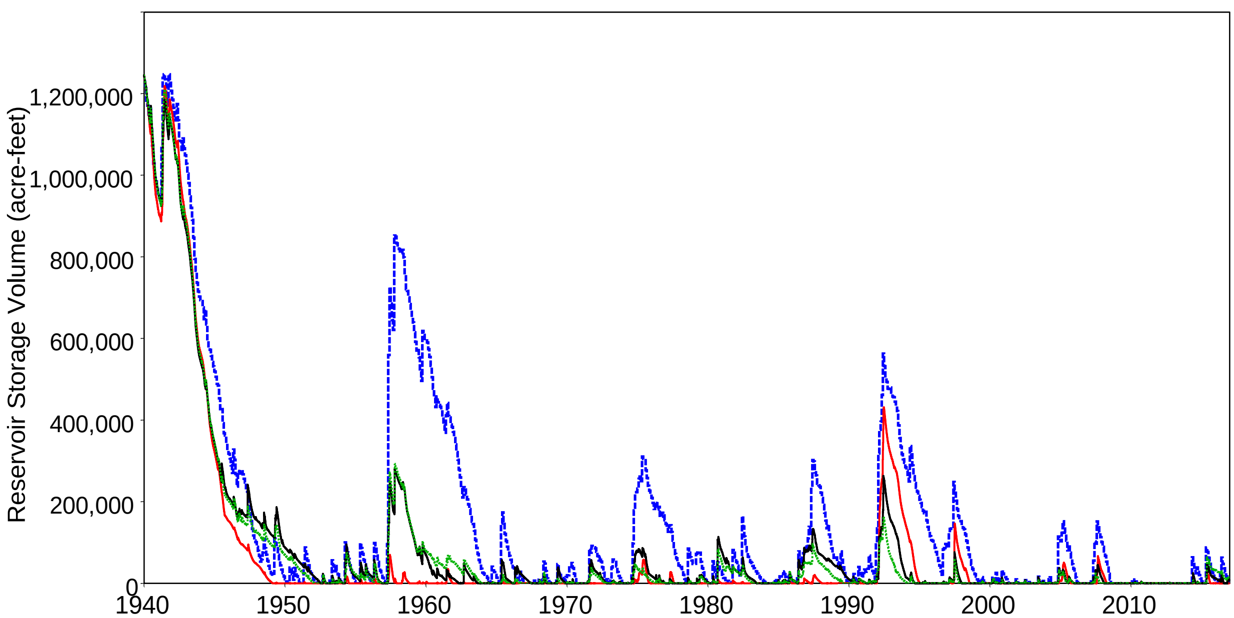

Figure 7.12 Summation of Storage in Three CRMWD Reservoirs for
Simulations M1, D1, D3, and D4

Legend for Figures 7.10, 7.11, and 7.12

- - - - -	blue dashes	M1 monthly
———	red solid	D1 daily with no routing
———	black solid	D3 daily with routing at the 30 control points in Table 3.6
·········	green dots	D4 daily with routing at six control points below Lake Travis

Routing and Forecasting in Simulations D5 and D6

Routing and forecasting deal with the actions of water rights occurring in the current day affecting stream flow in future days. Concepts and computations are explained in detail in the *Daily Manual* [4]. Optional routing computations are included in *SIMD* to simulate the lag and attenuation of flow alterations resulting from filling reservoir storage, releasing flows from reservoirs, and water supply diversions and return flows. Forecasting is relevant in *SIMD* only if routing is employed. Forecasting should not be activated without routing. Forecasting serves the two purposes of:

1. protecting downstream senior rights from the actions of junior water rights occurring in previous days as the effects on stream flow propagate downstream over time
2. preventing excessive flood releases in the current day that contribute to exceeding maximum allowable non-damaging flow levels at downstream locations in future days

WAM variation D5 is identical to variation D3 except forecasting is activated with a forecast period of three days. Variation D6 is identical to variation D5 except the forecast period is increased to seven days (Tables 7.1 and 7.2).

SIMD Input Data

Input data required to incorporate routing and forecasting in the daily Colorado WAM is covered in Chapter 3. *RT* records with the lag and attenuation routing parameters stored in the DIF file are replicated in Table 3.6. Forecasting is controlled by parameters on the *JU* record in the DAT file [2]. Simulation control (*JD*, *JO*, *JT*, *JU*, *OF*) records found at the beginning of the DAT file are replicated in Table 7.16 with input parameter values employed in simulation D5. The only change from D5 to D6 is increasing the forecast period on the *JU* record from 3 days to 7 days.

Table 7.16
DAT File Simulation Control Records with Values for Simulation D5

```
**-------1---------2---------3---------4---------5---------6---------7---------8
**345678901234567890123456789012345678901234567890123456789012345678901234567890
**      !       !       !       !       !       !       !       !       !       !
JD    77    1940       1       1       0               7                       18
JO     6           1       1       1                                   2
JT
JU     1   0   0   0   2   3   3
OF     0   0   3   4   0   0   1                              C3
OFV    1   2   3   9
```

Negative incremental flow ADJINC option 7 is activated in *JD* record column 56 for all simulations employing forecasting including D5 as reflected in Table 7.16. ADJINC option 4 is employed for the daily simulations without forecasting. Routing can be deactivating either by removing the DIF file *RT* records or using the NORT switch in *JU* record field 9 (column 36). Forecasting is not relevant and should not be activated unless routing is employed.

Input parameters WRMETH and WRFCST are entered in *JU* record columns 16 and 20. The defaults for WRMETH and WRFCST are adopted for all of the simulations presented in this report. Flow changes are placed at the beginning of the priority sequence in the next day of the simulation.

Input parameters FCST, FPRD, and APRD in *JU* record columns 24, 28, and 32 control forecasting. Simulation D5 is assigned a forecast period of 3 days. The following forecast parameter information is replicated from the *SIMD* message MSS file for simulation D5. All of this information except the forecast of 3 future days is the same regardless of the forecast period specified.

```
Daily simulation information:
484 control points form the longest flow path to the outlet.
 30 control points have routing coefficients in the DIF file.
 13 control points form the longest routing chain to the outlet.
 20 forecast days are required for the longest routing chain with normal flow parameters.
 13 forecast days are required for the longest routing chain with flood flow parameters.
  3 future time steps are covered during the forecast simulation.
```

Forecasting is activated with FCST in *JU* record field 6 (column 24). The forecast period FPRD is entered in *JU* record field 7 (column 28). A blank *JU* field 7 activates a *SIMD* routine that automatically computes the forecast period. The automatic default forecast period for the Colorado WAM is 41 days computed within *SIMD* as twice the longest flow path plus one day. As indicated by the *SIMD* message file information replicated above, the longest flow path is formed by 484 control points. The longest routing chain has normal flow lag times totaling 20 days. The default forecast period is 2×20 days + 1 day = 41 days. Forecasting future stream flows over the next 41 days is not appropriate for adoption in the daily Colorado WAM due to over-constraining stream flow availability.

<u>Comparison of Simulation Results</u>

The dataset for simulation D5 is adopted for purposes of the work documented by the remainder of this report. Reservoir flood control operations are added to the D5 dataset in the next section of the present Chapter 7. SB3 environmental flow standards are added in Chapter 8.

Selection of a forecast period of three days is somewhat arbitrary. A forecast period much longer than about seven days unrealistically constrains availability of stream flow for supplying water needs and refilling reservoir storage in the simulation model. Variation D1 of the WAM as well as variation D5 are considered to be reasonable daily simulation models. Version D1 has no routing and no forecasting. D5 includes routing at 30 control points and forecasting over a future forecast period of three days. The D5 version of the simulation model directly addresses the lag time aspects of stream flow alterations but necessarily in a very approximate manner.

Statistical frequency metrics for regulated and unappropriated flows from simulations with ten variations of the WAM, including variations D5 and D6, are tabulated in Tables 7.4-7.9. Statistics for reservoir storage contents are tabulated in Tables 7.11-7.13.

Storage plots comparing simulations MC, D1, D5, and D6 are presented as Figures 7.13, 7.14, and 7.15. Reservoir storage contents plots for simulations D1, D5, and D6 are close to each other but generally tend to be lower than the storage from for M1. Of the three daily simulations, D5 storage volumes are generally closest to simulation M1 storage volumes. Differences in storage levels computed with the daily simulations versus the monthly simulation are most pronounced for the 1950s drought. In Figures 7.13 and 7.15, the storage depletions during the 1950s drought and associated differences between monthly versus daily simulations propagate past the 1950s.

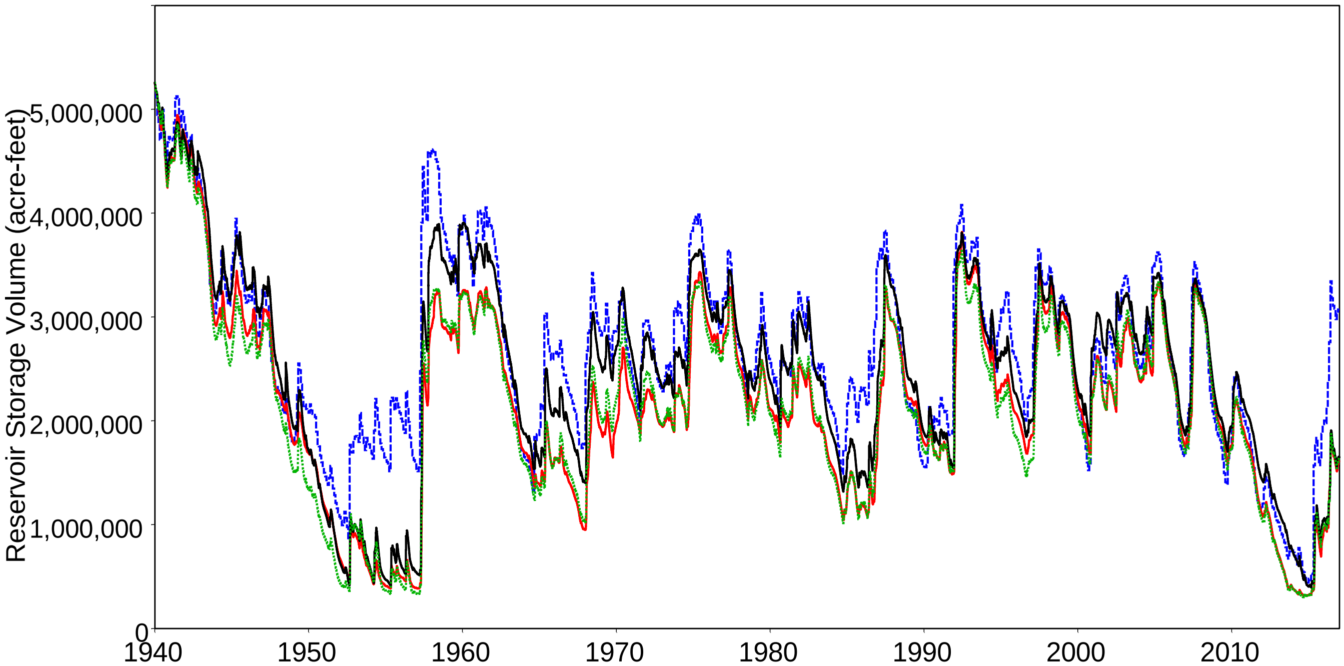

Figure 7.13 Summation of Daily Storage in All Reservoirs for M1, D1, D5, and D6

Legend for Figures 7.13, 7.14, and 7.15

- - - - - -	blue dashes	M1 monthly
———	red solid	D1 daily with no routing
———	black solid	D5 routing and 3-day forecast
....	green dots	D6 routing and 7-day forecast

Effects of Routing and Forecasting

The monthly *SIM* and daily *SIMD* simulation algorithms for determining the amount of stream flow available to each water right are employed within the framework of Table 7.3. Available stream flow quantities are computed 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 may result in over-constraining flow availability. Without forecasting, water rights may not be fully protected from the actions of junior rights in previous days, thus violating the water rights priority system.

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. Flood control operations are added in WAM variation D7 discussed in the next section.

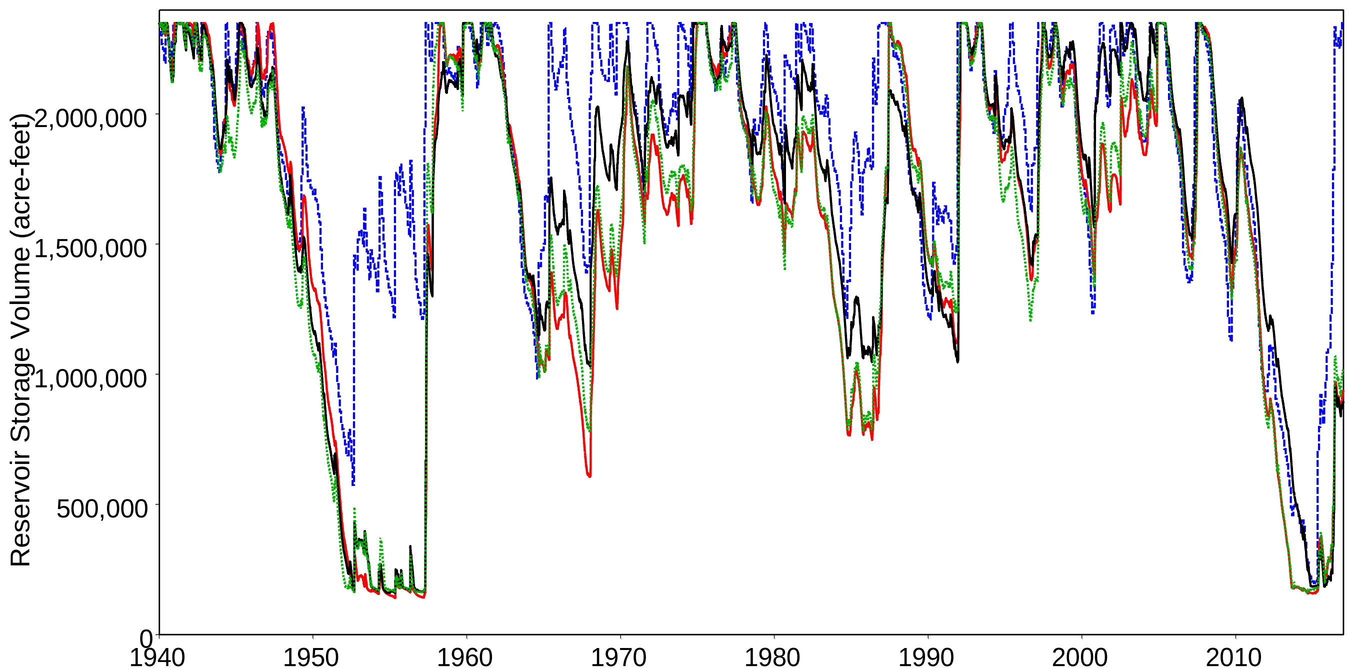

Figure 7.14 Summation of Daily Storage in Six Highland Lakes for M1, D1, D5, and D6

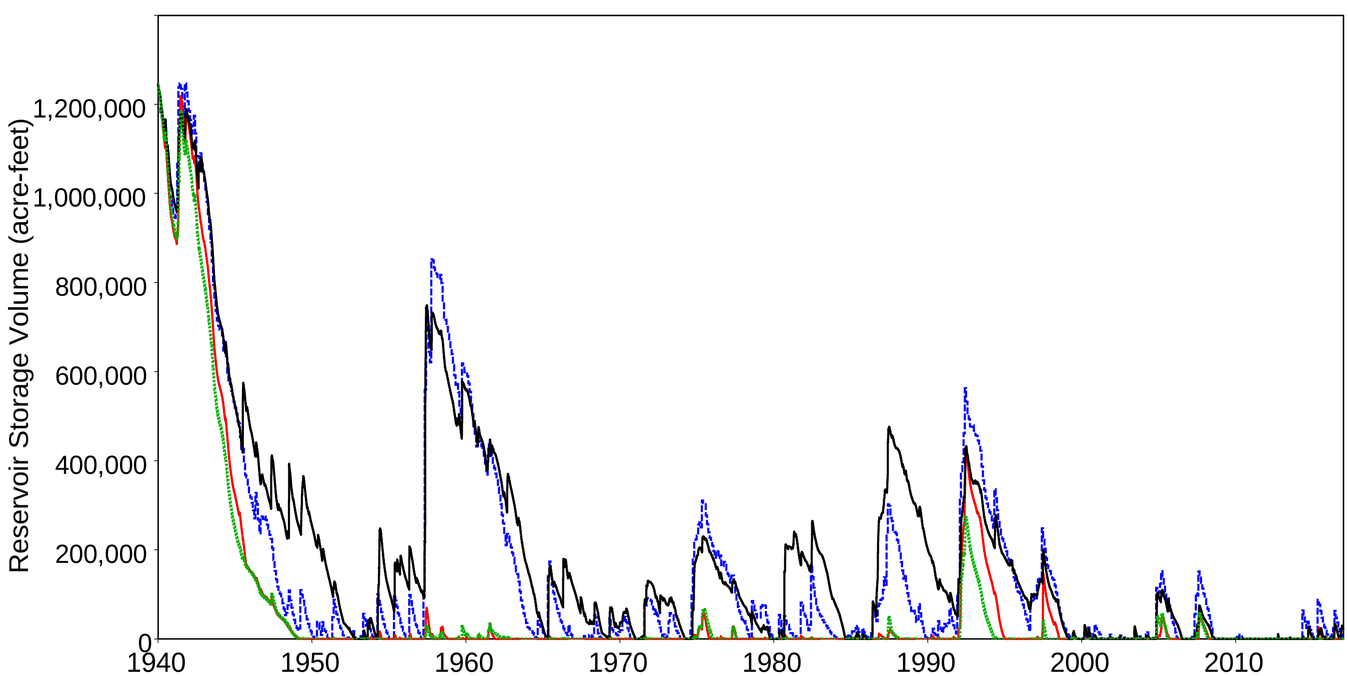

Figure 7.15 Summation of Daily Storage in Three CRMWD Reservoirs for M1, D1, D5, and D6

Legend for Figures 7.13, 7.14, and 7.15

- - - -	blue dashes	M1 monthly
———	red solid	D1 daily with no routing
———	black solid	D5 routing and 3-day forecast
········	green dots	D6 routing and 7-day forecast

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-world water management, with inaccuracies increasing with the length into the future of the forecast period. Forecasting in actual water management means predicting unknown future stream flows. Forecasting in a *SIMD* simulation consists of estimating the effects of current-day actions of water rights on stream flow availability in future days given known naturalized flows in future days. The selection of a *SIMD* forecast period is largely arbitrary. As discussed in Chapter 5, routing inaccuracies contribute to forecasting inaccuracies.

The monthly WAMs employed in simulations MC and M1 and daily WAMs employed in simulations D1, D2, D3, D4, and D5 are all considered to be valid and appropriate models. These models like all mathematical models reflect premises, approximations, and inaccuracies. However, these variations of the Colorado WAM generate meaningful information. Either of these variations of the WAM or other variations could be the optimal modeling choice depending on circumstances and requirements of particular applications.

Daily WAM version D5 is selected for the continuing studies described in the remainder of this report. Reservoir flood control operations are added to the D5 dataset in the next section of the present chapter. SB3 environmental flow standards are added in the next chapter.

Reservoir Flood Control Operations in Simulation D7

The *SIMD* input dataset labeled D7 was created by adding operations of federally designated flood control pools of four multiple purpose reservoirs to the *SIMD* input dataset labeled D5. Simulations with WAM dataset variations D5 and D7 are the same except for the addition of reservoir flood control operations in WAM variation D7 (Tables 7.1 and 7.2).

Actual procedures followed in flood control operations of Travis, Twin Buttes, O. C. Fisher, and Hords Creek Reservoirs are outlined in Chapter 4. *SIMD* modeling of the flood control operations of these multiple-purpose reservoirs is also explained in Chapter 4. Tables 4.4 and 4.5 are replicated below as Tables 7.17 and 7.18 for convenient reference. Input records added to the DAT file containing the information tabulated in these two tables are listed in Tables 4.6 and 4.7 of Chapter 4. *SIMD* methodologies are explained in the WRAP Daily and Users Manuals [2, 4].

Simulation Results

Statistical frequency metrics for regulated and unappropriated flows and reservoir storage volumes generated with the D7 simulation are included in Tables 7.4 through 7.13 along with the other alternative simulations selected for comparison. Storage contents of the four flood control reservoirs are plotted in Figures 7.18 and 7.20. Regulated flows below Mansfield Dam (Lake Travis) are plotted in Figure 7.19. Storage plots for the three groups of reservoirs described in Table 7.10 are provided as Figures 7.16, 7.17, and 7.18.

Table 7.17
Flood Control Reservoir *FR* Record Input Parameters

Reservoir	Reservoir Identifier	Control Point ID	Flood Control Pool FCBOTTOM	Flood Control Pool FCTOP	Limit FCMAX
			(ac-ft)	(ac-ft)	(cfs)
Travis	TRAVIS	I20000	1,170,752	1,969,005	7,500
Twin Buttes	TWINBU	C20260	186,200	640,564	-
O. C. Fisher	OCFISH	C20040	119,200	396,174	-
Hords Creek	HORDSC	F30370	7,959	25,262	-

Table 7.18
Maximum Allowable Flood Flow Limits at USGS Stream Gage Stations

Control Point	Stream	Nearest City	Drainage Area	Flood Flow Limit
			(sq miles)	(cfs)
C20000	Concho River	San Angelo	4,139	25,000
C10000	Concho River	Paint Rock	5,185	25,000
F30300	Hords Creek	Coleman	107	10,000
I10000	Colorado River	Austin	27,611	30,000
J30000	Colorado River	Bastrop	28,580	45,000
J10000	Colorado River	Columbus	30,244	50,000

As indicated in Table 7.17, in the simulation model, storage capacities of Lake Travis impounded by Mansfield Dam at the top of conservation pool and flood control pool are 1,170,752 and 1,969,005 acre-feet, respectively. The simulated Lake Travis storage levels encroach into the flood control frequently as shown in Figure 7.16. Two flood events result in the flood control pool storage contents reaching capacity resulting in regulated flows of the Colorado River downstream of the dam plotted in Figure 7.17 exceeding the designated maximum release rate of 7,500 cfs (Table 7.17). The 7,500 cfs maximum release is designed to reduce flooding along the river downstream of the dam. In actual operations, the 7,500 cfs maximum release limit can be increased as flood control pool storage capacity is depleted to reduce flood damages upstream of the dam. However, for purposes of the simulation study, the maximum release limit is fixed at 7,500 cfs until the flood control storage capacity is exceeded.

Figure 7.18 shows that storage levels of Twin Buttes, O. C. Fisher, and Hords Creek Reservoirs never encroach into the flood pool during the 1940-2016 hydrologic period-of-analysis. The full authorization scenario simulation results is severe conservation pool storage depletions. The plots of actual historical storage contents of Figures 4.2, 4.3, and 4.4 also show dramatic storage draw-downs in these three reservoirs. As indicated by Figure 7.19 and similar plots in previous sections of this chapter, in full authorization scenario simulations, storage levels of many of the reservoirs in the Colorado River Basin are well below conservation storage capacity most of the time. These reservoirs store flood waters when available, incidentally reducing flood flows.

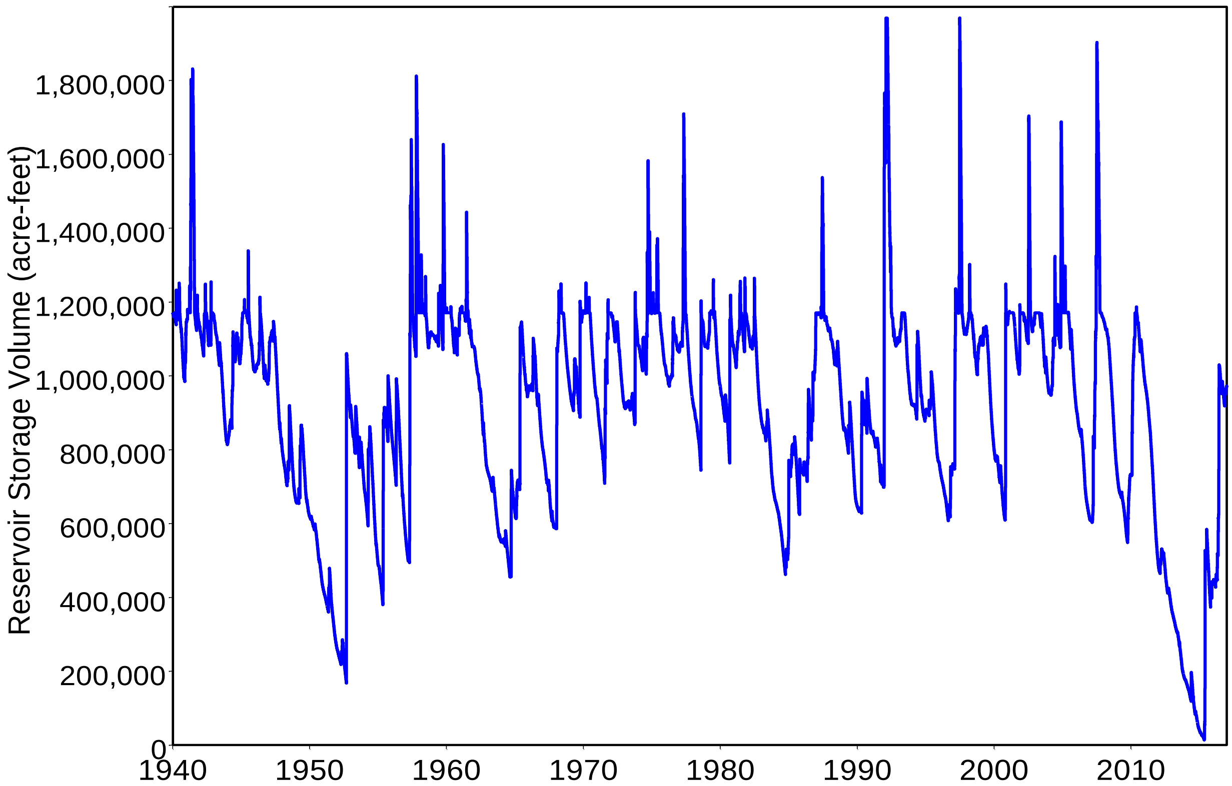

Figure 7.16 Simulation D7 Storage in Lake Travis

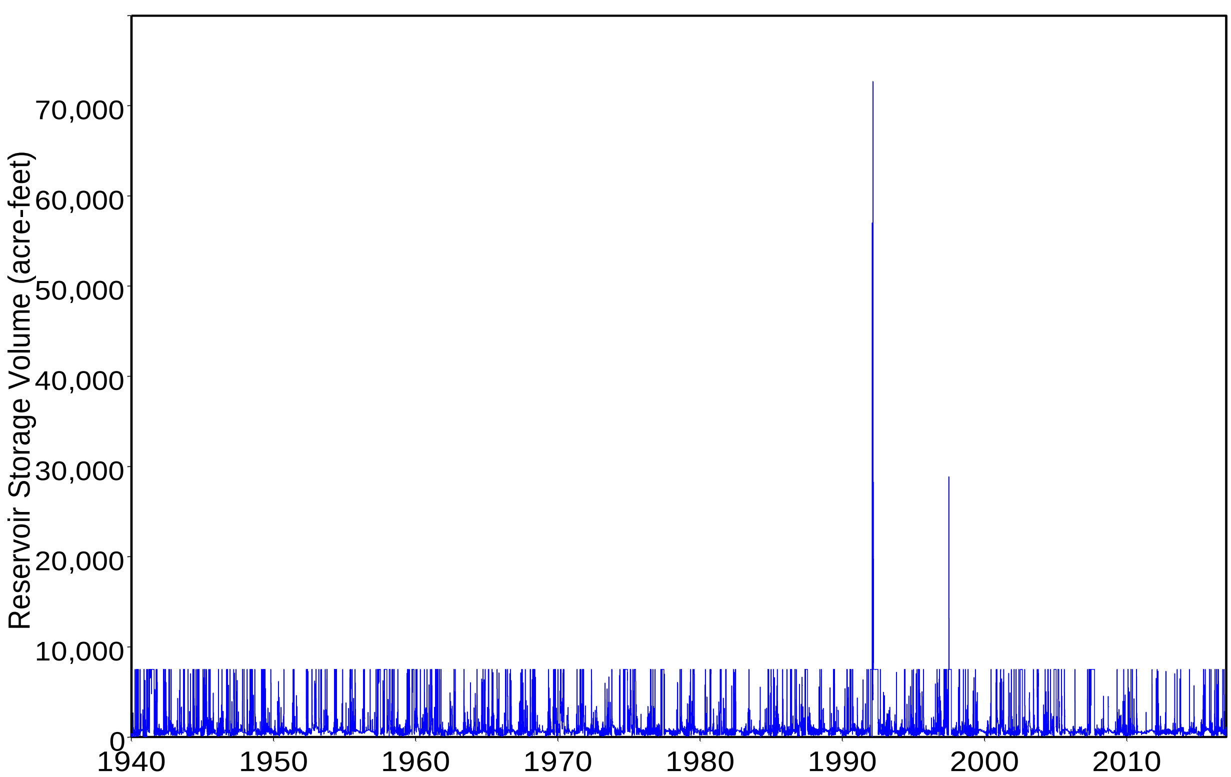

Figure 7.17 Simulation D7 Regulated Flows of Colorado River below Mansfield Dam (I20000)

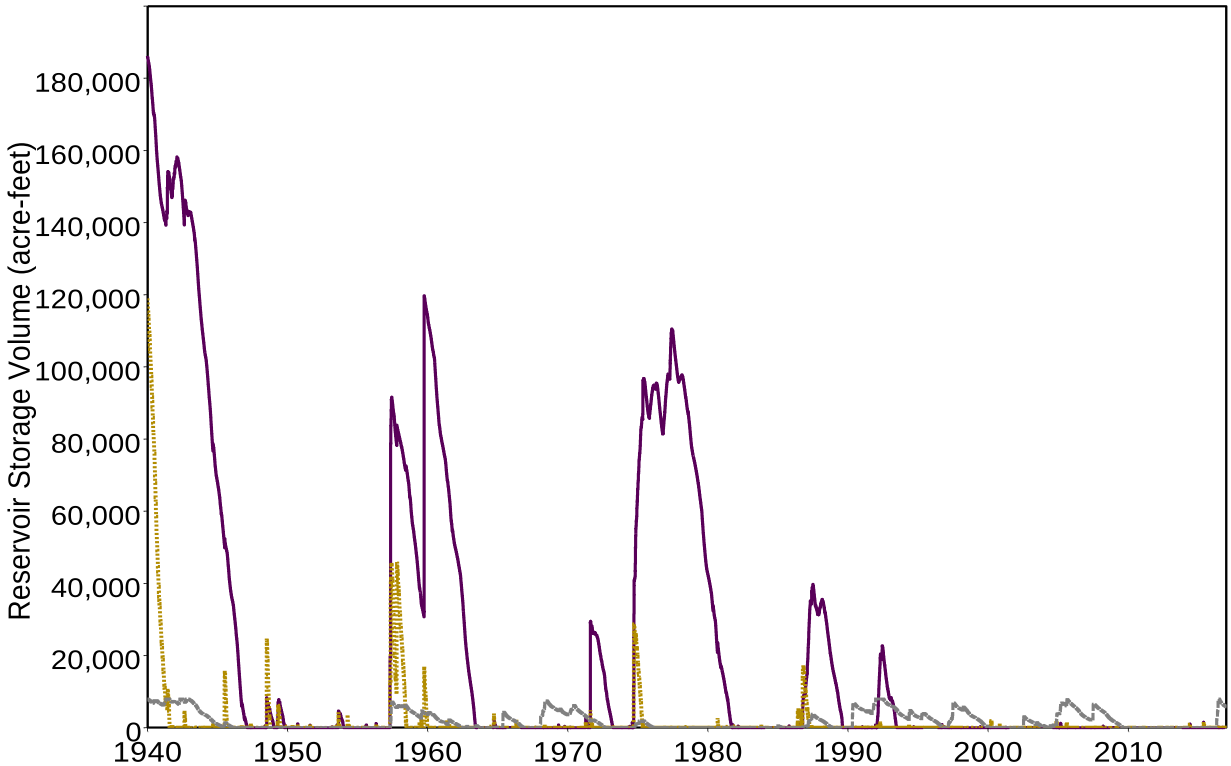

Figure 7.18 Simulation D7 Storage in Twin Buttes (purple solid), O. C. Fischer (orange dots), and Hords Creek (gray dashes) Reservoirs

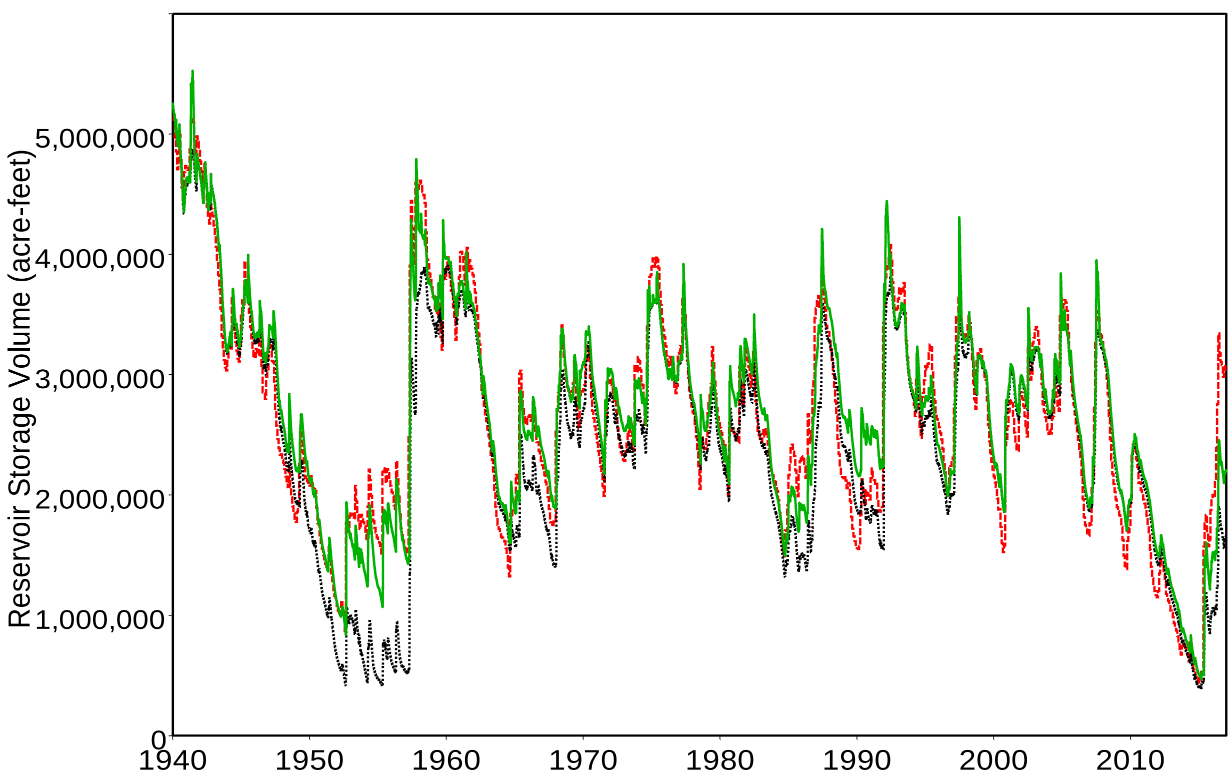

Figure 7.19 Total Storage for M1 (red dashes), D5 (black dots), and D7 (green solid)

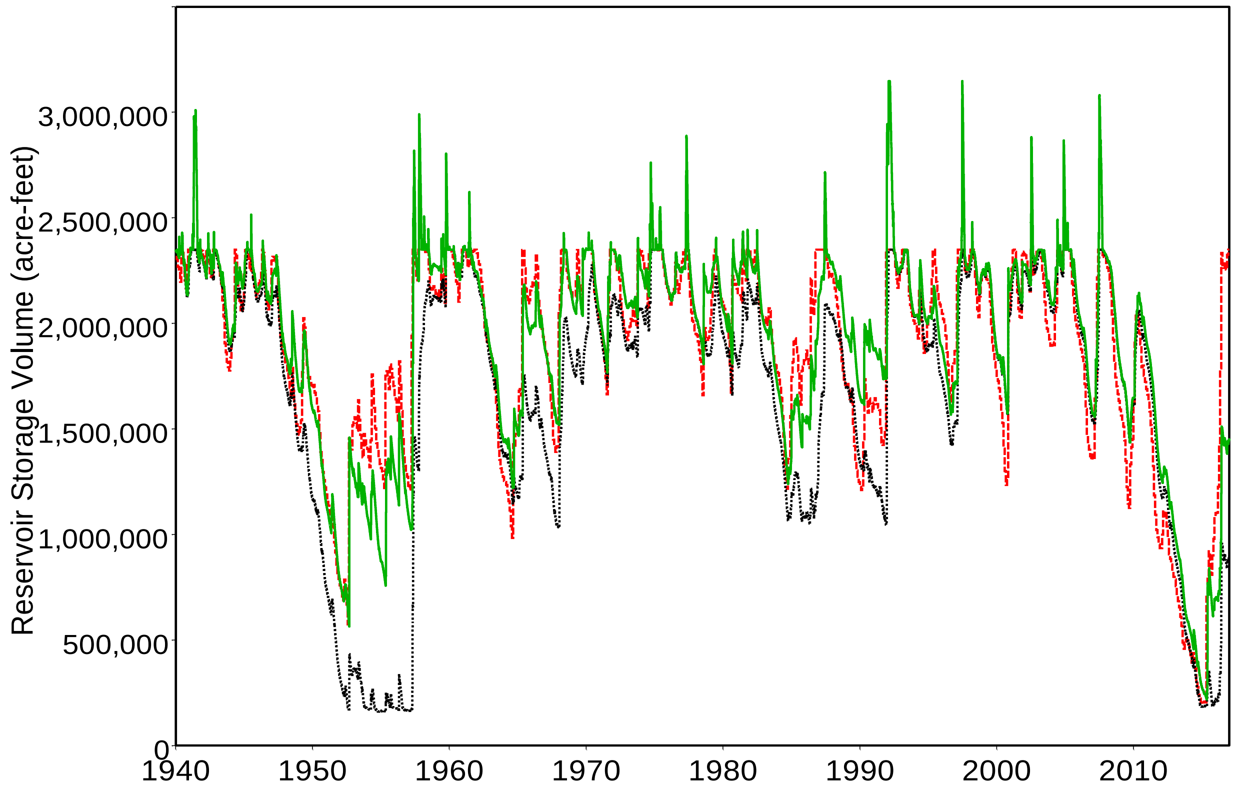

Figure 7.17 Highland Lakes Storage for M1 (red dashes), D5 (black dots), and D7 (green solid)

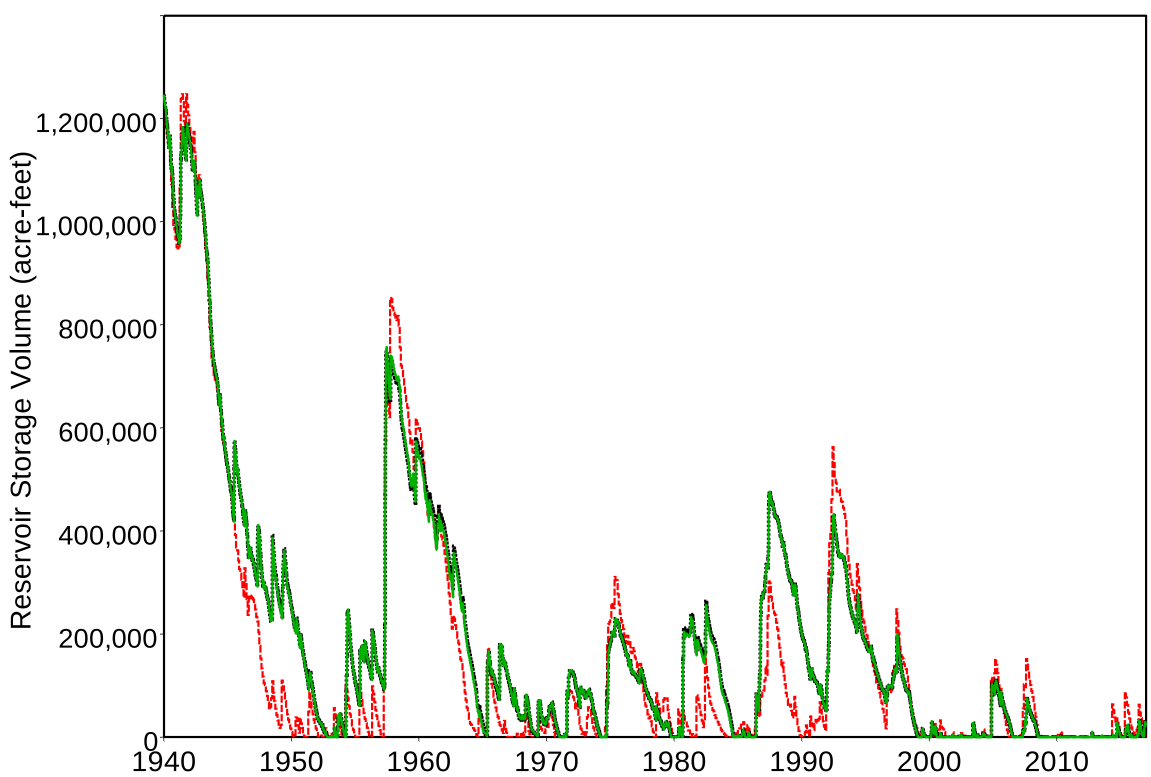

Figure 7.18 CRMWD Storage for M1 (red dashes), D5 (black dots), and D7 (green solid)

Summary of Comparative Analyses of Alternative Simulations

Ten alternative simulations with variations of the Colorado WAM employing different optional WRAP modeling capabilities are defined in Tables 7.1 and 7.2. The simulation study included many other simulations to detect and correct input data errors and explore various issues along with these ten selected for inclusion in the comparative analyses presented in this chapter. Modeling features reflected in the monthly variations of the WAM labeled MC and M1 and daily variations labeled D1 through D7 are the focus of the discussions presented in Chapter 7.

The primary motivation for developing daily WRAP/WAM modeling capabilities is to improve capabilities for incorporating into the TCEQ WAM System the environmental flow standards (EFS) developed through the process created by the 1997 Senate Bill 3 (SB3). Chapter 8 focuses specifically on modeling and analysis of SB3 EFS. The WAM variation labeled C3D in Tables 7.1 and 7.2 consists of adding SB3 EFS to version D7 as described in the next chapter.

The primary reason for supplementing monthly WAM capabilities with a daily version of the WAM is to capture the within-month variability of stream flow. Daily stream flow variability is important in modeling SB3 EFS, particularly high flow pulse components of the EFS. A daily (or smaller) time interval is also necessary for simulating reservoir flood control operations.

River flows actually vary continuously in reality. Averaging instantaneous flows over a computational time interval dampens variations (smooths out or averages out variability). Variability is reduced with increases in the length of the averaging time step. 924 within-month means exhibit less variability than 28,125 means of instantaneous flows averaged within each individual day. However, starting with the same long time series of instantaneous flows, the long-term (1940-2016) means of annual, monthly, daily, or hourly flows are the same. Standard deviations and exceedance frequency quantities for daily versus monthly flow rates vary significantly as demonstrated by statistics presented in Table 6.3 and multiple tables in Chapter 7.

Monthly versus daily relationships between flow rates or volumes versus storage volumes are different. Monthly flow rates are averaged over each of the 924 months of 1940-2016. Daily flow rates are averaged over each of the 28,125 days. The 28,125 end-of-day storage volumes for each reservoir in the 1940-2016 simulation are a subset of the 924 end-of-month storage volumes.

Frequency statistics for regulated and unappropriated flows generated with the two monthly and eight daily variations of the simulation model defined in Table 7.1 are compared in Tables 7.4 through 7.9. The frequency metrics are presented for the three USGS gage locations on the Colorado River at or near San Saba, Austin, and Wharton.

Frequency statistics for end-of-month and end-of-day reservoir storage contents are compared in Tables 7.11, 7.12, and 7.13 for three groups of reservoirs described in Table 7.10. End of day or month storage contents are summed for all reservoirs in the group. The largest group contains all 484 reservoirs in the WAM. These 484 reservoirs are located at 470 control points and exclude reservoirs designated as artificial. The other two groupings adopted are the six Highland Lakes operated by the LCRA and the three largest CRMWD reservoirs. Time series plot of end-of-month and end-of-day storage contents comparing selected simulations are presented throughout the chapter.

Stream flow throughout the Colorado River Basin and throughout Texas is extremely variable. The variability includes continuous within-day variability and daily within-month variability as well as monthly, seasonal, and annual variability. The variability includes continual fluctuations as well as the extremes of intense floods and severe multiple years droughts.

The effects of within-month daily variability are explored in this chapter through comparisons of WAM variations D1 and M1 defined in Table 7.1. Monthly-to-daily disaggregation of monthly naturalized flows to daily is the key most important aspect of converting the monthly Colorado WAM to a daily version of the WAM.

The following two aspects of water availability modeling are important in the consideration of inaccuracies and approximations of monthly versus daily WAM modeling.

1. Preserving the water rights priority system representing the Texas prior appropriation doctrine based water rights permit system is essential to water availability modeling.
2. Alterations to stream flow resulting from refilling of reservoir storage and supplying water supply diversion targets by water rights in the current day may require several days to affect flows at locations various distances downstream.

The actions of water rights in the current day may decrease the amount of stream flow available to more senior water rights in future days.

The monthly WAM reflects the premise that effects of water rights on available stream flow propagate to the river basin outlet in the same month that the water right streamflow depletions or return flows occur. This premise is a significant approximation that significantly simplifies the WAM. Routing and forecasting are introduced in the daily simulation model to model the propagation of streamflow depletions over multiple days while still preserving the water rights priority system. As discussed in Chapters 3 and 7 routing and forecasting are necessarily very approximate. Forecasting is not employed unless routing is activated.

Routing and forecasting are investigated through simulations D3, D4, D5, and D6. The routing parameters are admittedly very approximate (Chapters 3 and 7). Selecting an optimal forecast period is largely subjective. WAM variation D7 with a forecast period of three days was selected to carry forward to the modeling and analysis of SB3 EFS reported in Chapter 8. However, a shorter or longer forecast period or inclusion of no routing or forecasting would also result in a valid and appropriate daily WAM. Lengthening the forecast period too much, say perhaps to more than a week, over-constrains stream flow availability and would not be appropriate.

The daily Colorado WAM also facilitates modeling reservoir flood control pool operations. WAM variation D7 includes adding the flood control pools of Lakes Travis, Twin Buttes, O.C. Fischer, and Hords Creek. However, the full authorization scenario WAM simulation results show Lake Travis as being the only reservoir actually storing water in the flood control pool. Twin Buttes, O.C. Fischer, and Hords Creek Reservoirs are continuously drawn down below the top of conservation pool (bottom of flood control pool). These three reservoirs and many other reservoirs in the WAM reduce flood flows by refilling depleted conservation storage capacity with high flows during floods. Employing *SIMD* flood control pool features significantly affect the operation of Lake Travis but does not affect the operation of the three other flood control reservoirs.

CHAPTER 8
MODELING AND ANALYSIS OF ENVIRONMENTAL FLOW STANDARDS

Environmental flow standards (EFS) at 14 gage sites in the Colorado River Basin established by the TCEQ in collaboration with a science team and stakeholder committee following procedures established by the 2007 Senate Bill 3 (SB3) are described in Chapter 5. The *SIMD* methodology for modeling the SB3 EFS is also described in Chapter 5. The set of input data records created to simulate the SB3 EFS is replicated as Table 5.12 of Chapter 5. The daily WAM with simulation results presented in Chapter 8 was developed by inserting the input records of Table 5.12 into the D7 variation of the WAM developed in the preceding Chapter 7.

Chapter 8 focuses on employing the daily Colorado WAM to compute instream flow targets for the SB3 EFS. A procedure introduced in Chapter 5 is implemented in Chapter 8 in which daily instream flow targets for the SB3 EFS computed in a daily *SIMD* simulation are summed to monthly totals and incorporated in the monthly *SIM* input dataset for the monthly Colorado WAM. Chapter 8 also includes various comparative analyses of the SB3 EFS instream flow targets and shortages in meeting the targets.

Instream Flow Requirements in the Colorado WAM

Instream flow requirements are modeled in the WAMs as *IF* record water rights that set targets in terms of targeted minimum limits on regulated stream flow rates. Diversions and reservoir storage by junior *WR* record water rights are curtailed in the simulation as necessary to protect the minimum regulated flow limits established by more senior *IF* record right targets at downstream control points. Redundancies may occur in cases where curtailment of *WR* record water right diversions and/or reservoir storage refilling to meet minimum flow targets set by a particular senior *IF* record instream flow right incidentally also preserves flows protecting the minimum flow limits set by other *IF* record rights at the same or other locations.

The 120 instream flow *IF* records in the Colorado WAM last updated by the TCEQ in February 2020 are listed in Table 2.5 of Chapter 2. These 120 *IF* record rights have priorities ranging from December 31, 1904 (19041231) to August 4, 2010 (20100804). The additional *IF* record rights modeling the new SB3 EFS described in Chapter 5 are inserted in the daily WAM in Chapter 8 with a priority date of March 1, 2011 (20110301). The 120 existing *IF* record rights in the monthly Colorado WAM are not altered in the conversion to a daily WAM other than uniformly distributing the monthly instream flow targets to the 28, 29, 30, or 31 days in each month.

The LCRA Water Management Plan (WMP) includes releases of water from Lakes Travis and Buchanan to supply environmental needs for instream flows of the Colorado River between Lake Travis and the outlet and inflows to Matagorda Bay as discussed in Chapters 2 and 5. The LCRA WMP and SB3 EFS are overlapping but protect environmental flows differently. The LCRA WMP includes protection of environmental flows as part of the LCRA reservoir system operating plan. The SB3 EFS constrain appropriation of set-asides by more junior water right applicants but does not affect LCRA reservoir system operations or other more senior water rights.

The LCRA WMP incorporated in the 2020 monthly WAM includes subsistence and base flows at the three USGS gages on the Colorado River at Columbus, Wharton, and Bay City and only subsistence flows at one other site, the gage on the Colorado River at Austin. These subsistence and base flow limits at sites below Lake Travis reflect the same flow rates specified in the SB3 EFS. However, unlike the SB3 EFS, the WMP environmental flows are supplied as necessary by releases of stored water based on three levels of instream flow criteria that decrease releases as combined storage levels in Lakes Buchanan and Travis decrease.

LCRA WMP requirements for maintaining freshwater inflows for Matagorda Bay ecosystems are modeled in the 2020 monthly WAM based on criteria that vary with drought severity and water availability. For each criteria level, requirements for reservoir releases decrease as combined storage levels in Lakes Buchanan and Travis decrease along with curtailment of interruptible stored water for agriculture.

The May 2019 and later versions of the WRAP simulation models *SIM* and *SIMD* include *ES*, *HC*, *PF*, and *PO* records designed for modeling environmental instream flow requirements formulated in the format adopted by the 2007 SB3 process. Both *SIM* and *SIMD* include *ES* and *HC* records. *PF* and *PO* records are applicable only in a daily *SIMD* simulation. These recently added record types are used in the new daily Colorado WAM to model the SB3 EFS. The newer record types are not employed in the current or previous versions of the monthly Colorado WAM. Instream flow requirements are modeled with the 120 *IF* records in Table 2.5 in combination with *UC*, *WS*, *TO*, *FS*, and/or *DI/IS/IP/IM* records. Previous monthly Colorado WAM versions have no high flow pulse targets relevant to *PF* and *PO* records. Although applicable for daily or monthly instream flow requirements other than SB3 EFS, the new *ES* and *HC* records are not used for any of the 120 *IF* record rights listed in Table 2.5. The addition of SB3 EFS to the daily *SIMD* input DAT file as described in Chapter 8 employs only *IF*, *ES*, *HC*, *PF*, and *PO* records.

Environmental Flow Standards Established Pursuant to the Senate Bill 3 Process

The SB3 EFS for the Colorado River Basin are found in "*Subchapter D: Colorado and Lavaca Rivers and Matagorda and Lavaca Bays*" which was adopted August 8, 2012 and became effective on August 30, 2012 [11]. The priority date for these EFS and the associated set-asides to be incorporated in the water availability modeling system is March 1, 2011. Only new water rights and water right amendments that are submitted after the March 1, 2011 priority date are subject to the new requirements established pursuant to the 2007 Senate Bill 3.

The EFS established through the process created by the 2007 SB3 consist of subsistence flow, base flow, and high flow pulse components that vary seasonally and with hydrologic conditions [11]. The metrics specified in the standards are tabulated in Tables 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8, 5.9, and 5.10 of Chapter 5. The set of instream flow *IF*, hydrologic condition *HC*, environmental standard *ES*, pulse flow *PF*, and pulse flow options *PO* records inserted in the DAT file of the daily Colorado WAM to model the SB3 EFS are presented in Table 5.12. The added new *IF* record instream flow water rights modeled with the *IF*, *HC*, *PF*, and *PO* records of Table 5.12 are inserted into the DAT file of daily WAM variation D7 of Chapter 7.

The 14 locations with SB3 EFS in the Colorado River Basin are listed with descriptive information in Table 5.1. Locations of the 14 SB3 EFS sites in relation to the ten largest reservoirs in the river basin are shown on the map of Figure 5.1. Table 5.1 and Figure 5.1 are replicated here as Table 7.1 and Figure 7.1 for convenient reference in the discussion of simulation results.

Table 8.1
Locations of SB3 EFS in the Colorado River Basin

WAM CP ID	USGS Gage No.	Gage and Control Point Location	Watershed Area (square miles)
B20000	08123850	Colorado River above Silver	1,575
C30000	08128000	South Concho River at Christoval	5,046
C10000	08136500	Concho River at Paint Rock	5,046
D40000	08126380	Colorado River near Ballinger	13,788
D30000	08127000	Elm Creek at Ballinger	464
E10000	08146000	San Saba River at San Saba	3,048
F20000	08143600	Pecan Bayou near Mullin	19,830
F10000	08147000	Colorado River near San Saba	19,830
G10000	08151500	Llano River at Llano	19,830
H10000	08153500	Pedernales River near Johnson City	901
J50000	08158700	Onion Creek near Driftwood	30,244
J30000	08159200	Colorado River at Bastrop	27,611
J10000	08161000	Colorado River at Columbus	27,611
K20000	08162000	Colorado River at Wharton	30,601

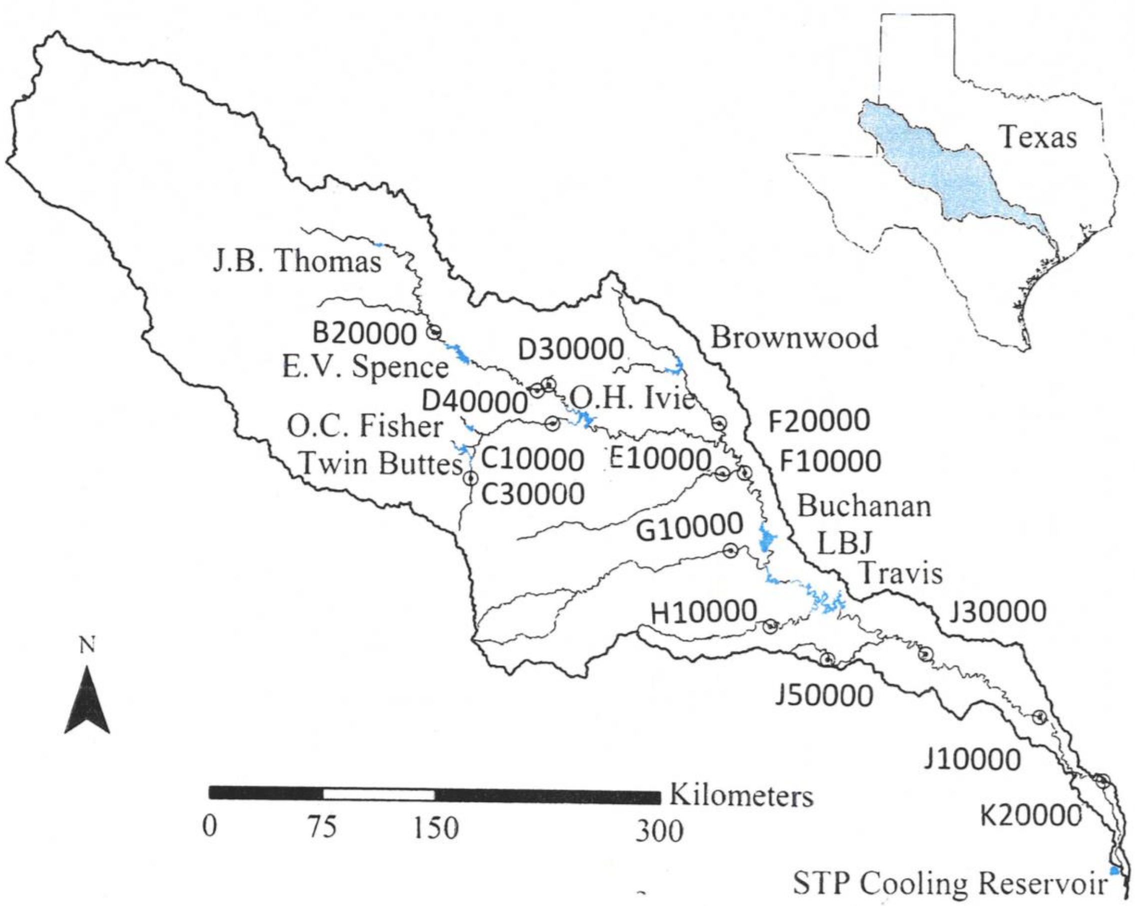

Figure 8.1 Locations of 14 Environmental Flow Standards and 10 Largest Reservoirs

Comparison of Simulation Results for Alternative Variations of the WAM

This section is a comparative analysis of the variations of the Colorado WAM defined in Table 8.2. The remainder of the chapter after this section focuses on instream flow targets associated with final daily and monthly WAM versions labeled C3D and C3M in Table 8.2.

Alternative Variations of the WAM

Alternative Colorado WAM simulations discussed here in this section are defined in Table 8.2. The versions of the WAM labeled MC and D7 were introduced in the preceding Chapter 7. The versions labeled C3D, C3DJ, C3DS, and C3M are added in Chapter 8.

Table 8.2
Simulations with Alternative Variations of the *SIM* or *SIMD* Input Datasets

MC - The full authorization scenario (run 3) monthly Colorado WAM dataset last updated by the TCEQ in February 2020 has the filename root C3. WAM version MC consists of this initial C3 dataset with modifications described in Chapter 2 that do not affect simulation results.

D7 - Daily WAM version D7 developed in Chapter 7 includes monthly-to-daily naturalized flow disaggregation, routing at 30 control points, forecasting with a three-day forecast period, and flood control operations of the four reservoirs with designated flood control pools. SB3 environmental flow standards are added to WAM version D7 in Chapter 8 to create the final adopted daily WAM which is labeled C3D.

C3D - The WAM version labeled C3D is the full authorization scenario (TCEQ WAM System run 3) daily Colorado WAM with *IF* record instream flow rights modeling the SB3 EFS with a priority of March 1, 2011. WAM version C3D is version D7 with SB3 EFS added.

C3DJ - Variation C3DJ is identical to C3D except the priority numbers of the *IF* record water rights for the SB3 EFS are changed to 99999999 making them most junior of all rights.

C3DS - Variation C3DS is identical to C3D except the priority numbers of the *IF* record water rights for the SB3 EFS are changed to -9999999 making them most senior of all rights.

C3M - The WAM version labeled C3M is the monthly (M) full authorization scenario (run 3) Colorado (C) WAM with monthly SB3 EFS instream flow targets computed by summing daily targets in a daily simulation performed with the daily WAM version C3D.

The monthly full authorization scenario Colorado WAM dataset from the TCEQ WAM System last updated by the TCEQ in February 2020 is described in Chapter 2. This WAM dataset consists of *SIM* input files with filename root C3, where the 3 refers to the practice of calling the full authorization scenario run 3. Chapter 2 describes the following two modifications added to this WAM dataset. These changes do not affect computed values in simulation results.

1. designation of artificial control points, reservoirs, and water rights
2. consolidation of multiple time series input data files into a single DSS file

The label MC is adopted in Chapters 7 and 8 to refer to this initial enhanced version of the monthly WAM. Simulation results are not altered by the two modifications listed above except through the added capability to exclude designated control points, reservoirs, and water rights in summation totals. For example, totals of storage contents of 484 reservoirs cited in Chapters 7 and 8 do not include the 42 reservoirs that are classified as artificial as discussed in Chapter 2.

The official publication of the environmental instream flow standards [11] states that the priority date for the SB3 EFS and the associated set-asides to be incorporated in the water availability modeling system is March 1, 2011. The March 1, 2011 (20110311) priority is adopted for the SB3 EFS in WAM versions C3D and C3M.

The 120 *IF* record rights in Table 2.5 of Chapter 2 have priorities ranging from December 31, 1904 (19041231) to August 4, 2010 (20100804). Although many artificial rights in the WAM are assigned 99999999 or other arbitrarily large priority numbers, the most junior *WR* record diversion right with a priority based on the date in a water right permit has a priority of 20011116 (November 16, 2001). The Colorado WAM dataset includes water accounting schemes previously created that include *WR* record specifications (water rights) with priority numbers of 9999999 or similarly large priority numbers designed to make certain *WR* record specifications junior to all or most other water rights. The *FR* record flood control specifications of Chapter 4 also include arbitrarily large priority numbers making flood control junior to other water management purposes.

Simulation C3DJ is included in this section of Chapter 8 to analyze the effects on simulation results of assigning the SB3 EFS instream flow requirements the most junior priority in the WAM. Variation C3DJ is identical to C3D except for changing the *IF* record priority numbers for the SB3 EFS to 99999999.

Simulation C3DS provides insight on effects resulting from hypothetically assigning the SB3 EFS instream flow standards the most senior priority in the WAM. The *IF* record rights for the SB3 EFS are assigned negative priority numbers of -9999999 to make them senior to all other water rights in the WAM. Otherwise, WAM variations C3DS and C3D are identically the same.

The final monthly WAM version C3M is created as discussed later in this chapter by adding monthly instream flow targets for the SB3 EFS recorded on target series *TS* records to the DSS file input dataset read by the monthly *SIM*. The monthly *TS* record targets are created by summing daily targets computed in a daily *SIMD* simulation. *IF* record water rights are inserted in the C3M DAT file that reference the *TS* records of monthly instream flow targets read from the input file.

<u>Comparison of Results of the Alternative Simulations</u>

Frequency statistics for simulation results generated with the MC, D7, and C3D variations of the WAM are included in Tables 7.4-7.9 and 7.11-7.13 of Chapter 7. Means and standard deviations of regulated and unappropriated flows at two control points and total storage contents of three groups of reservoirs (Table 7.10) computed in simulations with the six alternative variations of the WAM (Table 8.2) are compared in Tables 8.3 and 8.4. Time series of total storage contents for the three groups of reservoirs of Table 7.10 are plotted in Figures 8.2, 8.3, and 8.4. Simulation results for all five of the WAM variations are similar. Storage contents and regulated flows for simulations with WAM variations D7, C3D, and C3DJ are identical.

Table 8.3
Means and Standard Deviations of Regulated and Unappropriated Flows

Simulation	MC	D7	C3D	C3DJ	C3DS
Flows (cfs) of Colorado River at San Saba (Control Point F10000)					
Mean Regulated Flow	701.9	657.9	657.9	657.9	663.5
Mean Unappropriated Flow	106.7	113.5	97.62	97.62	103.2
Standard Deviation Regulated Flow	1,176	2,660	2,660	2,660	2,667
Standard Deviation Unappropriated	651.0	1,157	1,027	1,027	1,067
Flows (cfs) of Colorado River at Wharton (Control Point K20000)					
Mean Regulated Flow	1,547	1,545	1,545	1,545	1,698
Mean Unappropriated Flow	399.7	312.6	283.8	283.8	266.2
Standard Deviation Regulated Flow	2,369	4,758	4,758	4,758	4,694
Standard Deviation Unappropriated	1,991	1,699	1,625	1,625	1,536

Table 8.4
1940-2016 Means of Reservoir Storage Contents for Alternative Simulations

	Summation of Reservoir Storage Volumes (acre-feet)				
Simulation	MC	D7	C3D	C3DJ	C3DS
All 484 Reservoirs	2,650,684	2,697,437	2,697,437	2,697,437	2,606,441
Six Highland Lakes	1,879,317	1,911,659	1,911,659	1,911,659	1,866,407
Three CRMWD Lakes	171,309	197,160	197,160	197,160	199,628

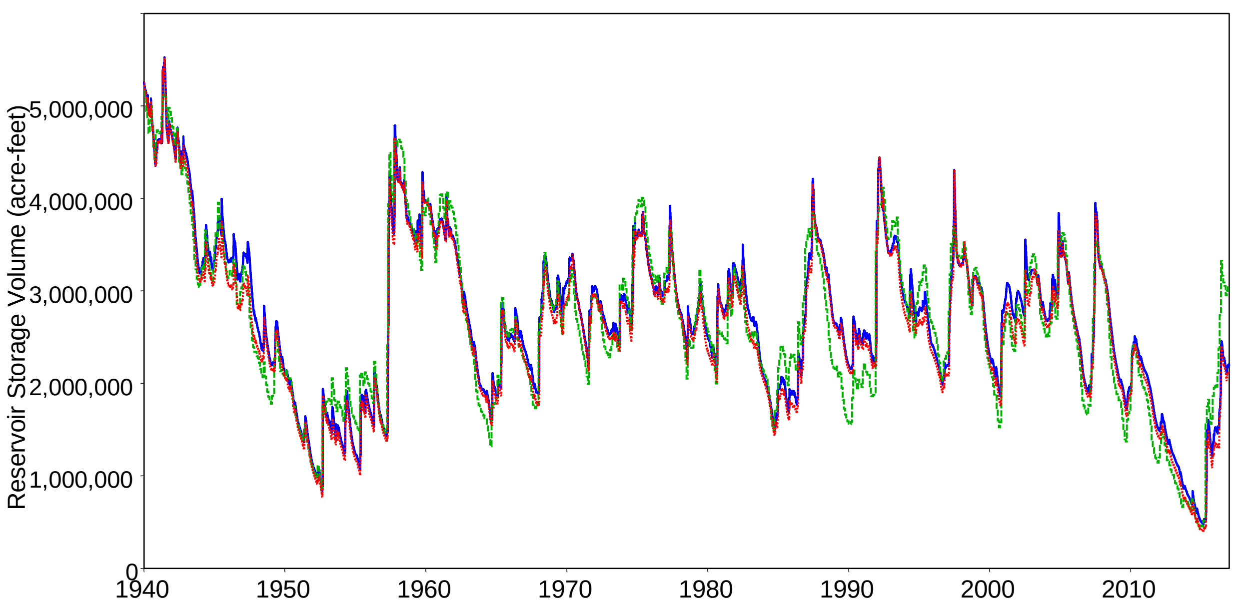

Figure 8.2 Storage Contents of the 484 Reservoirs for MC (green dashes), C3DS (red dots), D7 (blue solid), C3D (blue solid), C3DJ (blue solid)

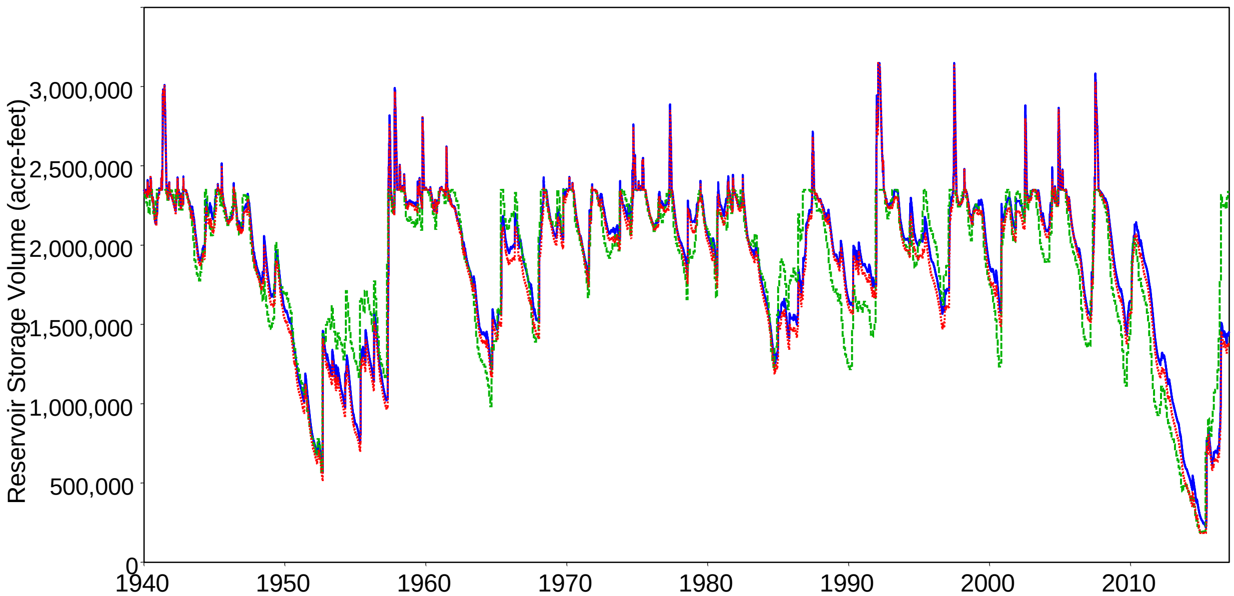

Figure 8.3 Storage Contents of the Six Highland Lakes for MC (green dashes), C3DS (red dots), D7 (blue solid), C3D (blue solid), C3DJ (blue solid)

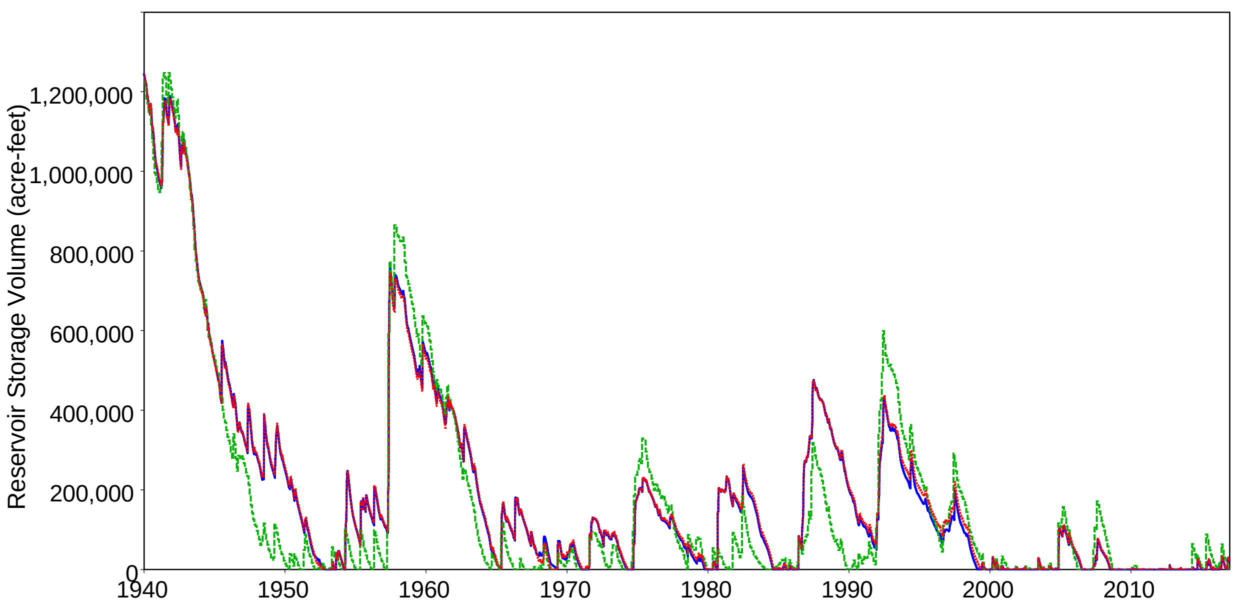

Figure 8.4 Storage Contents of Three CRMWD Reservoirs for MC (green dashes), C3DS (red dots), D7 (blue solid), C3D (blue solid), C3DJ (blue solid)

The storage contents and regulated flows for simulations with WAM variations D7, C3D, and C3DJ are identically the same. The blue line in Figures 8.2, 8.3, and 8.4 represents the same storage for all three of these simulations. Unappropriated flows are the same for C3D and C3DJ. Storage contents and mean flows for the alternative daily simulations differ significantly but not excessively from results obtained with the monthly MC version of the WAM. Hypothetically, assigning the SB3 EFS the most senior priorities in the WAM have relatively minimal effect on the quantities of water available for the other water rights.

Instream Flow Targets for SB3 Environmental Flow Standards

The remainder of this chapter focuses on instream flow targets generated by simulations with full authorization scenario WAM versions C3D and C3M. Daily version C3D includes monthly-to-daily naturalized flow disaggregation, routing at 30 control points, forecasting with a three-day forecast period, flood control pools in four reservoirs, and the SB3 EFS as described in Chapters 3, 4, 5, and 7. The sets of *IF*, *HC*, *ES*, *PF*, and *PO* records replicated in Table 5.12 of Chapter 5 are incorporated in the DAT file of WAM version C3D. Monthly WAM version C3M includes monthly instream flow targets for the SB3 EFS computed as the summation of daily targets from a C3D simulation as discussed later in the present Chapter 8.

Multiple Instream Flow Targets or Target Components at the Same Control Point

Instream flow targets computed for different *IF* records at the same control point are combined as specified by IFM(if,2) in *IF* record field 7. IFM(if,2) option 2 is activated in column 36 of the *IF* records replicated in Table 5.12. With option 2, as the simulation progresses through the water right priority sequence, the largest target is adopted when combining the *IF* record target with a preceding target for another *IF* record right at the same 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, which is set at option 2 (adopt the largest) for the Colorado WAM SB3 EFS *IF* record rights (Tables 8.1, 5.12, 5.13). Although other options are available, in modeling the SB3 EFS in the Colorado WAM, multiple instream flow targets at the same control point are combined always using the option of adopting the largest target.

The computation of an instream flow target for the SB3 EFS at a control point location consists of computing a subsistence and base flow target as specified by *ES* records and a pulse flow target as specified by *PF* records. Pulse flow *PF* and subsistence/base flow *ES* records can be defined separately or alternatively combined as a single *IF* record instream flow water right at a control point. The pulse flow components are modeled as separate *IF* record rights in the dataset of Table 5.12 to facilitate recording *PO* record pulse flow targets in the simulation results separately from the *ES* record subsistence/base flow targets. This does not affect the total target quantities but allows the components of each target to be recorded separately.

The subsidence, base flows, and high flows pulses can be combined reducing the number of *IF* record water rights in Table 5.12 from 28 to 14 by removing the *IF*, *HC*, and *ES* record for each of the high flow pulse components as illustrated in Table 5.13. The simulation results presented in Table 8.5 employ the 28 *IF* record rights of Table 5.12 allowing the high flow pulse targets and the subsidence/base flow targets to be recorded separately.

The Colorado WAM already had 120 *IF* record rights (Table 2.5) before adding the new *IF* record rights modeling the SB3 EFS (Table 8.1). Control points C30000, F10000, and H10000 include both pre-existing *IF* record rights (Table 2.5) and SB3 EFS *IF* record rights (Table 8.1). The other 11 SB3 EFS control points listed in Table 8.1 have no other *IF* record rights. Many of the 120 *IF* records in Table 2.5 may contribute to redundancies that decrease the impact of the SB3 EFS on the amount of water available to other water rights. The 120 other *IF* record rights are all senior to the SB3 EFS *IF* record rights. The SB3 EFS *IF* record rights adopt the larger of the latter and preceding targets in the priority sequence if multiple *IF* rights are at the same control point.

The *SIM*/*SIMD OF* record controls selection among 43 time series variables that may be included in the simulation results DSS output file. 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 Table 8.5. The second column of Table 8.5 refers to the *OF* record labels listed in the *Users Manual* [2] that are used to select variables for inclusion in the output DSS file. The labels in DSS pathname part C of the output records are listed in the third column. These labels are adopted in Table 8.6 and the following discussion to refer to the alternative forms instream flow targets and shortages.

Table 8.5
Labels for Instream Flow Target and Shortage Quantities

Instream Flow Target or Shortage Quantity	*SIM/SIMD OF* Record	DSS Record Part C
final target at control point	15. IFT	IFT-CP
shortage for final control point target	16. IFS	IFS-CP
combined target for IF water right	27. IFT	IFT-WR
shortage for IF water right	28. IFS	IFS-WR
individual target for IF water right	29. TIF	TIF-WR

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. An IFT-CP instream flow 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.

The instream flow shortage (IFS-CP) associated with a control point is the amount by which the daily regulated flow falls below the regulated flow (REG-CP) at the end of the simulation water rights priority sequence. The instream flow shortage (IFS-WR) associated with a water right is the amount by which the daily regulated flow falls below the regulated flow (REG-CP) at the priority of the water right in the priority sequenced simulation computations.

<u>Instream Flow Targets Computed in a Daily Simulation with the C3D WAM</u>

Daily regulated flows, instream flow targets, shortages in meeting the targets, and other flow quantities are computed in *SIMD* in units of acre-feet/day. The flows are converted from units of acre-feet/day to cfs in *HEC-DSSVue* by multiplying the quantities by 0.50416667.

The daily *SIMD* simulation model computes all flow quantities including daily instream flow target volumes for each of the 28,125 days of the 1940-2016 hydrologic period-of-analysis in acre-feet/day. *SIMD* also sums the daily flow volumes to monthly volumes in acre-feet/month and includes both the simulated daily volumes and monthly summations in the simulation results output file. The daily final instream flow targets (IFT-CP) for the *SIMD* simulation with the C3D dataset are plotted in Figures 8.5, 8.7, 8.9, 8.11, 8.13, 8.15, 8.17, 8.19, 8.21, 8.23, 8.25, 8.27, 8.29, and 8.31. The daily targets computed in *SIMD* in units of acre-feet/day were converted to cfs in HEC-DSSVue along with preparing the plots. The monthly summations in acre-feet/month of the daily targets from the *SIMD* simulation results for the C3D WAM are plotted in Figures 8.6, 8.8, 8.10, 8.12, 8.14, 8.16, 8.18, 8.20, 8.22, 8.24, 8.26, 8.28, 8.30, and 8.32.

Means and the minimum and maximum daily quantities during the 28,125 days of the 1940-2016 simulation are tabulated in Table 8.6 for the 14 control points listed in Table 8.1. The mean, minimum, and maximum of the 28,125 daily regulated flows from simulation C3D for the 14 control points with SB3 EFS are tabulated in column 2 of Table 8.6. For example, the simulated regulated flow of the Colorado River at Wharton (control point K20000) ranges from 0.00 to 138,677 cfs with a 1940-2016 mean of 1,545 cfs.

The target and shortage quantities in Table 8.6 are defined in Table 8.5. In each day of the *SIMD* simulation, the simulation computations proceed through the water rights priority sequence. The target setting and shortage computations for the *IF* record rights for the SB3 EFS are controlled by the input records of Table 5.12. The priority date of March 1, 2011 (20110301) makes the SB3 EFS rights junior to the instream flow rights defined by the other 120 IF records (Table 2.5) in the WAM. Three of the SB3 EFS control points (C30000, F10000, H10000) include other more senior *IF* record rights in addition to the SB3 EFS rights. With more than one target at the same control point the combining option each day is to adopt the largest target.

The *SIMD* input records for the *IF* record rights for the SB3 EFS replicated in Table 5.12 of Chapter 5 separate the subsistence/base (*ES* record) and pulse flow (*PF* record) components of the SB3 EFS. The subsistence/base ES component precedes the pulse flow PF component in the water right priority sequenced simulation computations. The combining option consists of adopting the larger of the two targets each day.

The mean, minimum, and maximum of the SB3 EFS instream flow targets are tabulated in columns 4 through 8 of Table 8.6. IFT-CP quantities in column 4 are for the instream flow targets at the control point at the completion of the water rights priority sequence (Table 8.5). The final IFT-CP targets are plotted in Figures 8.5 through 8.32.

IFT-WR-ES and IFT-WR-PF quantities in column 5 and 6 of Table 8.6 reflect the instream flow targets after the *ES* record rights and *PF* record rights, respectively, are considered in the water rights priority sequence. For the Colorado WAM, Table 8.6 columns 4 and 6 are identical. Columns 7 and 8 of Table 8.6 contain metrics for the individual TIF-WR targets for the ES and PF rights before or without combining with targets for other rights (Table 8.5).

The IFS-CP shortages in column 9 of Table 8.6 refer to failures in meeting the final IFT-CP targets at the completion of the water rights priority sequence. The IFS-WR shortages in columns 10 and 11 refer to the IF-WR-ES and IF-WR-PF targets after consideration of the subsistence/base (*ES* record) and pulse flow (*PF* record) components of the SB3 EFS. For the Colorado WAM, the shortages are the same in all three columns for each of the 14 control points, meaning that all target shortages are associated with the subsistence and base flow (*ES* record) components of the SB3 EFS.

Table 8.6
Means, Minima, and Maxima of Daily Instream Flow Targets and Shortages in cfs

Control Point Stream Town		Regulated Flow (cfs) REG-CP	Instream Flow Target (cfs) IFT CP	IFT-WR ES	IFT-WR PF	TIF-WR ES	TIF-WR PF	Shortage (cfs) IFS-CP CP	IFS-WR ES	IFS-WR PF
1	2	3	4	5	6	7	8	9	10	11
B20000	Mean	117.8	17.83	1.361	17.83	1.361	16.54	0.1980	0.1980	0.1980
Colorado R.	Min	0.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000
near Silver	Max	31,708	3,000	2.000	3,000	2.000	3,000	1.667	1.667	1.667
C30000	Mean	21.10	9.548	9.095	9.548	5.913	0.4864	1.747	1.747	1.747
South Concho	Min	0.000	8.786	8.786	8.786	2.000	0.000	0.000	0.000	0.000
at Christoval	Max	21,336	420.0	9.099	420.0	9.000	420.0	9.099	9.099	9.099
C10000	Mean	80.21	16.30	4.371	16.30	4.371	12.25	0.1706	0.1706	0.1706
Concho River	Min	0.000	1.000	1.000	1.000	1.000	0.000	0.0000	0.0000	0.0000
at Paint Rock	Max	44,293	3,000	12.00	3,000	12.00	3,000	7.811	7.811	7.811
D40000	Mean	133.5	21.80	-	21.80	-	19.54	0.2551	-	0.2551
Colorado R.	Min	0.000	1.000	-	1.000	-	0.000	0.0000	-	0.0000
Ballinger	Max	39,024	3,200	-	3,200	-	3,200	3.9722	-	3.9722
D30000	Mean	37.65	6.778	1.000	1.000	1.000	0.000	0.3629	0.3629	0.3629
Elm Creek	Min	0.000	1.000	1.000	6.778	1.000	5.819	0.0000	0.0000	0.0000
at Ballinger	Max	21,190	1,900	1.000	1,900	1.000	1,900	1.0000	1.0000	1.0000
E10000	Mean	166.5	57.348	40.32	57.35	40.32	18.73	0.3207	0.3207	0.3207
San Saba R.	Min	0.000	3.000	3.000	3.000	3.000	0.000	0.0000	0.0000	0.0000
at San Saba	Max	36,682	5,500	56.00	5,500	56.00	5,500	22.000	22.000	22.000
F20000	Mean	175.5	25.38	2.270	25.38	2.270	23.32	0.1735	0.1735	0.1735
Pecan Bayou	Min	0.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000
near Mullin	Max	30,240	3,500	3.000	3,500	3.000	3,500	1.000	1.000	1.000
F10000	Mean	657.9	273.3	136.3	273.3	30.00	146.3	33.02	33.02	33.02
Colorado R.	Min	0.000	74.68	74.68	74.68	79.18	0.000	0.000	0.000	0.000
at San Saba	Max	59,160	18,900	332.3	18,900	120.0	18,900	332.2	332.2	332.2
G10000	Mean	352.8	115.2	72.36	115.2	72.36	46.52	1.020	1.020	1.020
Llano River	Min	0.000	3.000	3.000	3.000	3.000	0.000	0.000	0.000	0.000
at Llano	Max	85,563	9,100	100.0	9,100	100.0	9,100	44.00	44.00	44.00
H10000	Mean	189.7	54.90	30.63	54.90	17.09	25.27	6.366	6.366	6.366
Pedernales R.	Min	0.000	16.63	16.63	16.63	1.000	0.000	0.000	0.000	0.000
Johnson City	Max	128,823	6,980	50.55	6,980	29.00	6,980	50.55	50.55	50.55
J50000	Mean	47.57	8.787	1.979	8.787	1.979	6.952	0.1184	0.1184	0.1184
Onion Creek	Min	0.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000
Driftwood	Max	5,161	1,200	4.000	1,200	4.000	1,200	1.000	1.000	1.000
J30000	Mean	1,720	556.6	441.1	566.6	441.1	148.5	75.25	75.25	75.25
Colorado R.	Min	23.48	123.0	123.0	123.0	123.0	0.000	0.000	0.000	0.000
at Bastrop	Max	133,766	8,000	824.0	8,000	824.0	8,000	779.6	779.6	779.6
J10000	Mean	1,712	874.6	680.3	874.6	680.3	235.3	203.3	203.3	203.3
Colorado R.	Min	1.465	190.0	190.0	190.0	190.0	0.000	0.000	0.000	0.000
at Columbus	Max	140,823	27,000	1,440	27,000	1,440	27,000	1,422	1,422	1,422
K20000	Mean	1,545	919.2	732.3	919.2	732.3	228.2	294.0	294.0	294.0
Colorado R.	Min	0.000	107.0	107.0	107.0	107.0	0.000	0.000	0.000	0.000
at Wharton	Max	138,677	27,000	1,440	27,000	1,440	27,000	1,440	1,440	1,440
1	2	3	4	5	6	7	8	9	10	11

The daily *IF* record instream flow targets for the SB3 EFS at 14 control points (Table 8.1) computed in the *SIMD* simulation with the input dataset labeled C3D in Table 8.2 are plotted in Figures 8.5, 8.7, 8.9, 8.11, 8.13, 8.15, 8.17, 8.19, 8.21, 8.23, 8.25, 8.27, 8.29, and 8.31. The *SIMD* simulation results for the C3D version of the WAM also include the monthly summations of the daily targets. The monthly summations of simulated daily targets are plotted in Figures 8.6, 8.8, 8.10, 8.12, 8.14, 8.16, 8.18, 8.20, 8.22, 8.24, 8.26, 8.28, 8.30, and 8.32.

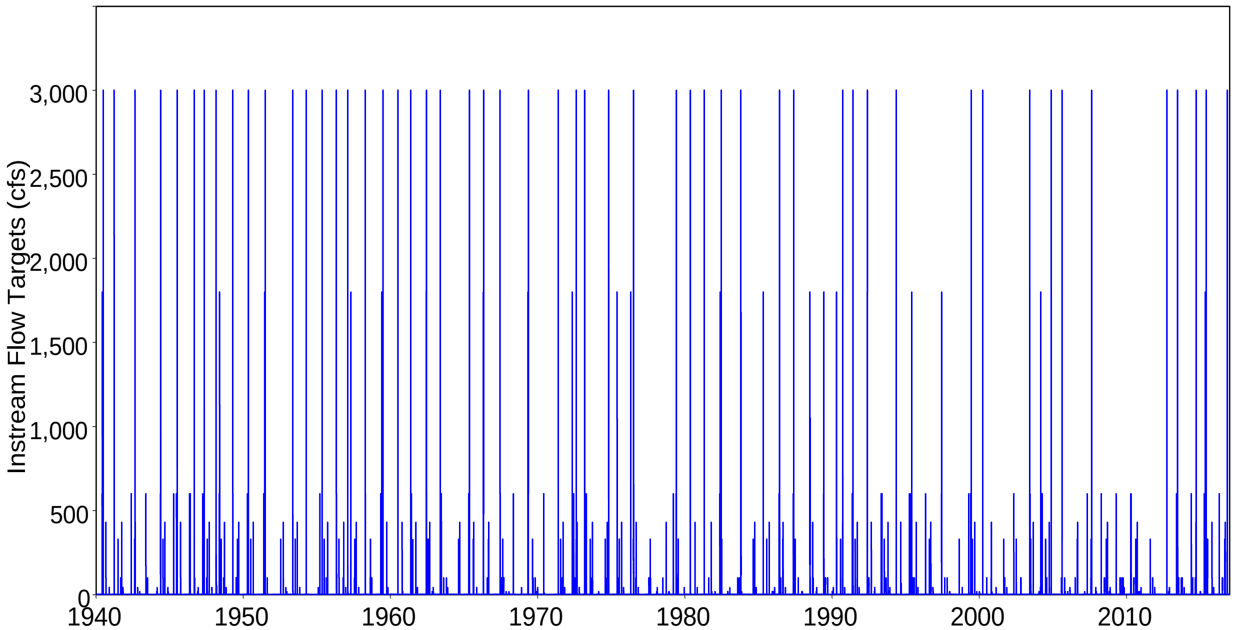

Figure 8.5 Daily IFS Targets (cfs) for Colorado River above Silver (B20000)

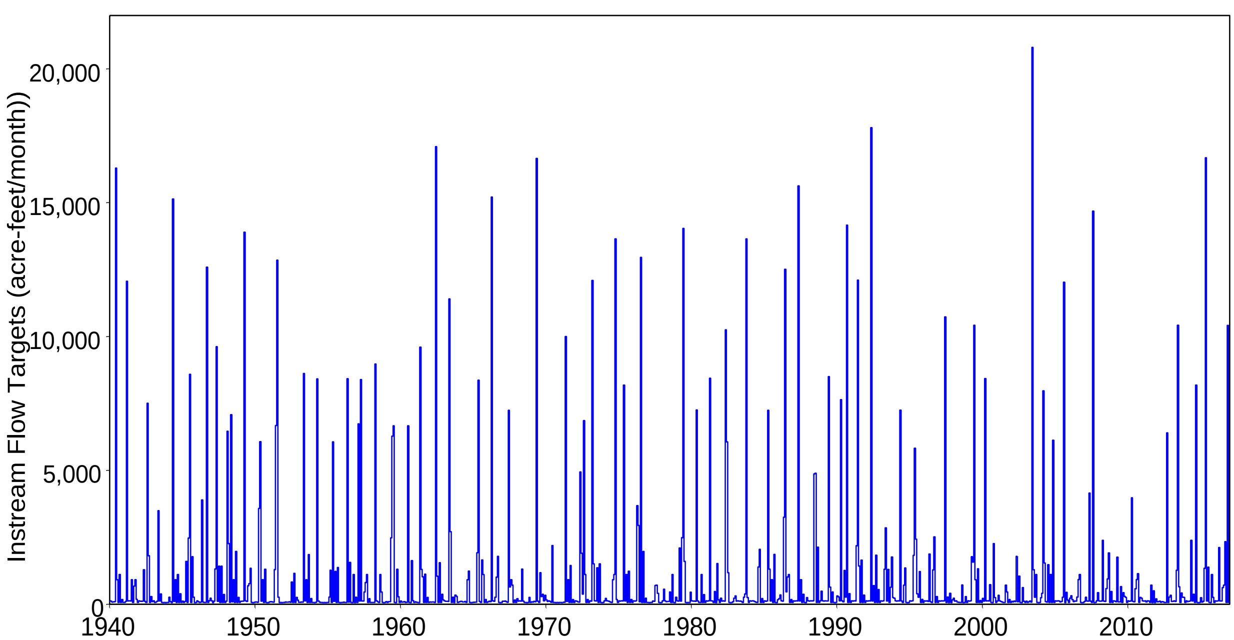

Figure 8.6 Monthly IFS Targets (acre-feet) for Colorado River above Silver (B20000)

The flow rate metrics for the SB3 EFS are tabulated in units of cfs in Tables 5.5, 5.6, 5.7, 5.8, 5.9, and 5.10 of Chapter 5. Flow rate input parameters are entered on the *ES* and *PF* records of Table 5.12 in cfs. The daily flow targets are plotted here in cfs to facilitate convenient comparison with the SB3 EFS metrics. Flow rates from *SIMD* simulation results are converted from units of acre-feet/day to cfs in *HEC-DSSVue* by multiplying the quantities by 0.50416667.

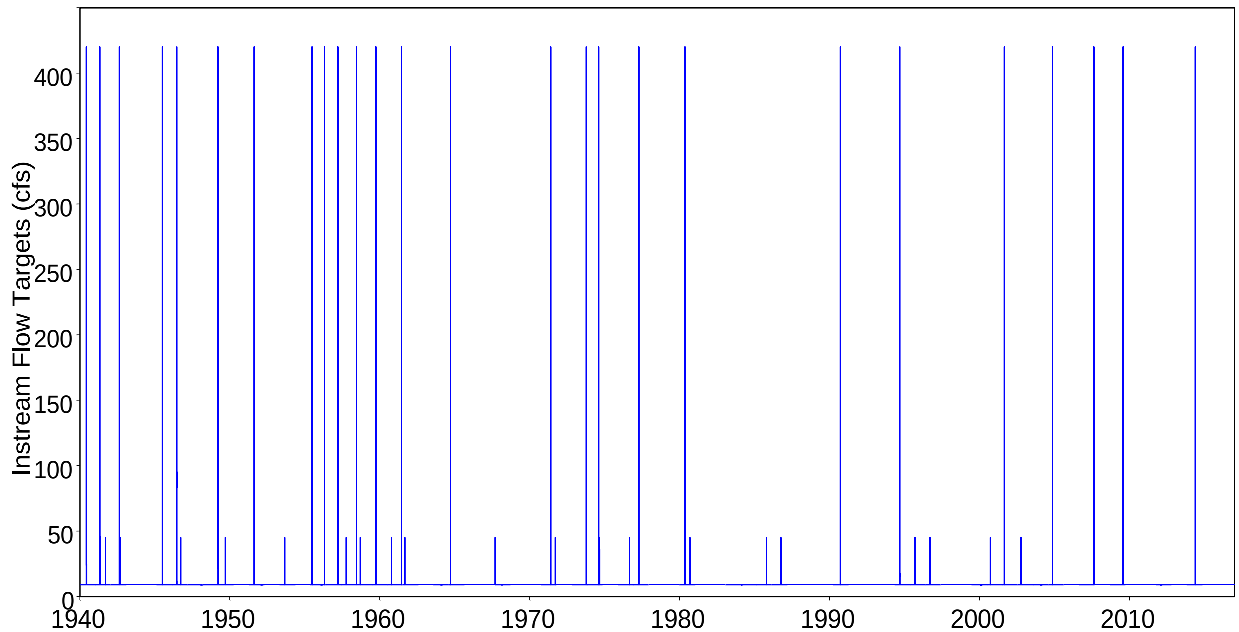

Figure 8.7 Daily IFS Targets (cfs) for South Concho River at Christoval (C30000)

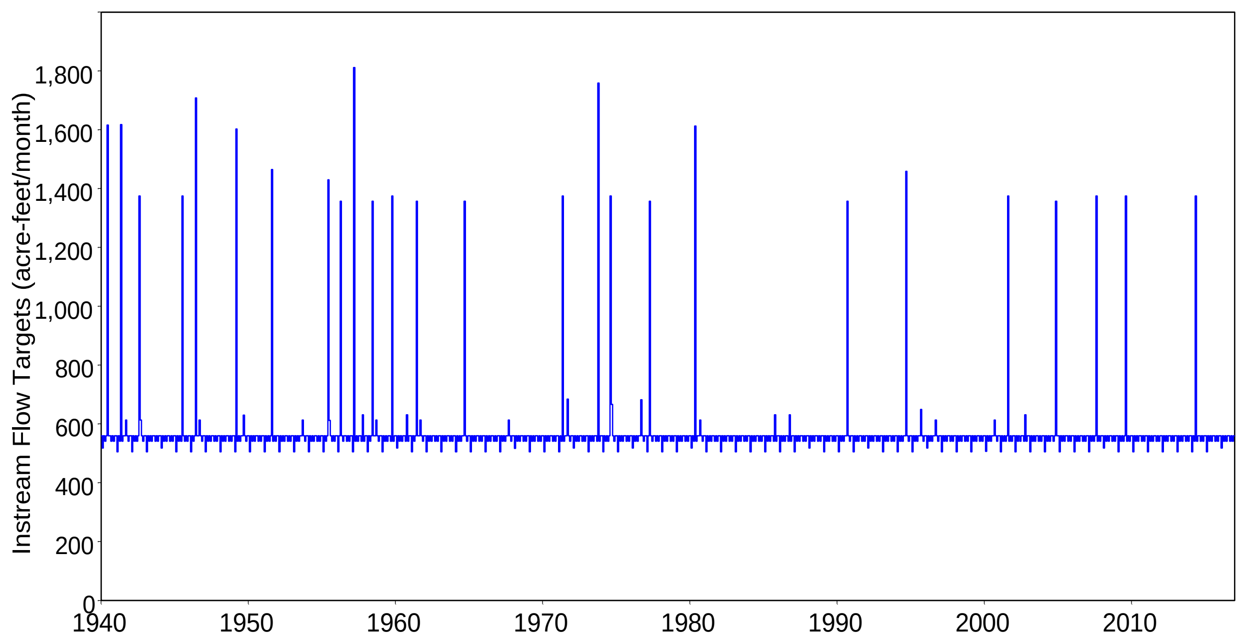

Figure 8.8 Monthly IFS targets (acre-feet) for South Concho River at Christoval (C30000)

Flow quantities in *SIMD* daily and *SIM* monthly simulation computations are in units of acre-feet/day and acre-feet/month, respectively. The monthly flow targets in acre-feet/month plotted in these figures were computed within *SIMD* by summing daily target volumes in acre-feet/day. The monthly flow targets in acre-feet/month are converted to target series *TS* records for inclusion in the input dataset for *SIM* monthly simulations as discussed later in this chapter.

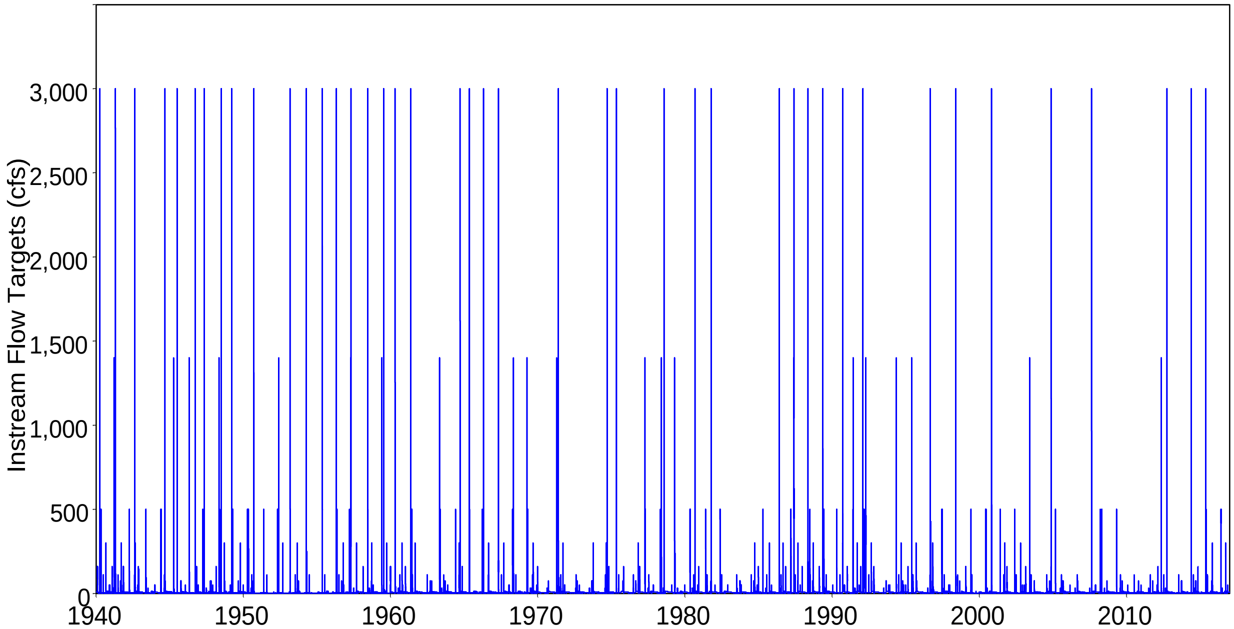

Figure 8.9 Daily EFS Targets (cfs) for Concho River at Paint Rock (C10000)

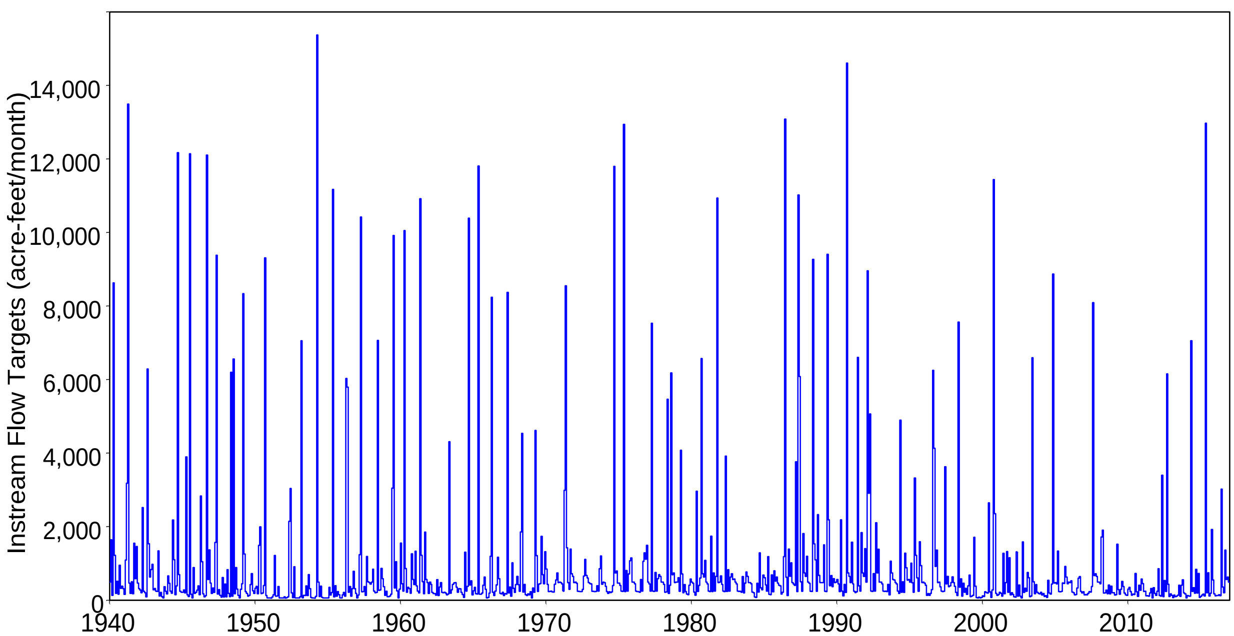

Figure 8.10 Monthly IFS targets (acre-feet) for Concho River at Paint Rock (C10000)

Figures 8.5, 8.7, 8.9, 8.11, 8.13, 8.15, 8.17, 8.19, 8.21, 8.23, 8.25, 8.27, 8.29, and 8.31 are plots of the instream flow targets recorded at the completion of the water right priority sequence computations in each of the 28,125 days of the C3D simulation. These targets are labeled IFT-CP in Tables 8.5 and 8.6. The targets for each day consist of the larger of the *ES* record subsistence and base flow target and the *PF* record high flow pulse target.

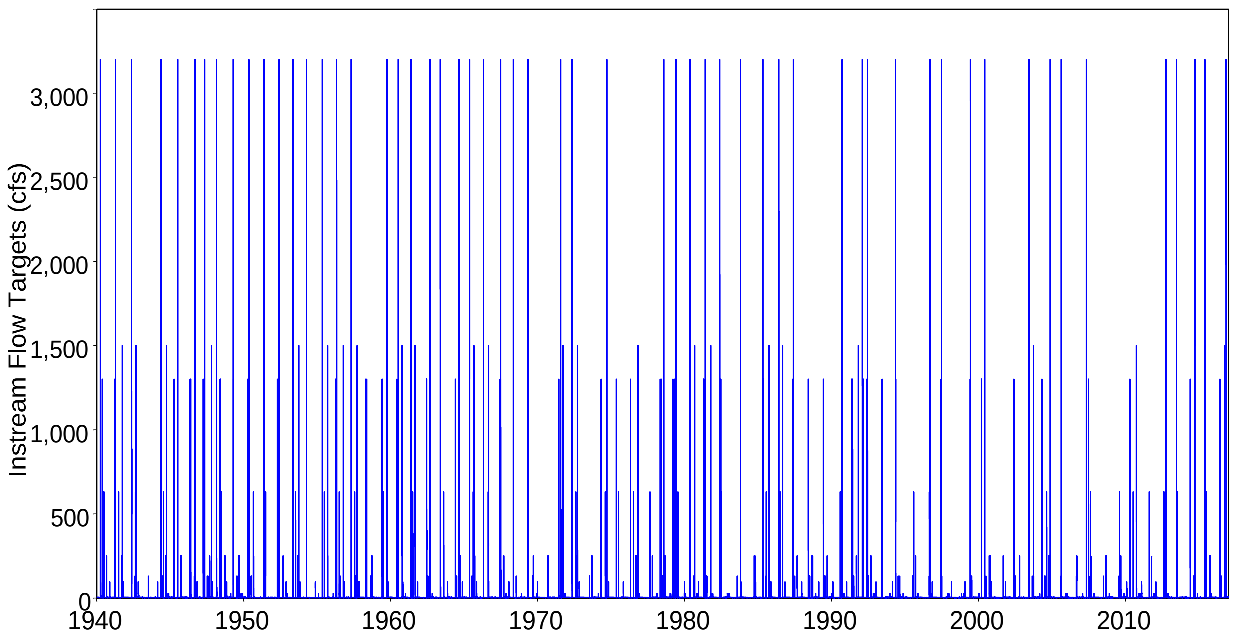

Figure 8.11 Daily EFS Targets (cfs) for Colorado River near Ballinger (D40000)

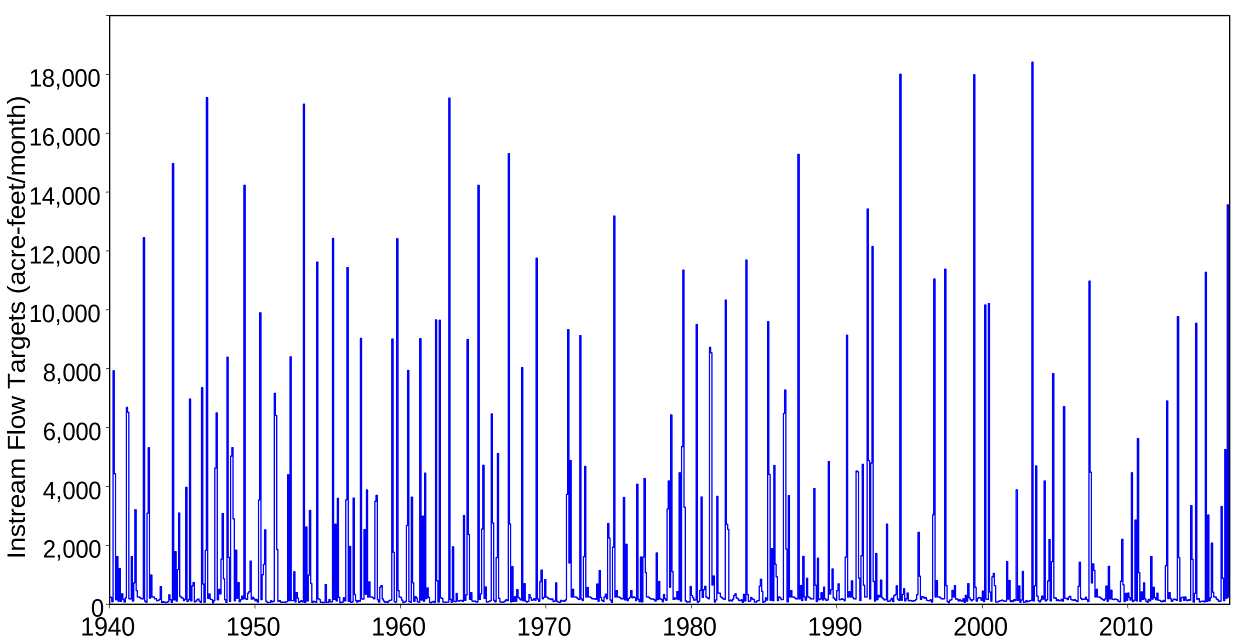

Figure 8.12 Monthly EFS Targets (acre-feet/month) for Colorado River near Ballinger (D40000)

The monthly summations of simulated daily targets plotted in Figures 8.6, 8.8, 8.10, 8.12, 8.14, 8.16, 8.18, 8.20, 8.22, 8.24, 8.26, 8.28, 8.30, and 8.32 are incorporated into the *SIM* simulation input dataset for the monthly WAM labeled C3M as explained later in this chapter.

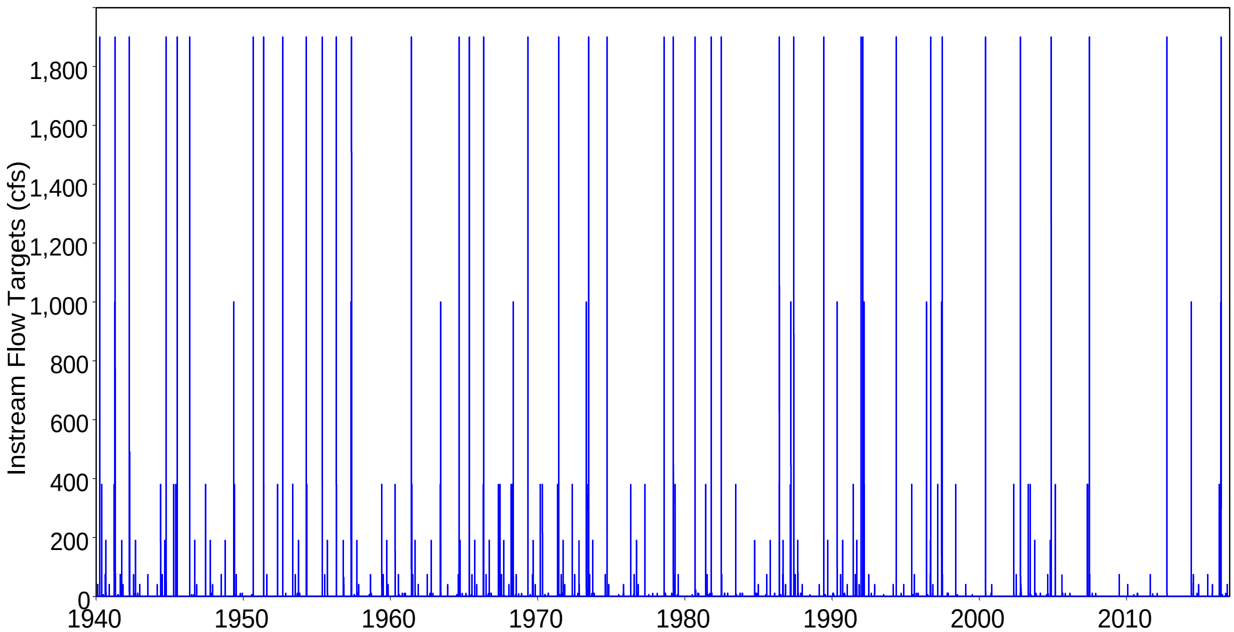

Figure 8.13 Daily EFS Targets (cfs) for Elm Creek at Ballinger (D30000)

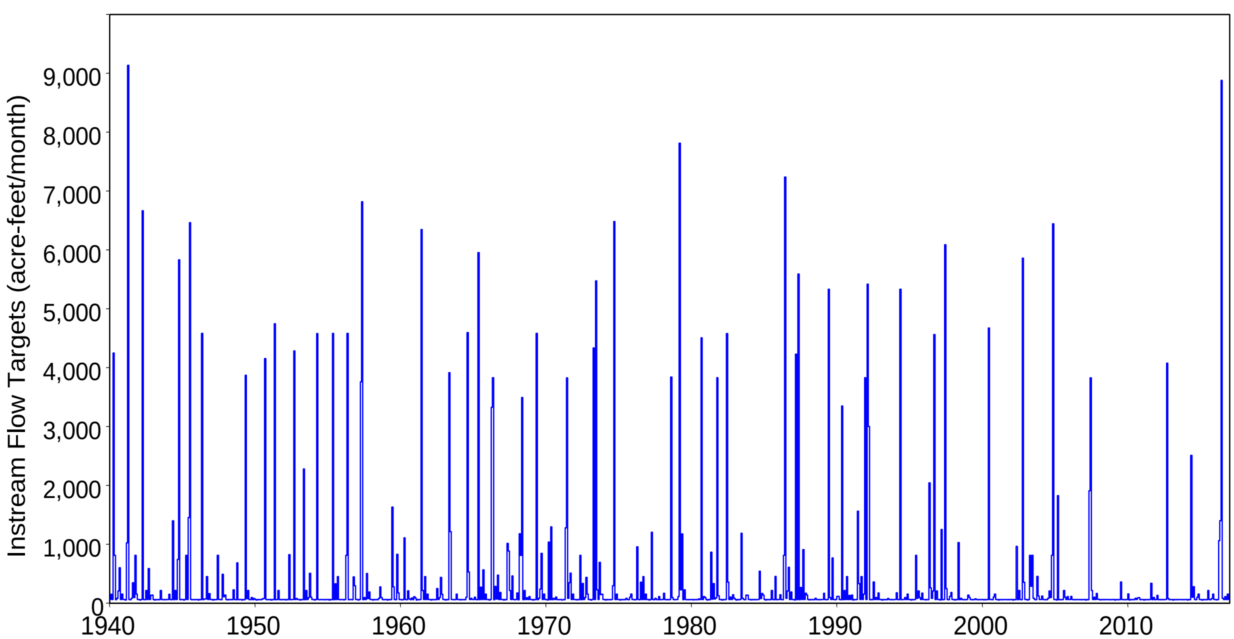

Figure 8.14 Monthly IFS targets (acre-feet) for Elm Creek at Ballinger (D30000)

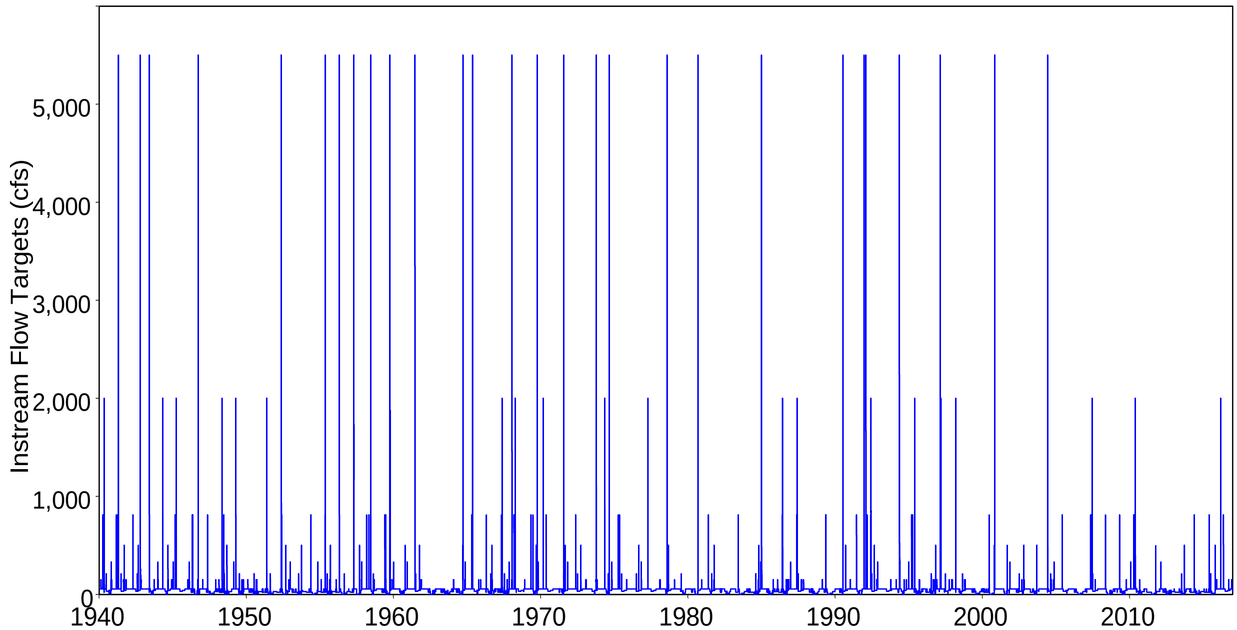

Figure 8.15 Daily EFS Targets (cfs) for San Saba River at San Saba (E10000)

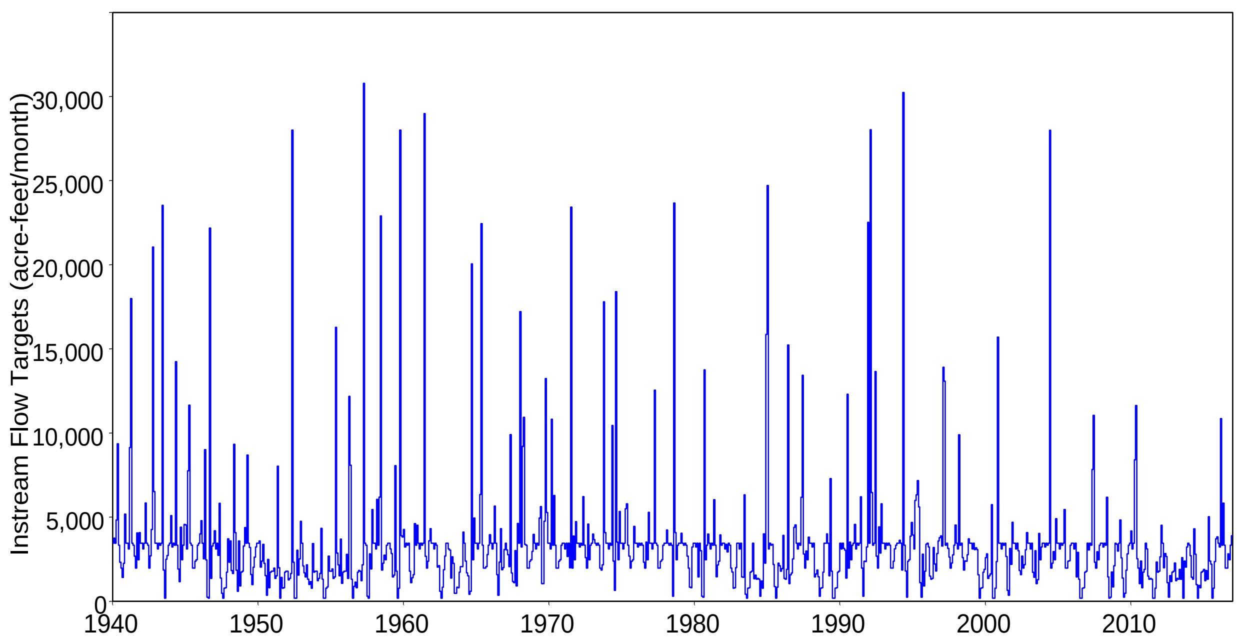

Figure 8.16 Monthly IFS targets (acre-feet) for San Saba River at San Saba (E10000)

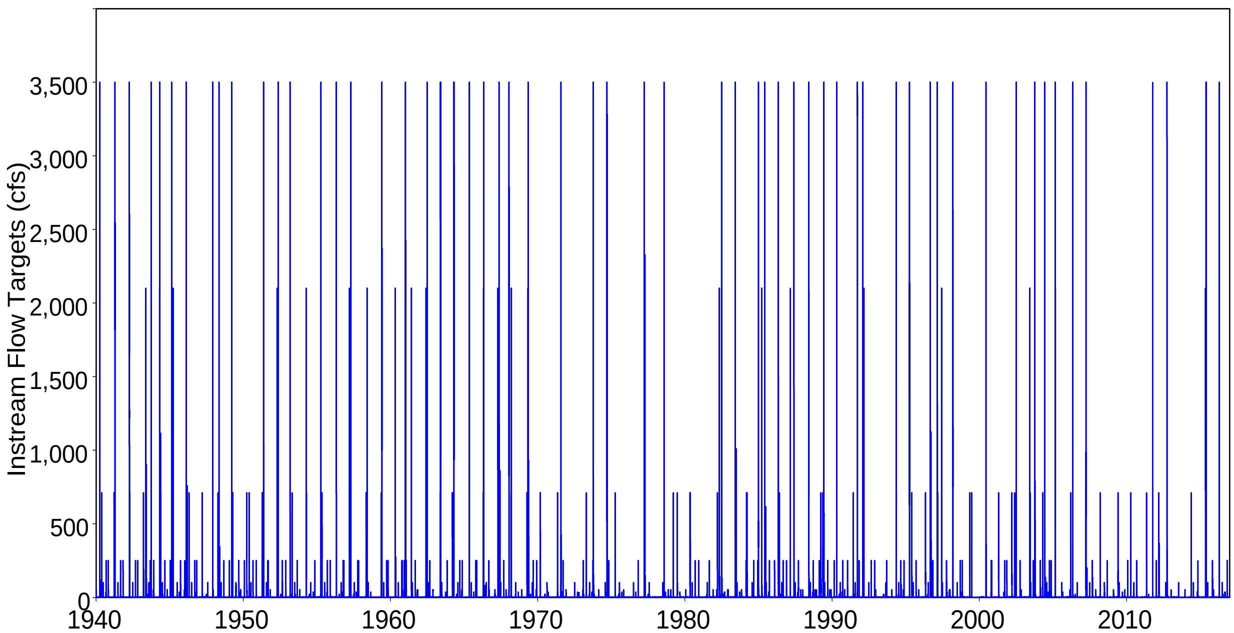

Figure 8.17 Daily EFS Targets (cfs) for Pecan Bayou near Mullin (F20000)

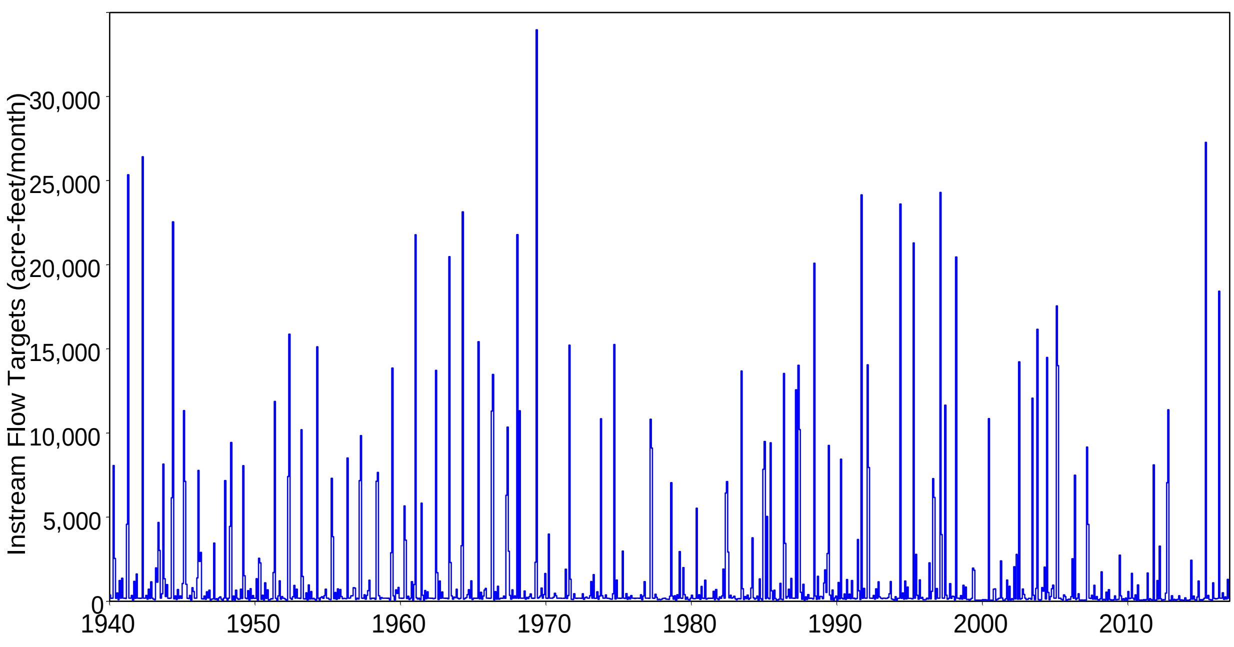

Figure 8.18 Monthly IFS targets (acre-feet) for Pecan Bayou near Mullin (F20000)

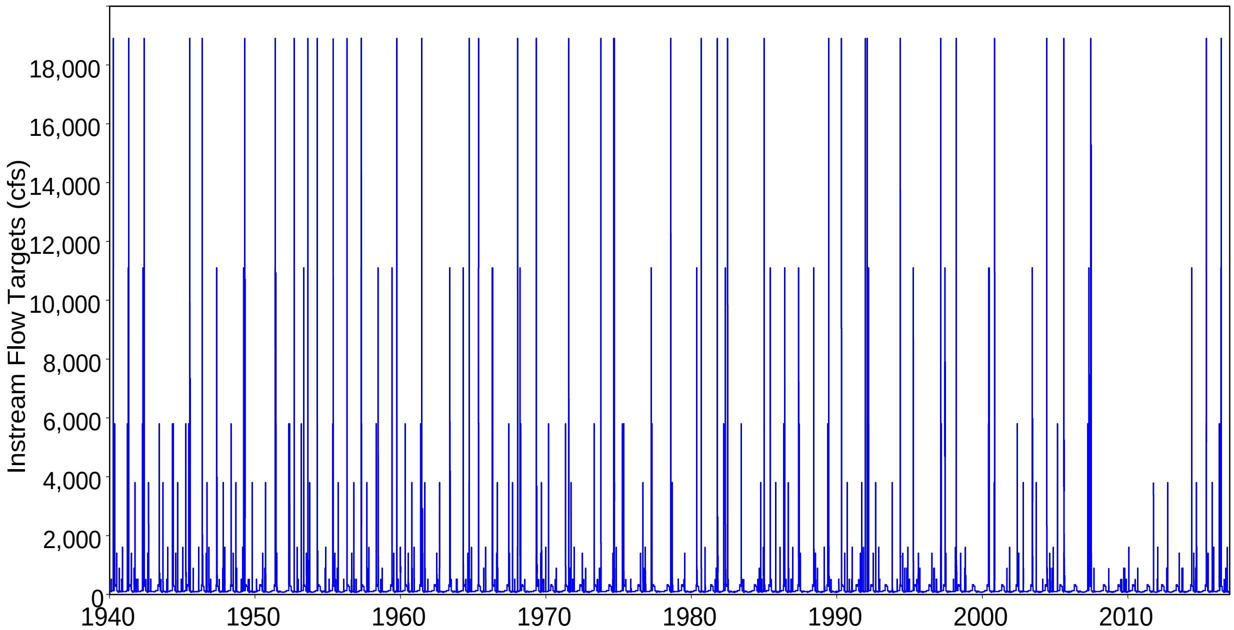

Figure 8.19 Daily EFS Targets (cfs) for Colorado River near San Saba (F10000)

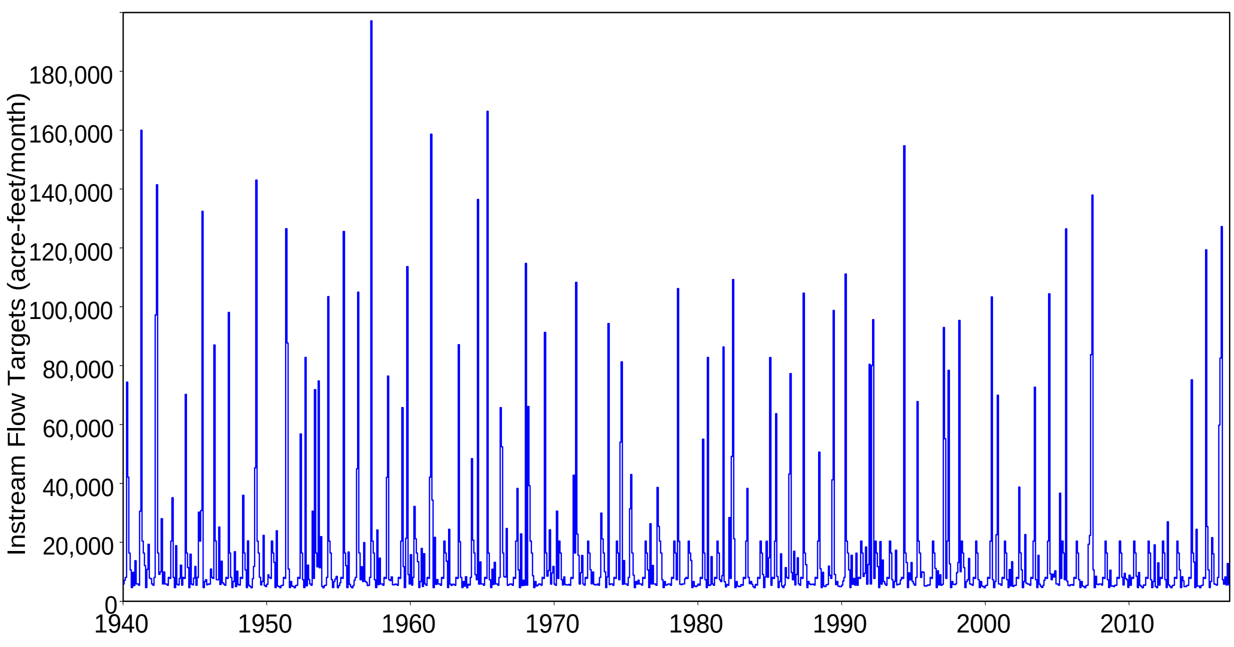

Figure 8.20 Monthly EFS Targets (acre-feet/month) for Colorado River near San Saba (F10000)

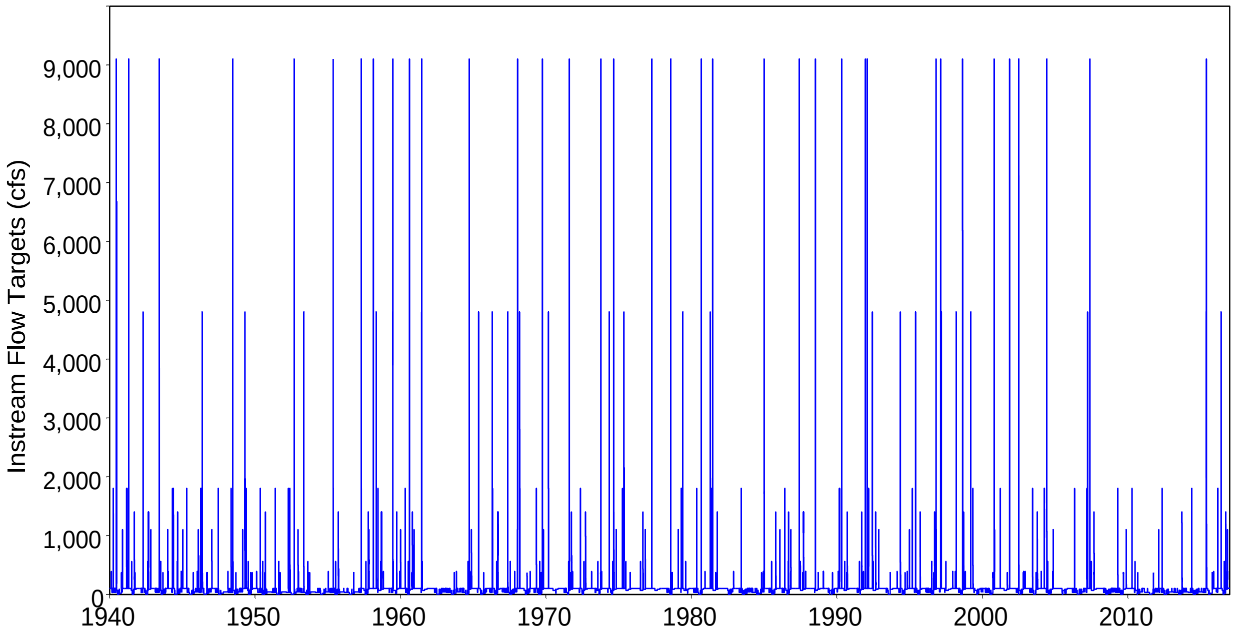

Figure 8.21 Daily EFS Targets (cfs) for Llano River at Llano (G10000)

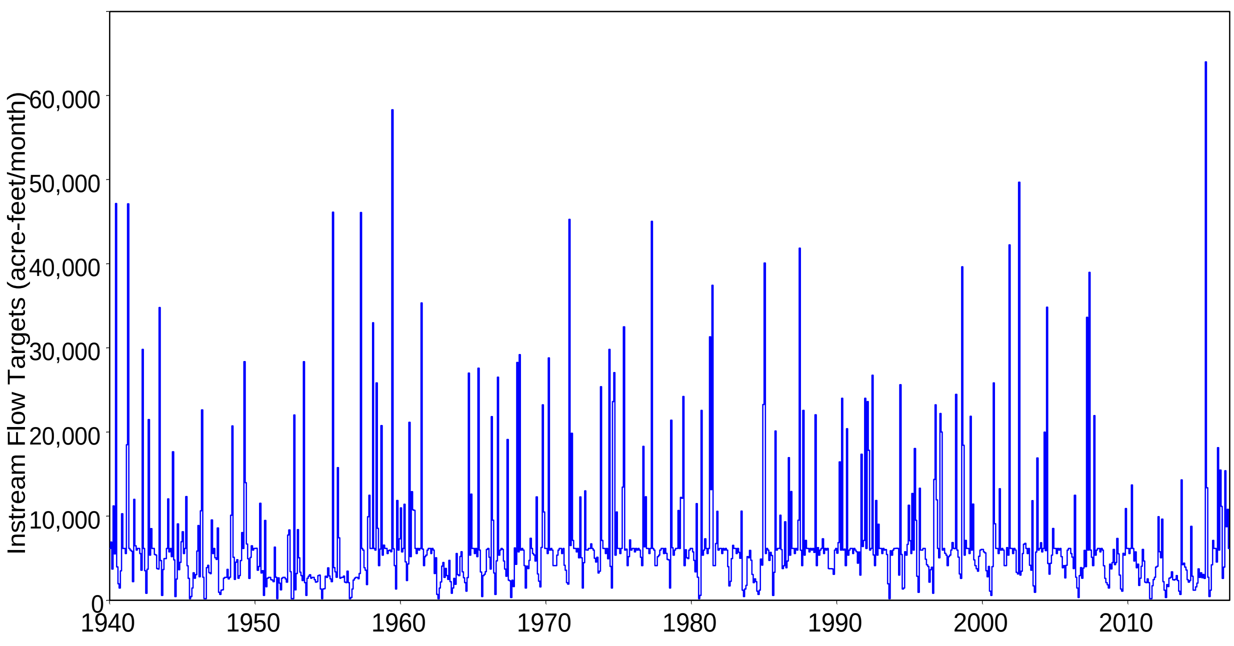

Figure 8.22 Monthly IFS targets (acre-feet) for Llano River at Llano (G10000)

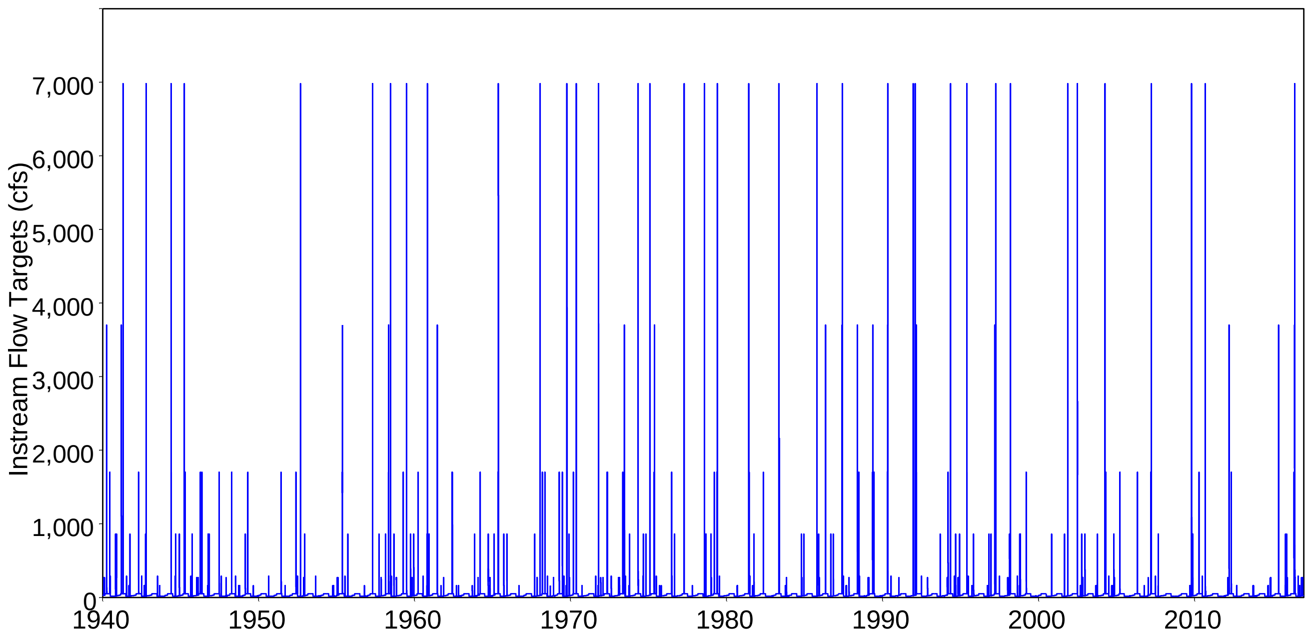

Figure 8.23 Daily EFS Targets (cfs) for Pedernales River near Johnson City (H10000)

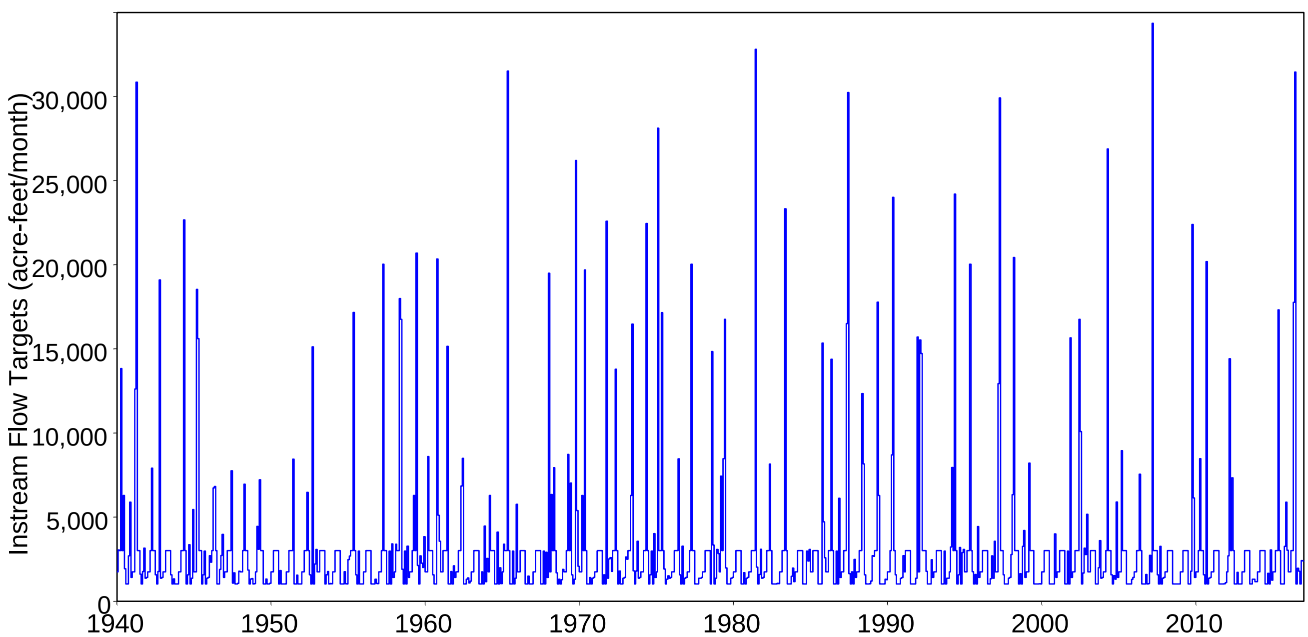

Figure 8.24 Monthly IFS targets (acre-feet) for Pedernales River near Johnson City (H10000)

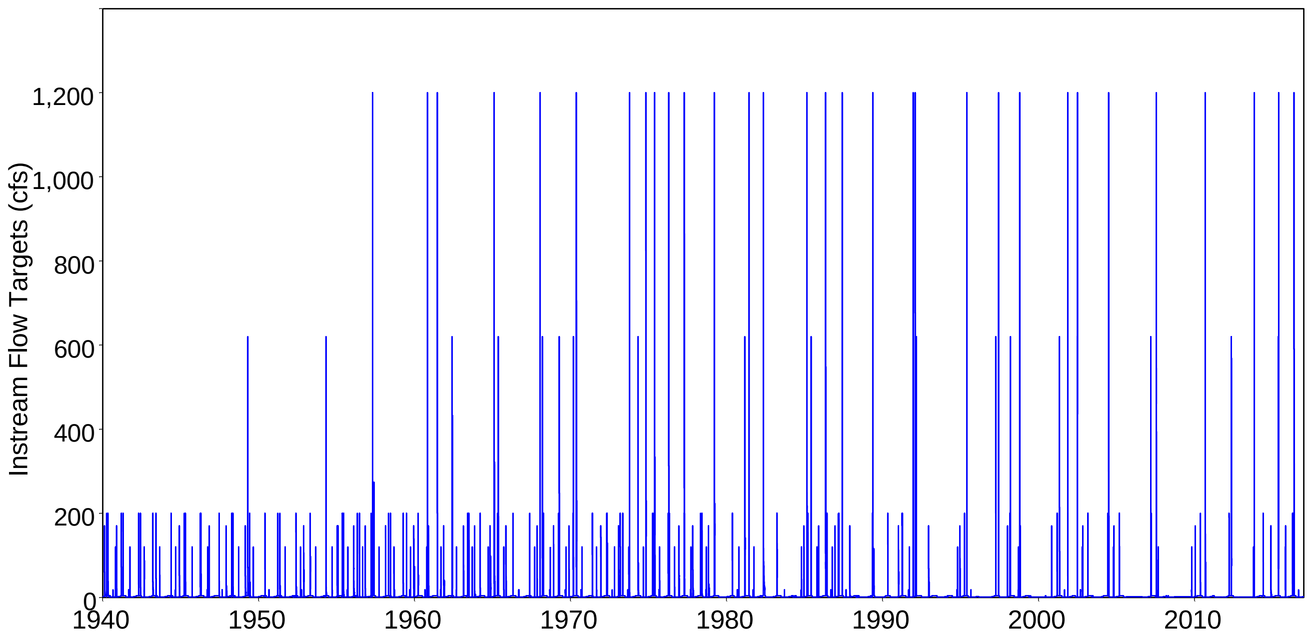

Figure 8.25 Daily EFS Targets (cfs) for Onion Creek near Driftwood (J50000)

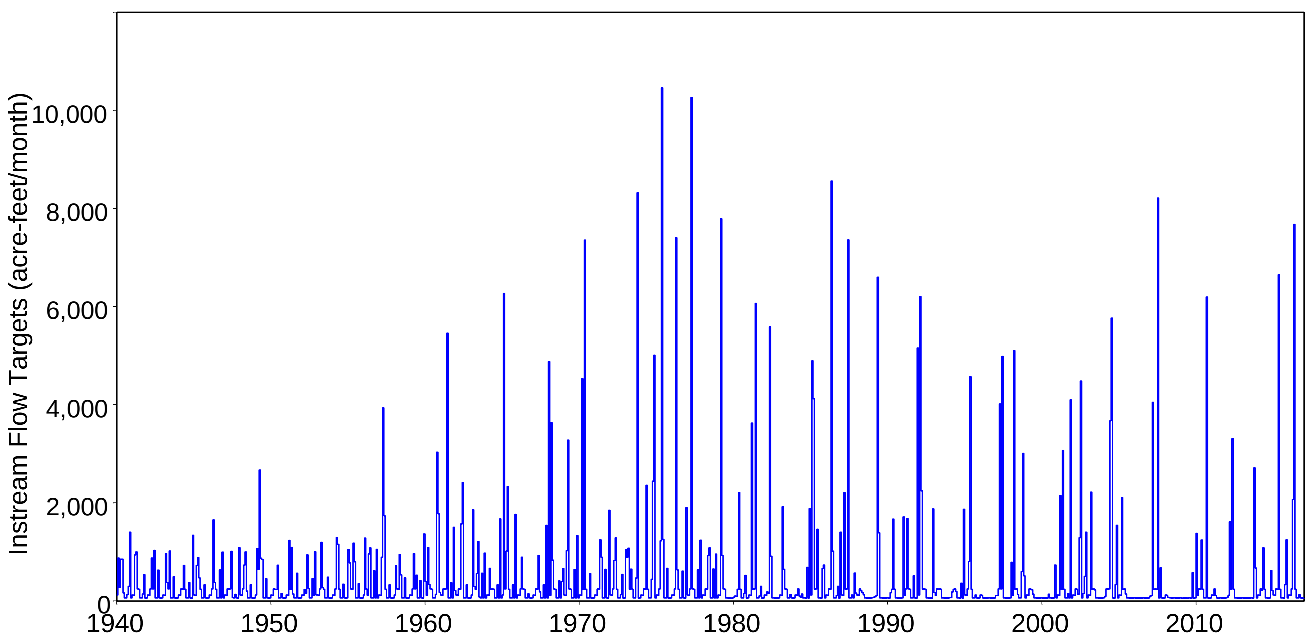

Figure 8.26 Monthly IFS targets (acre-feet) for Onion Creek near Driftwood (J50000)

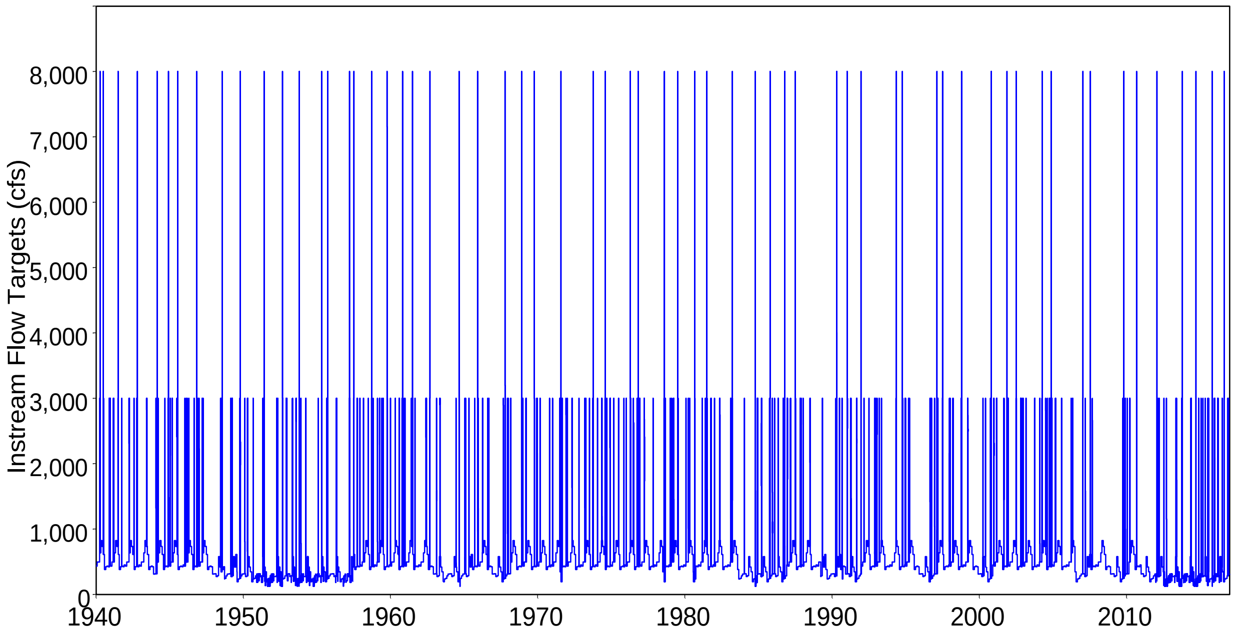

Figure 8.27 Daily EFS Targets (cfs) for Colorado River at Bastrop (J30000)

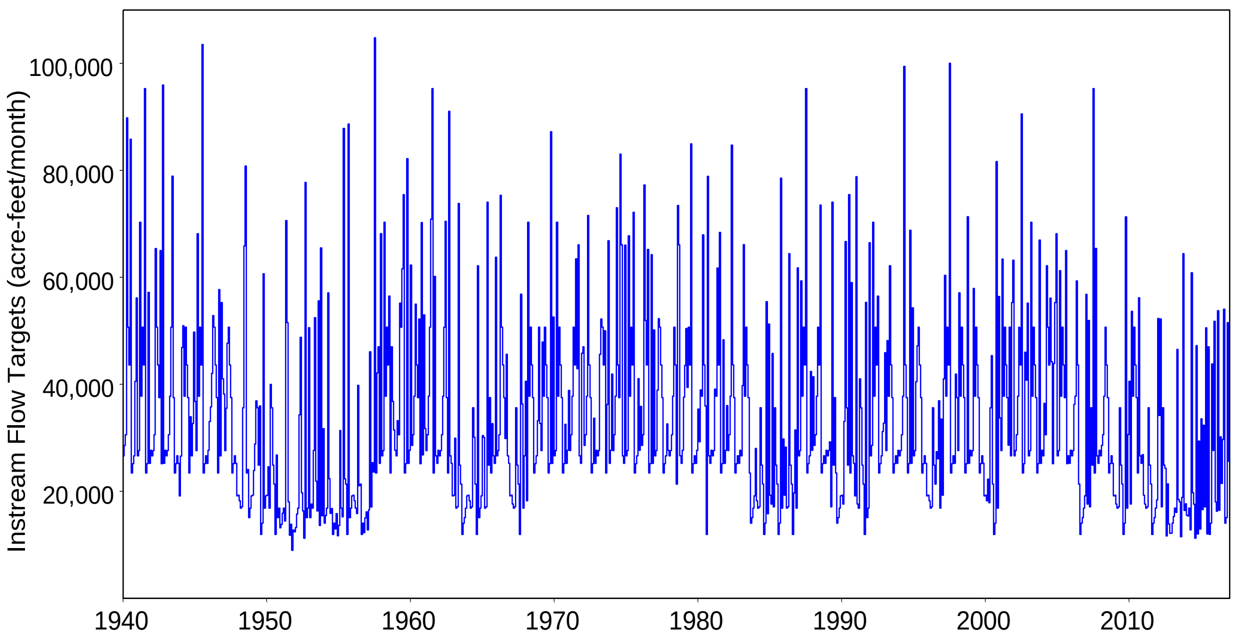

Figure 8.28 Monthly IFS targets (acre-feet) for Colorado River at Bastrop (J30000)

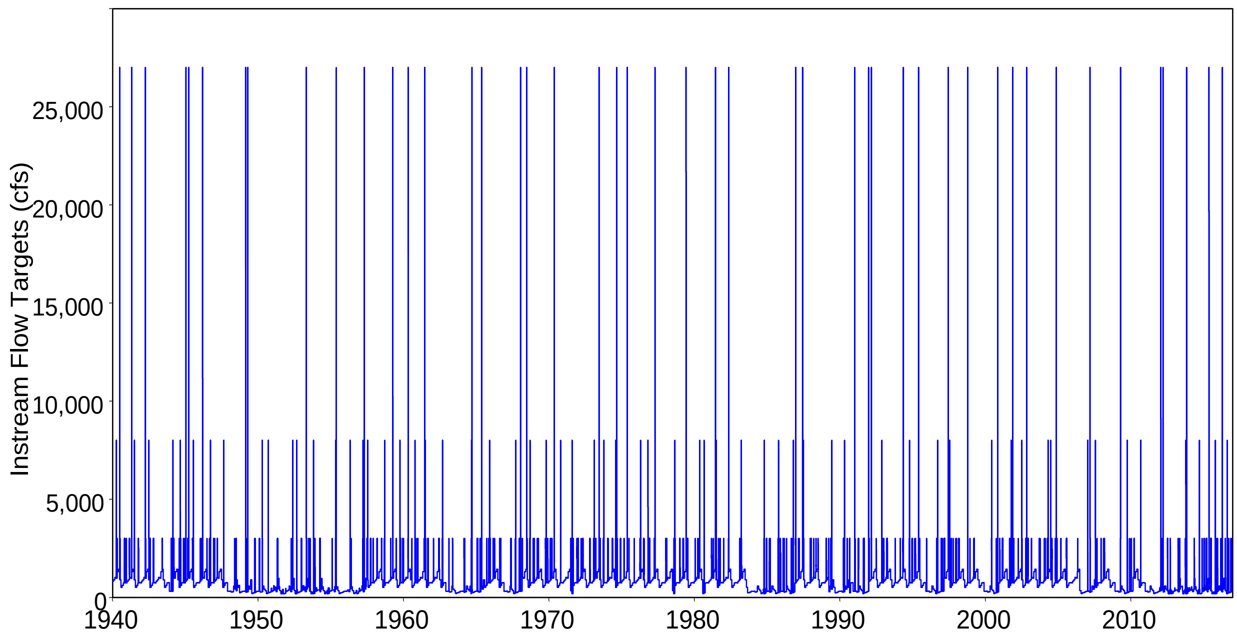

Figure 8.29 Daily EFS Targets (cfs) for Colorado River at Columbus (J10000)

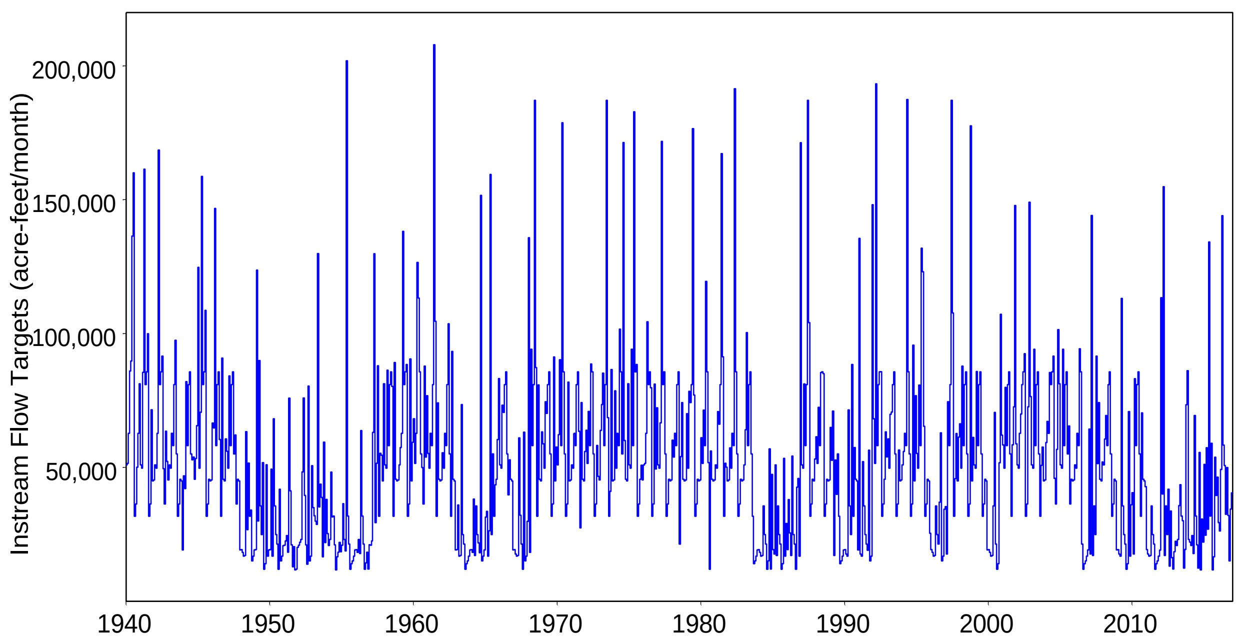

Figure 8.30 Monthly IFS targets (acre-feet) for Colorado River at Columbus (J10000)

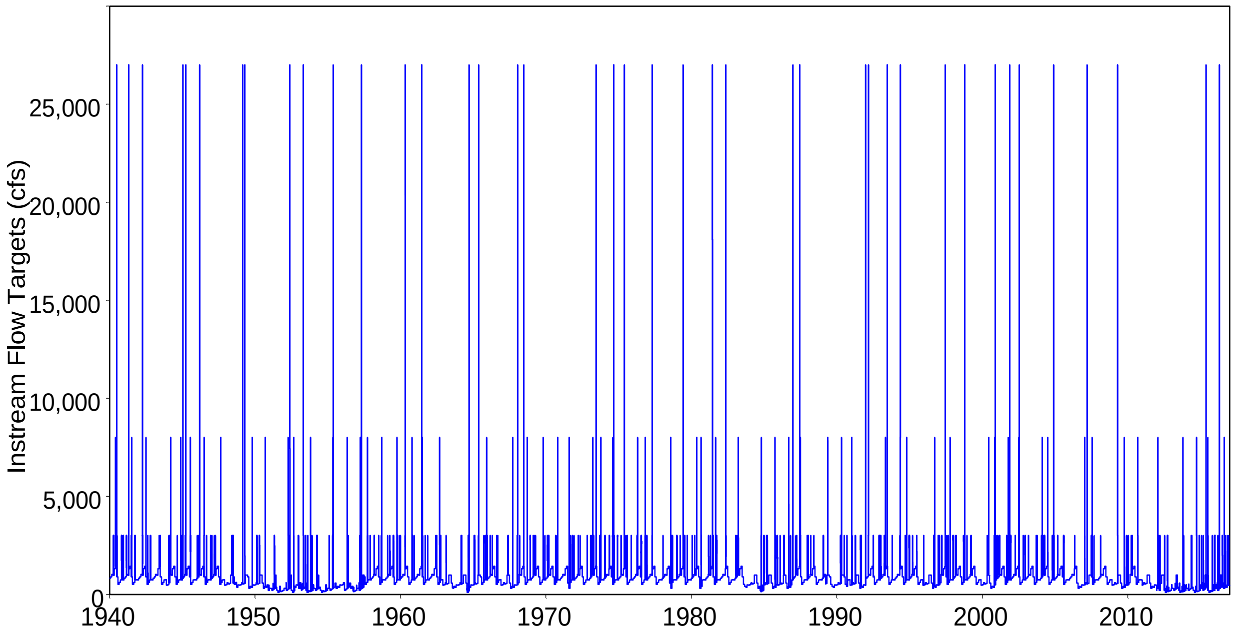

Figure 8.31 Daily EFS Targets (cfs) for Colorado River at Wharton (K20000)

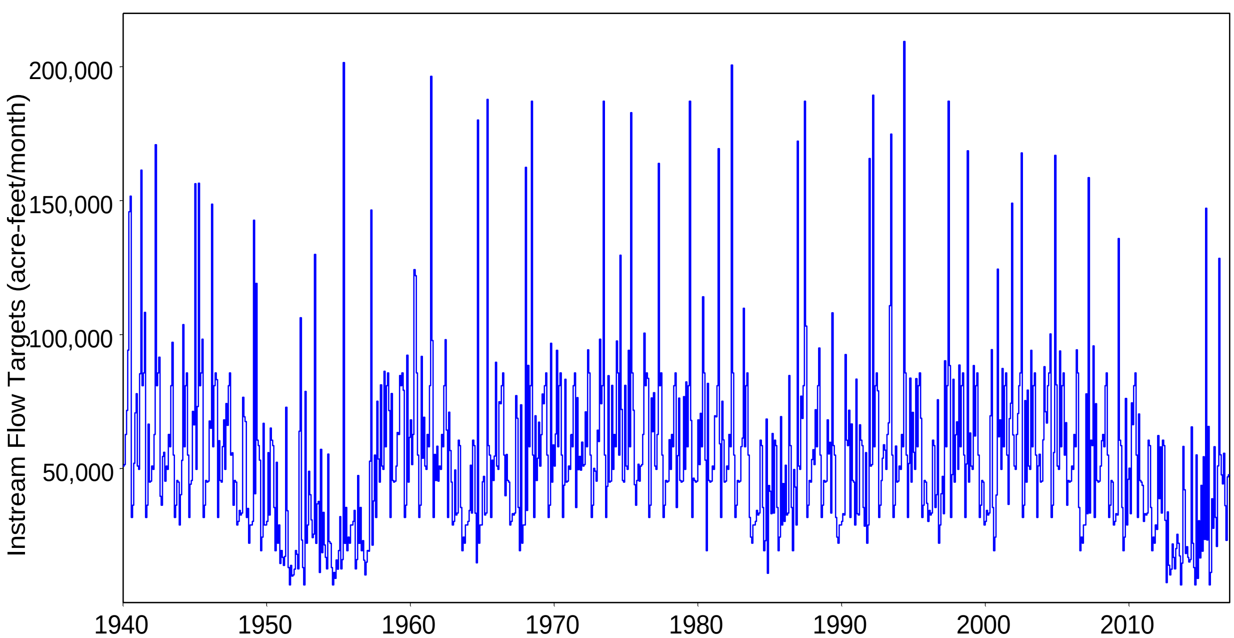

Figure 8.32 Monthly IFS targets (acre-feet) for Colorado River at Wharton (K20000)

Daily and Monthly Regulated Flows from a Daily *SIMD* Simulation with the C3D Dataset

The preceding figures compare daily and monthly SB3 EFS flow targets from a single daily *SIMD* simulation with WAM dataset C3D. Regulated flows generated with the C3D WAM simulation are plotted in the following Figures 8.33-8.38. The time series plots include daily regulated flows computed by *SIMD* in acre-feet/month and converted to cfs in *HEC-DSSVue* and monthly means at control points B2000, F10000, and K20000. Means and standard deviations of the 28,185 daily means of regulated flows in cfs or 924 monthly means in cfs of the regulated flows plotted in the figures are shown below the figure captions. Observed and naturalized daily flows at selected sites are plotted in Chapter 6.

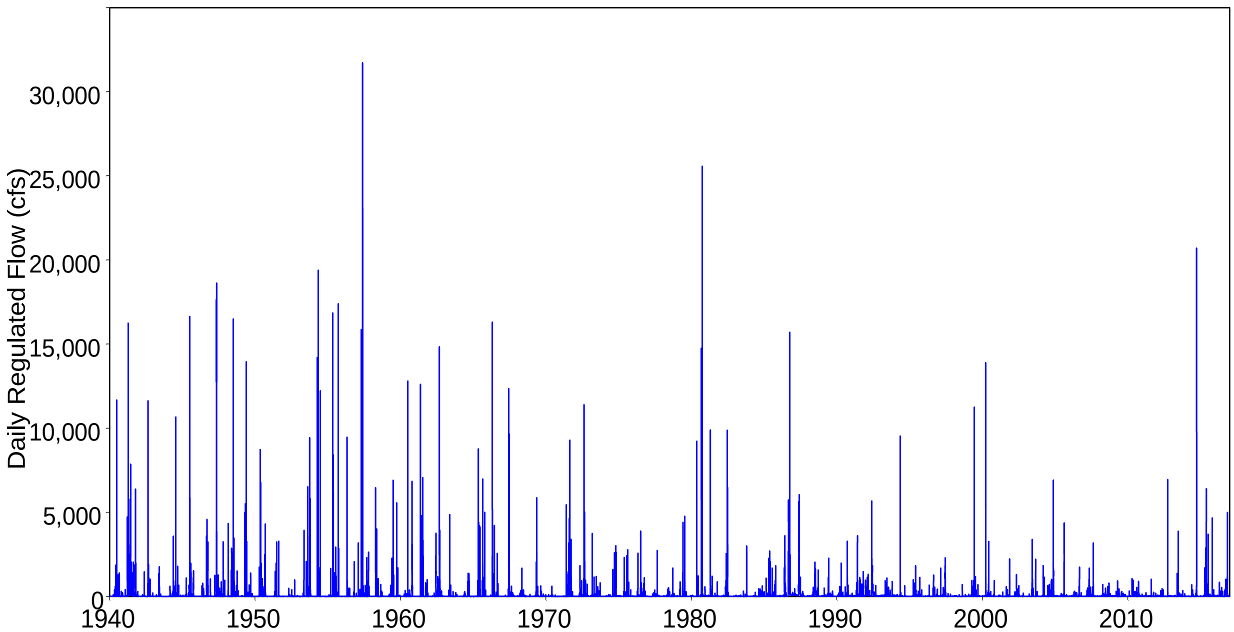

Figure 8.33 Daily Regulated Flow of the Colorado River above Silver (B20000)

average of 28,125 daily means = 117.8 cfs; standard deviation = 775.7 cfs

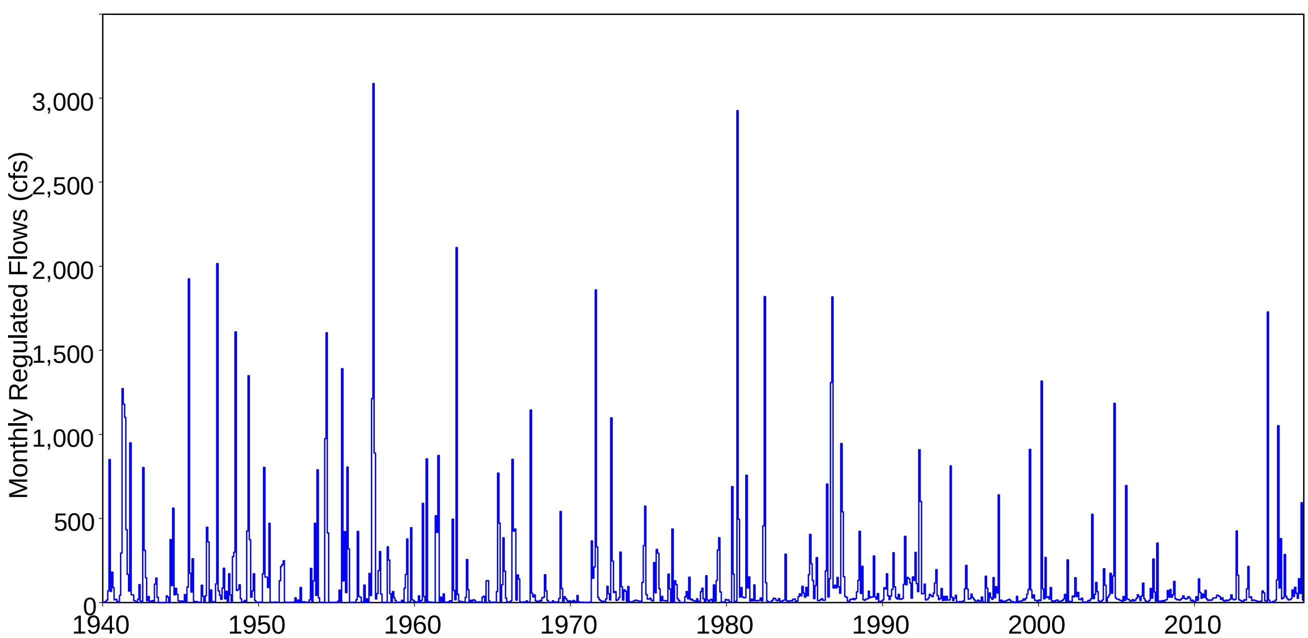

Figure 8.34 Monthly Regulated Flow of the Colorado River above Silver (B20000)

average of 924 monthly means = 117.4 cfs; standard deviation = 296.7 cfs

Daily means of flows during 28,125 days and monthly means of flows during 924 months are plotted in Figures 8.33-8.38. The averages of the daily and monthly flows shown below the plots would be exactly the same if every month had exactly the same number of days. However, the number of days in each month varies between 28, 29 (February of leap years), 30, and 31. Therefore, the 1940-2016 daily versus monthly averages are almost but not exactly the same.

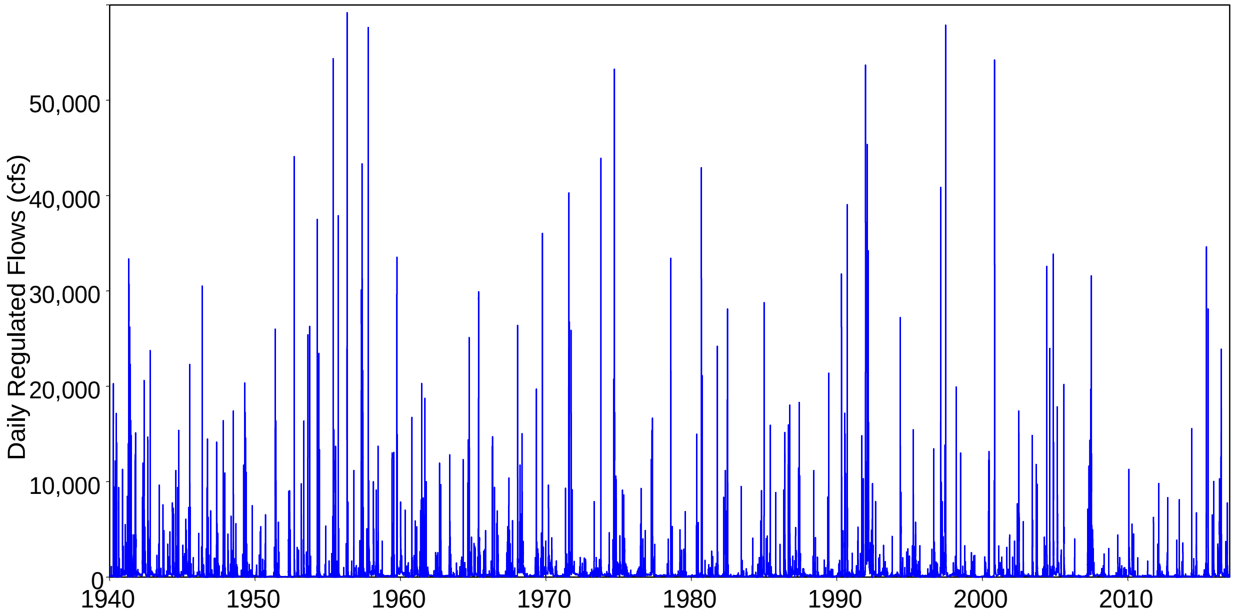

Figure 8.35 Daily Regulated Flow of the Colorado River near San Saba (F10000)

average of 28,125 daily means = 657.9 cfs; standard deviation = 2,660 cfs

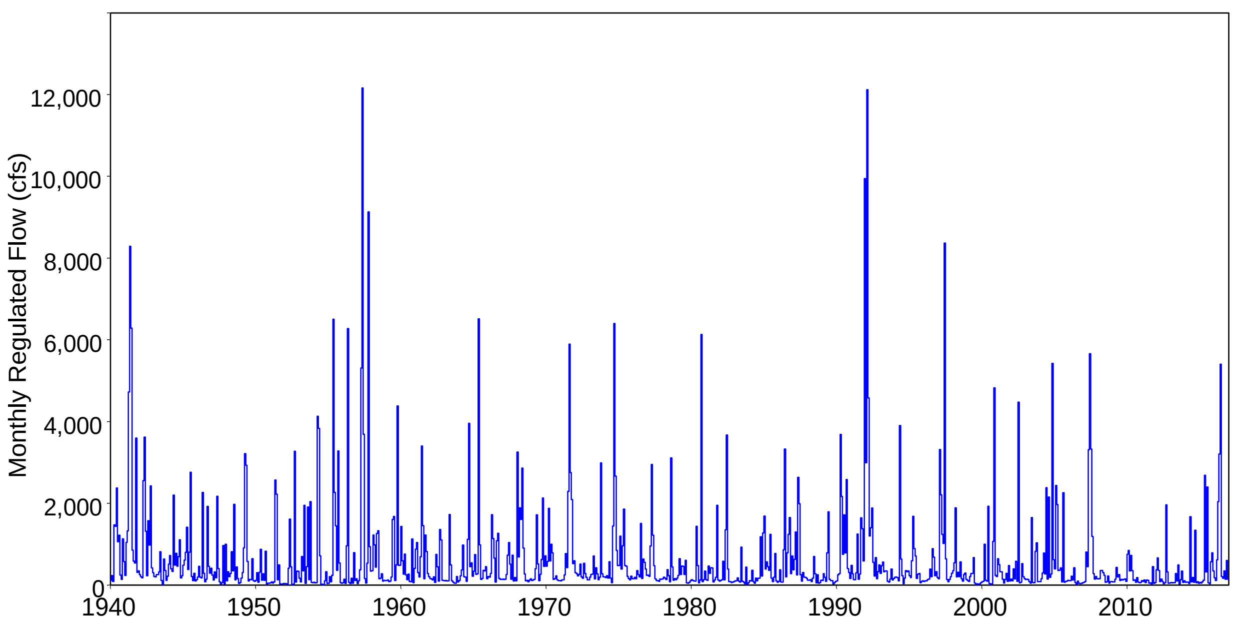

Figure 8.36 Monthly Regulated Flow of the Colorado River near San Saba (F10000)

average of 924 monthly means = 657.5 cfs; standard deviation = 1,240 cfs

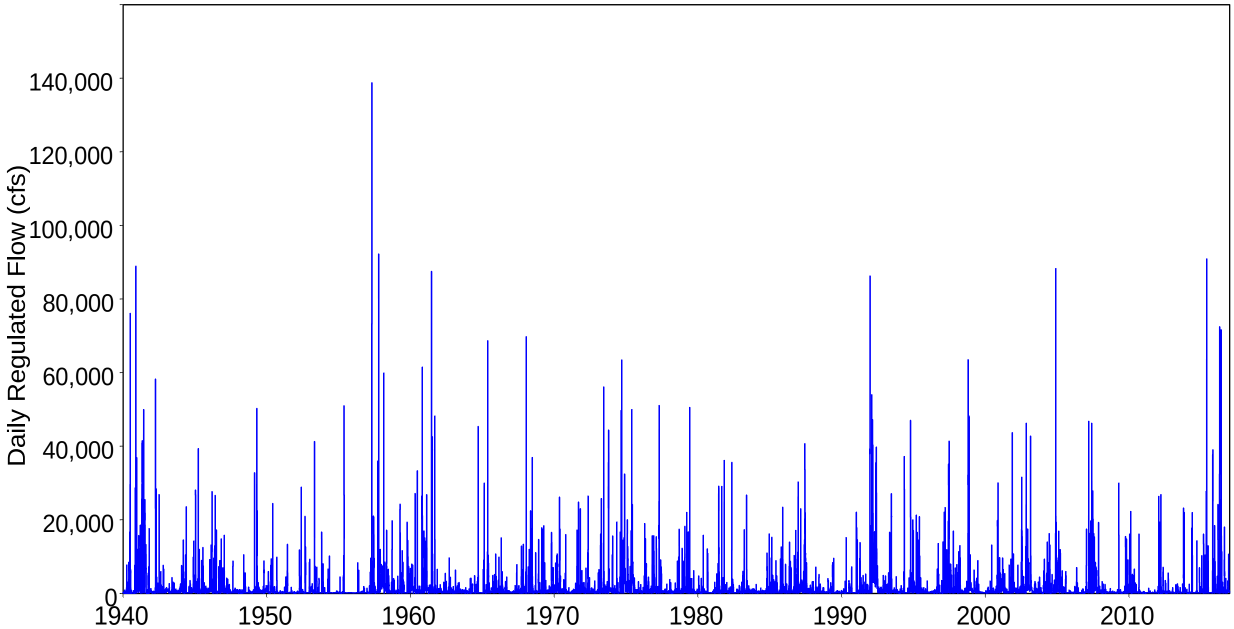

Figure 8.37 Daily Regulated Flow of Colorado River at Wharton (K20000)
mean of 28,125 daily means = 1,545 cfs; standard deviation = 4,757 cfs

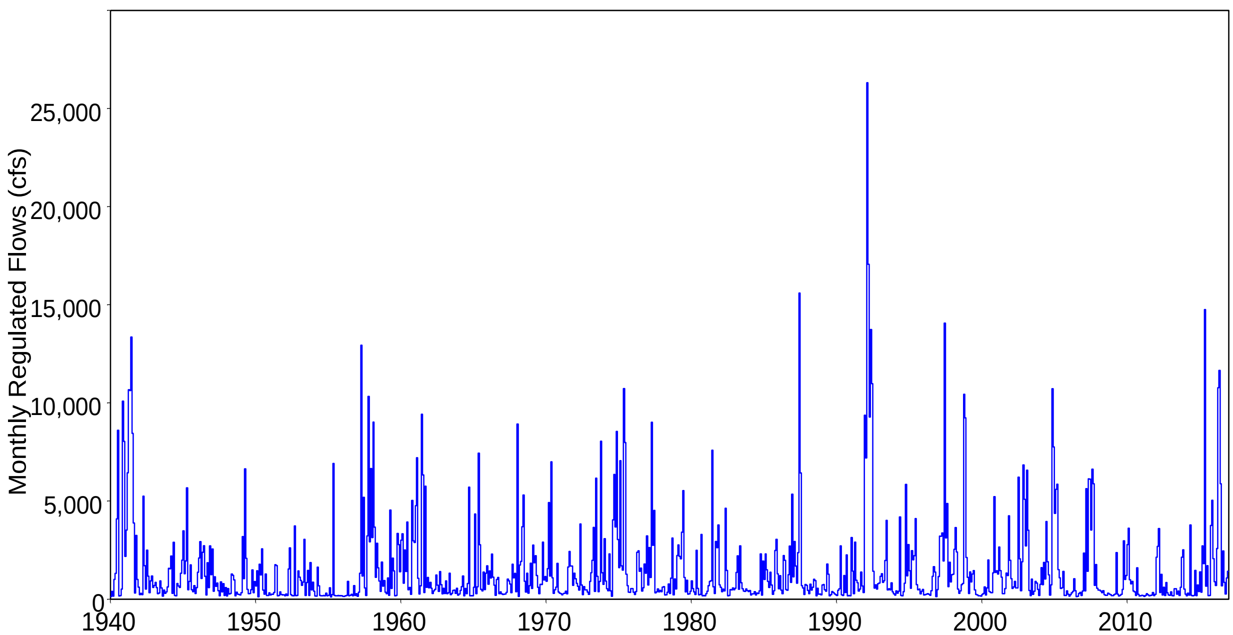

Figure 8.38 Monthly Regulated Flow of Colorado River at Wharton (K20000)
mean of 924 monthly means = 1,549 cfs; standard deviation = 2,388 cfs

The simulation results presented in Table 8.6 and Figures 8.5 through 8.38 of this section are from a single execution of the daily *SIMD* with the input dataset labeled C3D. Simulation results produced with WAM variations MX, C3D, and C3M are compared in the next section.

Comparison of Annual Means of Flow Rate Quantities from Simulations with WAM Versions MC, C3D, and C3M

Annual means in acre-feet/year of naturalized flow, regulated flows, unappropriated flows, SB3 EFS instream flow targets and shortages in meeting the target are tabulated in Tables 8.7, 8.8, and 8.9 for simulations with WAM versions MC, C3D, and C3M, respectively. The WAM variation labels MC, C3D, and C3M are defined in Table 8.2.

Table 8.7
Annual Means in acre-feet/year of Flows from MC Monthly Simulation

Control Point	Control Point Location	Naturalized Flow (ac-ft)	Regulated Flow (ac-ft)	Unappropriated Flow (ac-ft)	Target (acre-feet)	Shortage (acre-feet)
B20000	Colorado River, Silver	98,729	86,642	1,384	none	none
C30000	South Concho River	8,500	15,499	359.4	none	none
C10000	Concho River, Paint Rock	89,541	66,281	949.0	none	none
D40000	Colorado River, Ballinger	148,486	115,237	2,535	none	none
D30000	Elm Creek, Ballinger	29,733	28,335	1,256	none	none
E10000	San Saba River, San Saba	104,994	128,862	22,607	none	none
F20000	Pecan Bayou, Mullin	187,257	124,566	36,045	none	none
F10000	Colorado River, San Saba	721,955	508,520	77,728	none	none
G10000	Llano River, Llano	267,941	260,323	53,044	none	none
H10000	Pedernales , Johnson City	139,978	138,657	35,529	none	none
J50000	Onion Creek, Driftwood	34,891	34,567	13,185	none	none
J30000	Colorado River, Bastrop	1,834,420	1,083,209	217,277	none	none
J10000	Colorado River, Columbus	2,285,666	1,310,352	272,809	none	none
K20000	Colorado River, Wharton	2,440,842	1,120,837	289,604	none	none

Table 8.8
Annual Means acre-feet/year of Flows from C3D Daily Simulation

Control Point	Control Point Location	Naturalized Flow (ac-ft)	Regulated Flow (ac-ft)	Unappropriated Flow (ac-ft)	Target (acre-feet)	Shortage (acre-feet)
B20000	Colorado River, Silver	98,729	85,337	39.6	12,915	32.5
C30000	South Concho River	8,500	15,287	42.2	6,918	1,175
C10000	Concho River, Paint Rock	89,541	58,109	519.7	11,808	9.76
D40000	Colorado River, Ballinger	148,486	96,707	832.7	15,790	16.70
D30000	Elm Creek, Ballinger	29,733	27,274	376.8	4,910	117.8
E10000	San Saba River, San Saba	104,994	120,619	19,191	41,547	148.9
F20000	Pecan Bayou, Mullin	187,257	127,143	27,747	18,389	27.45
F10000	Colorado River, San Saba	721,955	476,631	70,724	197,981	10.90
G10000	Llano River, Llano	267,941	255,613	172,925	83,428	313.4
H10000	Pedernales , Johnson City	139,978	137,400	30,210	39,773	3,187
J50000	Onion Creek, Driftwood	34,891	34,467	17,606	6,366	65.44
J30000	Colorado River, Bastrop	1,834,420	1,245,867	196,309	410,419	21,106
J10000	Colorado River, Columbus	2,285,666	1,239,961	210,434	633,628	79,112
K20000	Colorado River, Wharton	2,440,842	1,119,428	205,641	666,044	136,689

Table 8.9
Annual Means acre-feet/year of Flows from C3M Monthly Simulation

Control Point	Control Point Location	Naturalized Flow (ac-ft)	Regulated Flow (ac-ft)	Unappropriated Flow (ac-ft)	Target (acre-feet)	Shortage (acre-feet)
B20000	Colorado River, Silver	98,729	86,643	1,383	12,915	84.28
C30000	South Concho River	8,500	15,499	328.7	6,918	1,111
C10000	Concho River, Paint Rock	89,541	66,281	934.2	11,808	714.6
D40000	Colorado River, Ballinger	148,486	115,237	2,533	15,790	487.0
D30000	Elm Creek, Ballinger	29,733	28,335	1,253	4,910	102.8
E10000	San Saba River, San Saba	104,994	123,862	17,630	41,547	43.27
F20000	Pecan Bayou, Mullin	187,257	124,566	30,891	18,389	1,976
F10000	Colorado River, San Saba	721,955	508,520	66,266	197,981	9,968
G10000	Llano River, Llano	267,941	260,323	42,558	83,428	168.0
H10000	Pedernales , Johnson City	139,978	138,657	30,759	39,773	2,862
J50000	Onion Creek, Driftwood	34,891	34,567	10,280	6,366	61.43
J30000	Colorado River, Bastrop	1,834,420	1,083,209	201,618	410,419	18,967
J10000	Colorado River, Columbus	2,285,666	1,310,352	255,080	633,628	37,708
K20000	Colorado River, Wharton	2,440,842	1,120,837	273,681	666,044	104,134

Tables 8.7, 8.8, and 8.9 contain the 1940-2016 means of flow quantities at the 14 SB3 EFS control point locations included in Table 8.1 and Figure 8.1. Naturalized flows are identically the same for all variations of the WAM and thus all three of the tables.

The averages of the targeted minimum instream flow limits at each of the 14 control points are shown in the next-to-last column of Tables 8.7, 8.8, and 8.9. These are means of the instream flow target recorded at the completion of the water right priority sequence computations in each of the 28,125 days of the C3D simulation. These targets are labeled IFT-CP in Tables 8.5 and 8.6. The instream flow targets in the C3M simulation are the monthly summations of the C3D daily *SIMD* simulation read by the monthly *SIM* from the C3M input dataset. Version MC is the original monthly WAM, which does not include the SB3 EFS.

Daily WAM version C3D was employed to develop the SB3 EFS instream flow limit targets incorporated in the monthly C3M dataset. Therefore, the 1940-2016 means of the SB3 EFS instream flow targets are identically the same in Tables 8.8 and 8.9. However, the associated shortages in the last column differ significantly between Tables 8.8 and 8.9.

Shortages occur in periods in which the regulated flow is less than the instream flow target (minimum flow limit). The shortage is the difference between the target minimum flow limit less the regulated flow. The shortages averaged in the last column of Table 8.8 were computed in each of the 28,125 days of a daily *SIMD* simulation. Table 8.9 shows the means of the monthly instream flow shortage volumes computed in each of the 924 months of a monthly *SIM* simulation. The monthly computational time step reduces the variability of regulated flow relative to the daily time step. The total instream target volume for a particular month may be fully met without shortage even though the regulated flow drops below the daily target in one or several days of that month. Shortages in the monthly model are less accurate than the daily model based monthly targets.

SB3 Environmental Flow Standards in the Monthly WAM

Alternative variations of the Colorado WAM discussed in Chapter 8 are defined in Table 8.2. WAM variations MC, C3D, and C3M are relevant in the following discussion. Monthly summations of daily instream flow targets computed in a daily *SIMD* simulation with input dataset C3D are incorporated in the monthly WAM dataset MC to create dataset C3M.

The filename roots C3D and C3M are adopted for the full authorization scenario WAM daily and monthly versions C3D and C3M. The final daily WAM (version C3D) is comprised of *SIMD* input files with the following filenames: C3D.DAT, C3D.DIF, C3D.DIS, and C3HYD.DSS. The final monthly WAM (version C3M) consists of *SIM* input files with the following filenames: C3M.DAT, C3M.DIS, and C3HYD.DSS. The same flow distribution file, with filename C3D.DIS or C3M.DIS, and the hydrology time series file with filename C3HYD.DSS are applicable for both daily and monthly simulations.

The daily instream flow targets for the SB3 EFS computed in the daily C3D simulations are preserved in the monthly C3M simulation. Daily instream flow targets in acre-feet/day for the *IF* record rights modeling the SB3 EFS computed in a daily *SIMD* simulation were summed within the *SIMD* simulation to monthly totals in acre-feet/month that are included in the *SIMD* simulation results. The time series of monthly targets were converted to target series *TS* records within *HEC-DSSVue* and stored in the DSS input file to be read in monthly *SIM* simulations.

The 14 target series *TS* records of 924 monthly instream flow targets in acre-feet/month stored in the *SIM/SIMD* input DSS file have the pathname identifiers listed in Table 8.10. The target series *TS* records in the DSS file are referenced by 14 *TS* records in the DAT file of the monthly C3M dataset which are replicated in Table 8.11.

Table 8.10
Pathnames for *TS* Records for the SB3 EFS in the DSS Input File C3HYD.DSS

Part A	Part B	Part C	Part D	Part E
C3M	B20000	TS	01Jan1940-31Dec2016	1MON
C3M	C30000	TS	01Jan1940-31Dec2016	1MON
C3M	C10000	TS	01Jan1940-31Dec2016	1MON
C3M	D40000	TS	01Jan1940-31Dec2016	1MON
C3M	C30000	TS	01Jan1940-31Dec2016	1MON
C3M	E10000	TS	01Jan1940-31Dec2016	1MON
C3M	F20000	TS	01Jan1940-31Dec2016	1MON
C3M	F10000	TS	01Jan1940-31Dec2016	1MON
C3M	G10000	TS	01Jan1940-31Dec2016	1MON
C3M	H10000	TS	01Jan1940-31Dec2016	1MON
C3M	J50000	TS	01Jan1940-31Dec2016	1MON
C3M	J30000	TS	01Jan1940-31Dec2016	1MON
C3M	J10000	TS	01Jan1940-31Dec2016	1MON
C3M	K20000	TS	01Jan1940-31Dec2016	1MON

Table 8.11
Instream Flow Rights for the SB3 EFS in the
DAT File of the Monthly WAM (Filename C3M.DAT)

```
IFB20000                 20110301   2            B20000ES
TS       DSS
IFC30000                 20091201   2            C30000ES
TS       DSS
IFC10000                 20091201   2            C10000ES
TS       DSS
IFD40000                 20091201   2            D40000ES
TS       DSS
IFD30000                 20091201   2            D30000ES
TS       DSS
IFE10000                 20091201   2            E10000ES
TS       DSS
IFF20000                 20091201   2            F20000ES
TS       DSS
IFF10000                 20091201   2            F10000ES
TS       DSS
IFG10000                 20091201   2            G10000ES
TS       DSS
IFH10000                 20091201   2            H10000ES
TS       DSS
IFJ50000                 20091201   2            J50000ES
TS       DSS
IFJ30000                 20091201   2            J30000ES
TS       DSS
IFJ10000                 20091201   2            J10000ES
TS       DSS
IFK20000                 20091201   2            K20000ES
TS       DSS
```

Comparison of Simulation Results from Monthly C3M and Daily C3D Versions of WAM

Colorado WAM versions C3M and C3D have the same monthly volumes for the SB3 EFS instream flow targets, but the daily C3D simulates the within-month variability of the SB3 EFS instream flow targets. The monthly instream targets stored on the DSS records listed in Table 8.10 and referenced by the *IF* records listed in Table 8.11 are plotted in Figures 8.6, 8.8, 8.10, 8.12, 8.14, 8.16, 8.18, 8.20, 8.22, 8.24, 8.26, 8.28, 8.30, and 8.32. These instream flow targets were computed in a C3D simulation and are read as input in C3M simulations.

Daily regulated flows at three control points computed in a C3D simulation are compared with their monthly summations in Figures 8.33-8.38. The 1940-2016 means of the daily means of the regulated flows and 1940-2016 means of the monthly means of the daily means of the regulated flows are the same. However, the standard deviation of the monthly flows is about half the standard deviation of the daily flows. Removal of the within-month variability greatly reduces the overall variability of the regulated flows.

Annual means of naturalized flows, regulated flows, unappropriated flows, SB3 EFS instream flow targets, and shortages in meeting the instream flow targets are tabulated in Tables 8.8 and 8.9 for daily and monthly simulations with WAM versions C3D and C3M, respectively. The 14 control points with SB3 EFS are included in the tabulations. Annual means of naturalized flows and SB3 EFS instream flow targets are identically the same for C3D and C3M.

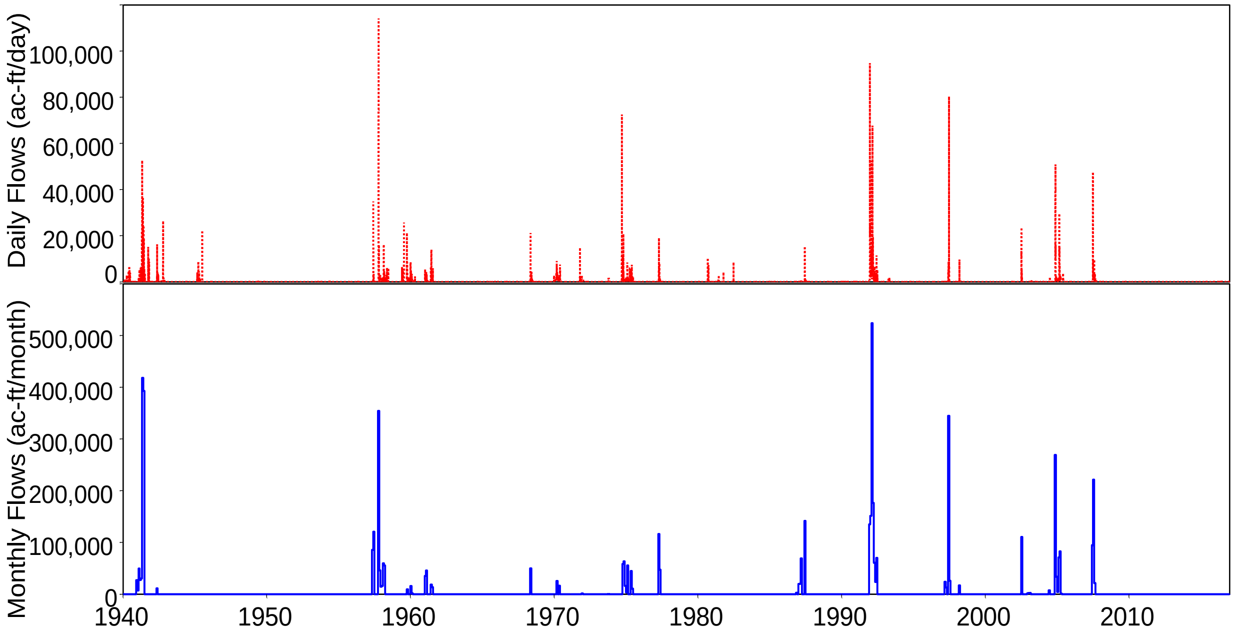

Figure 8.39 Monthly C3M (blue solid line) and Daily C3D (red dashed line) Unappropriated Flow of Colorado River near San Saba (F10000)

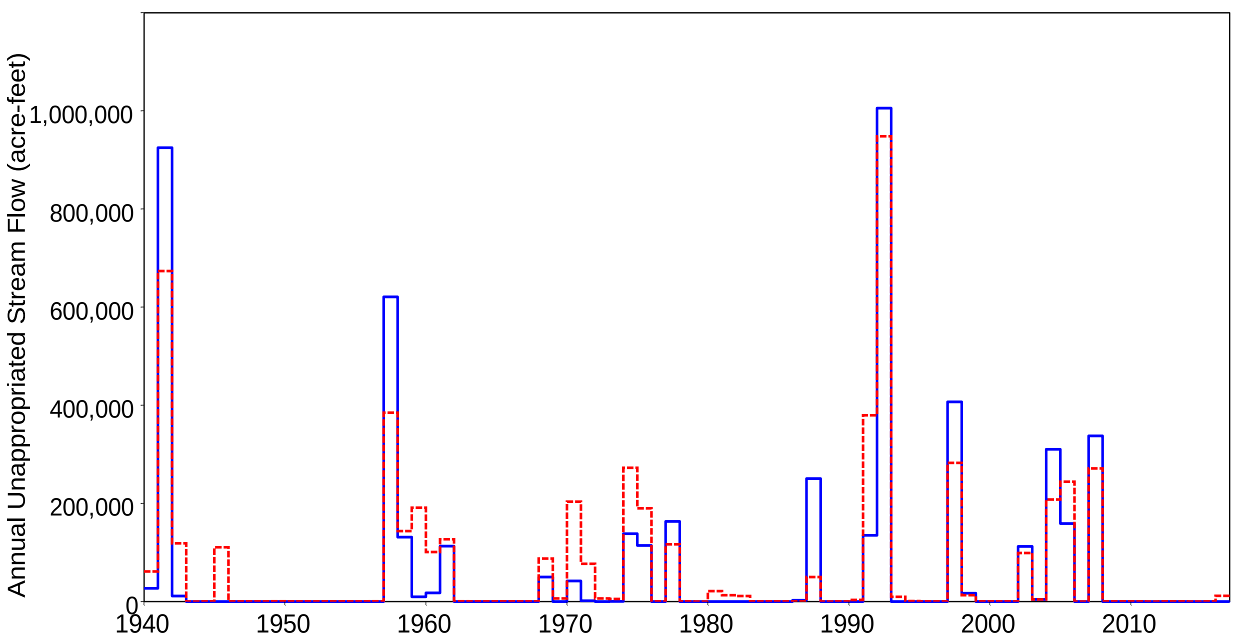

Figure 8.40 Annual Unappropriated Flow of Colorado River near San Saba (F10000) for Monthly C3M (blue solid) and Daily C3D (red dashed) WAMs

Although monthly and annual totals of SB3 EFS instream flow targets are the same for simulations with C3D and C3M, instream flow shortages and unappropriated flows vary significantly between the C3D and C3M simulations as illustrated by Tables 8.8 and 8.9 and the plots of daily, monthly, and annual unappropriated flows in Figures 8.39, 8.40, 8.41, and 8.42.

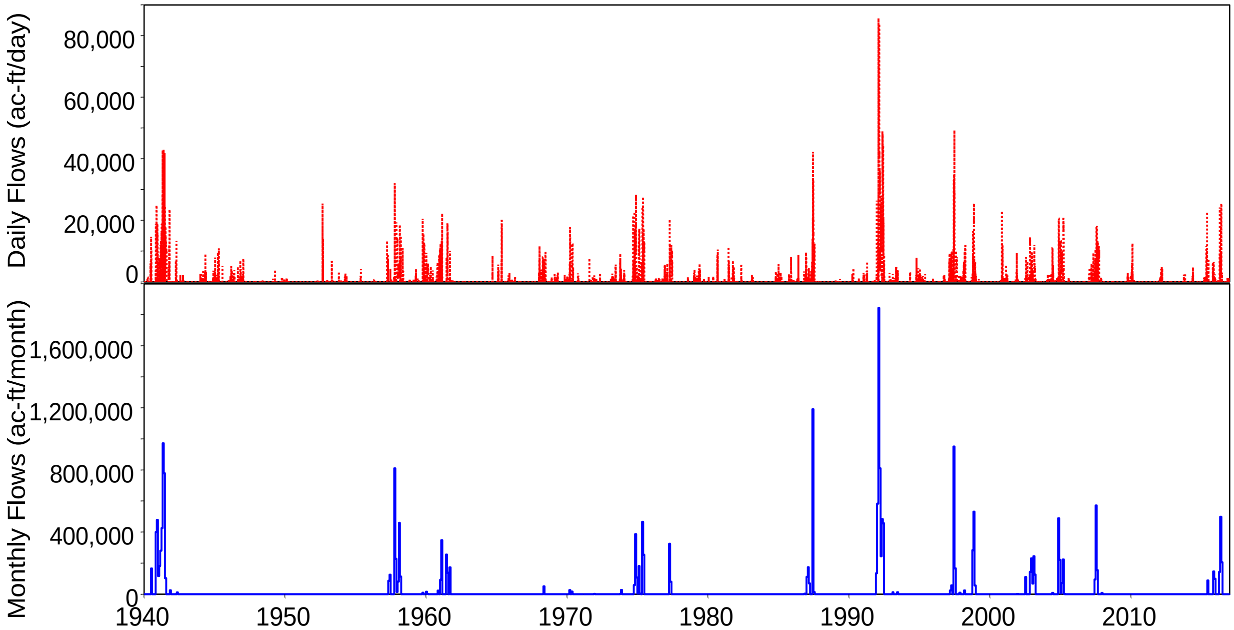

Figure 8.41 Monthly C3M (blue solid line) and Daily C3D (red dashed line) Unappropriated Flow of Colorado River at Wharton (K20000)

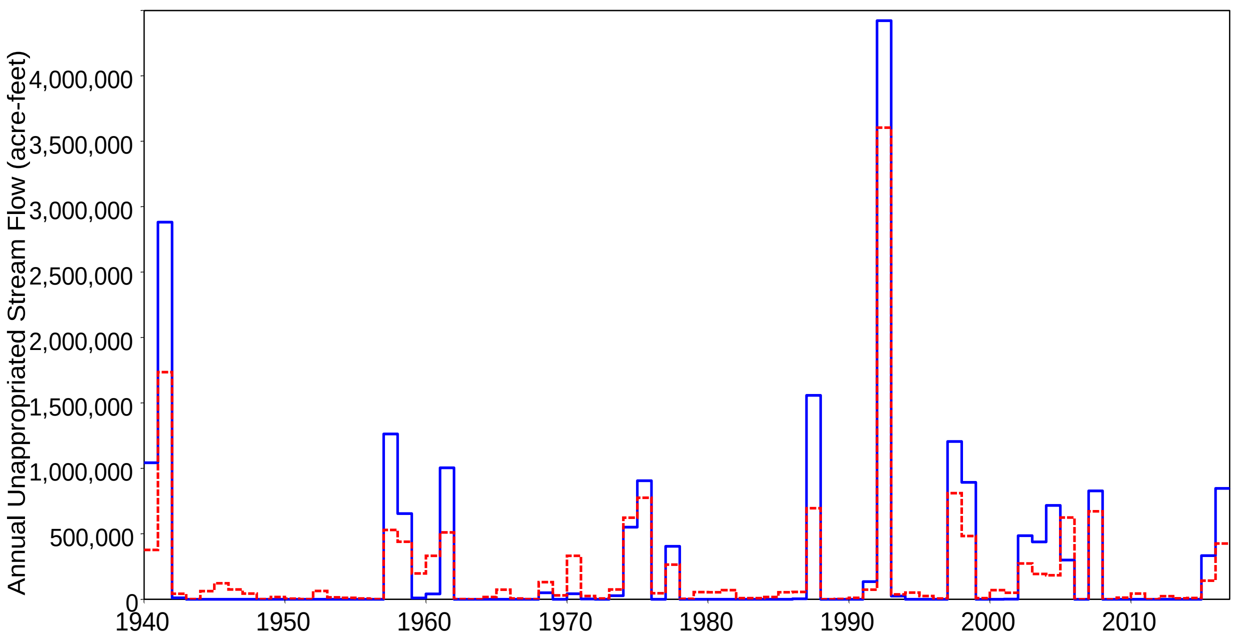

Figure 8.42 Annual Unappropriated Flow of Colorado River at Wharton (K20000) for Monthly C3D (blue solid) and Daily C3D (red dashed) WAMs

With priority dates of March 1, 2011, the SB3 EFS are junior to all other water rights in the WAM. The main effect of the SB3 EFS on other water rights is reducing unappropriated stream flows available to new water right permit applicants that may be considered for addition to the WAM in the future with priority dates junior to March 1, 2011. Unappropriated flows at sites on the Colorado near San Saba and Wharton (control points F10000 and K20000) are plotted in Figures 8.39-8.42. Unappropriated flows at sites located significant distances upstream of control point F10000 are minimal or essentially non-existent.

The within-month variability of unappropriated floes are illustrated in by the comparison C3D daily flows and C3M monthly flows in Figures 8.39 and 8.41. The plots of annual totals of unappropriated flows in Figures 8.40 and 8.42 show the differences in total volumes of unappropriated flows computed in C3M and C3D simulations.

<u>Comparison of Reservoir Storage for C3M and C3D</u>

Storage summation plots are presented throughout Chapters 7 and 8 for the three groups of reservoirs defined in Table 7.10. The summation of end-of-day storage contents of the 484 reservoirs in the WAM computed in a C3D simulation and the end-of-month storage contents from a C3M simulation are compared in Figure 8.43. The summation of storage contents in the six Highland Lakes from C3D and C3M simulations are plotted in Figure 8.44. Likewise, storage plots for the three largest CRMWD reservoirs are compared in Table 8.45.

The time series of storage volumes from simulations with the C3D and C3M WAM datasets plot reasonably close to each other. The most notable difference between C3D and C3M storage contents is storage in the Lake Travis flood control pool during floods.

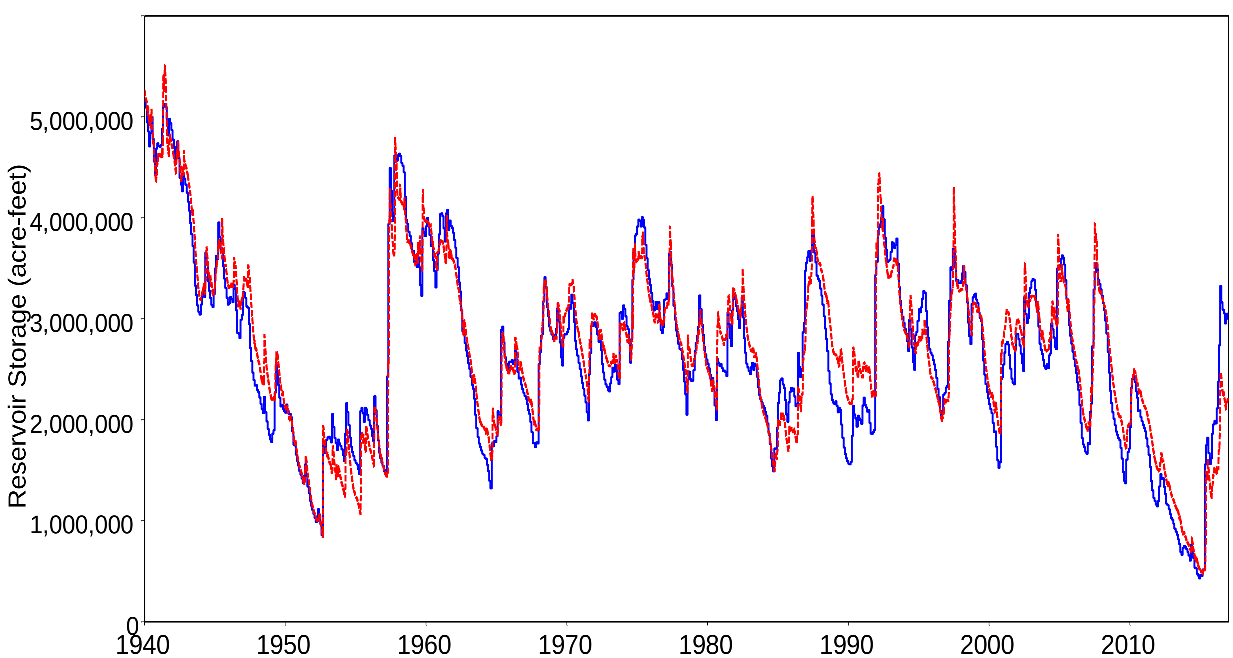

Figure 8.43 Storage Contents of 484 Reservoirs from Simulations with Monthly C3M (blue solid) and Daily C3D (red dashed) WAMs

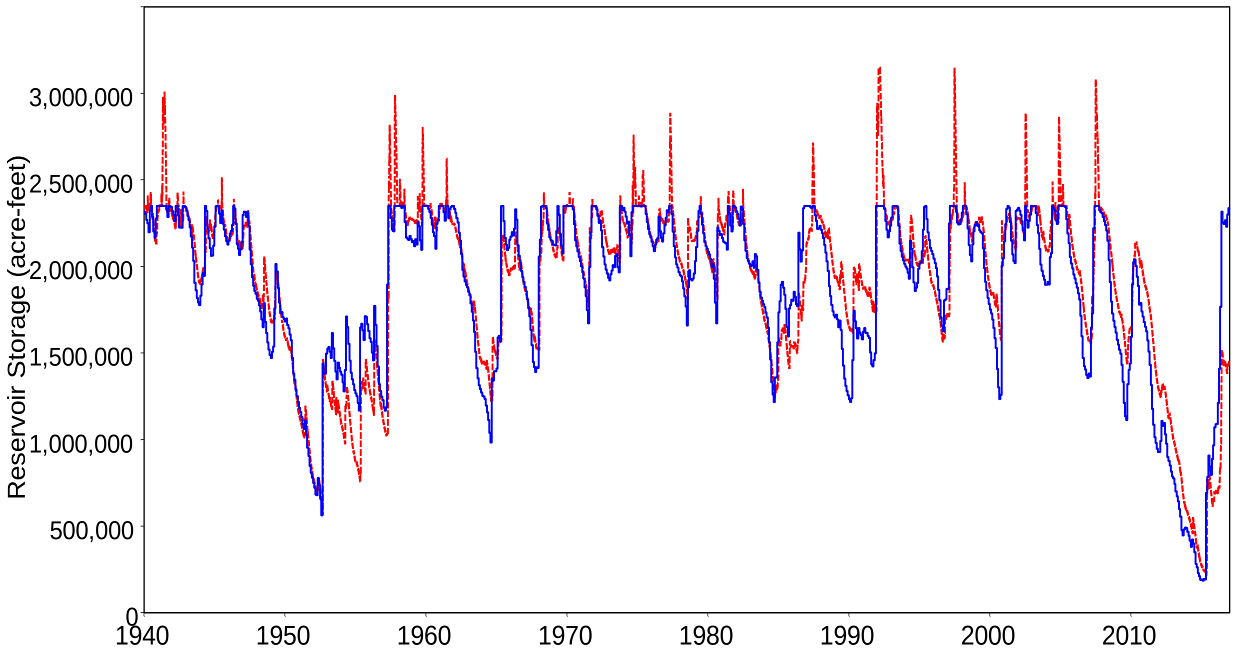

Figure 8.44 Storage Contents of Six Highland Lakes from Simulations with Monthly C3M (blue solid) and Daily C3D (red dashed) WAMs

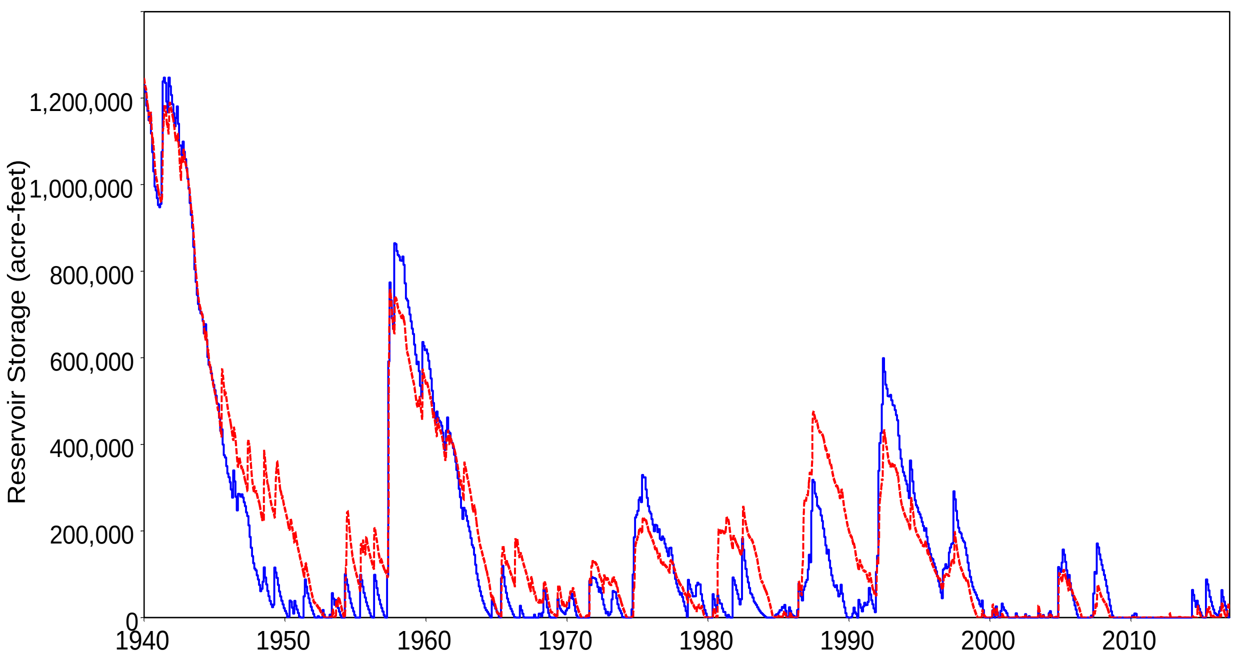

Figure 8.45 Storage Contents of Three CRMWD Reservoirs from Simulations with Monthly C3M (blue solid) and Daily C3D (red dashed) WAMs

CHAPTER 9
SUMMARY AND CONCLUSIONS

Daily and modified monthly versions of the Colorado WAM were developed as explained in this report following the general strategy adopted previously for the Brazos [8], Trinity [9], and Neches [10] WAMs. The Colorado and three other WAMs encompass four major river basins and two adjoining coastal basins. Characteristics of the river basins differ significantly from various perspectives. However, basic findings and observations from the development and application of the daily Colorado WAM are generally consistent with the Brazos, Trinity, and Neches WAMs. This report in combination with the three previous reports [8, 9, 10] document development of a significant experience base in daily WRAP/WAM modeling.

Daily WRAP/WAM Modeling System

The Water Rights Analysis Package (WRAP) is the generalized modeling system employed in the Water Availability Modeling (WAM) System maintained by the Texas Commission on Environmental Quality (TCEQ). The TCEQ WAM System provides WRAP simulation input datasets, called water availability models (WAMs), for all the river basins of Texas. WRAP software, manuals, training materials, and relevant publications are accessible at the WRAP website (https://wrap.engr.tamu.edu/) which links with the TCEQ WAM website providing the WAM datasets and a variety of WAM related information [23].

The routinely applied WAMs are based on a monthly computational time step. Daily WRAP modeling capabilities have been developed recently primarily for modeling and analysis of environmental flow standards (EFS) created through the process established by the 2007 Senate Bill 3 (SB3). Addition to the *SIMD* simulation model of capabilities for employing a daily computational time step was accompanied by addition of optional features for modeling reservoir operations for flood control, which is not possible with the monthly simulation model. Application of the daily WRAP modeling capabilities requires daily versions of the WAM simulation input datasets created by inserting additional information in the monthly WAM datasets. A daily version of the Colorado WAM was created by expanding the monthly WAM as described in this report.

March 2022 or later versions of *SIM* and *SIMD* should be executed with the C3M and C3D versions of the Colorado WAM described in Chapter 8. Development of daily and modified monthly versions of the Colorado WAM resulted in small improvements to *SIM* and *SIMD*. Likewise, the January 2021 versions of *SIM* and *SIMD* reflect improvements motivated by development of the Brazos, Trinity, and Neches daily WAMs [8, 9, 10].

Application of the Daily Colorado WAM to Model SB3 EFS

The work documented by this Colorado WAM report and the preceding Brazos, Trinity, and Neches daily WAM reports [8, 9, 10] is motivated by the need to improve capabilities for incorporating SB3 EFS in the TCEQ WAM System. A strategy was adopted 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 routinely applied monthly *SIM* simulation model. The monthly *SIM* simulation model is applied with the SB3 EFS modeled as *IF* record water rights with targets specified as target series *TS* records. Thus, the monthly instream flow target volumes from a daily *SIMD* simulation are replicated exactly in a monthly *SIM* simulation though the within-monthly variability of the daily targets is lost in the transfer from daily to monthly.

The SB3 EFS at 14 sites in the Colorado River Basin are described in Chapter 5. Simulation modeling studies focused on the SB3 EFS are reported in Chapter 8. The SB3 EFS with subsistence, base, and high pulse flow components have a priority date of March 1, 2011, making them the most junior of all *IF* and *WR* record water rights in the WAM. There are 120 other *IF* records in the WAM in addition to the *IF* record rights added to model the SB3 EFS. The SB3 EFS rights are modeled in *SIMD* using *IF*, *HC*, *ES*, *PF*, and *PO* records.

Monthly instream flow targets for the SB3 EFS at 14 USGS gage sites (WAM control points) are computed in a daily *SIMD* simulation and summed to monthly totals within the *SIMD* simulation. The monthly targets are converted to target series *TS* records within *HEC-DSSVue* and copied to the hydrology time series DSS input file. *IF* record instream flow rights incorporated in the DAT file for the monthly simulation access the *TS* record targets in the DSS input file.

This strategy precisely replicates monthly totals of daily SB3 EFS instream flow targets in the monthly WAM. However, shortages in meeting the targets may differ significantly between the monthly and daily simulations. Although the monthly summation of daily *IF* record targets for the SB3 EFS targets are replicated as input to the monthly WAM, monthly regulated flows and associated target shortages are computed within the monthly simulation. Unappropriated flows likewise vary between the daily and monthly simulations. The choice between subsistence and base flow targets in each day of the daily *SIMD* simulation is affected by within-month regulated stream flow variability. The determination of high pulse flow targets is almost totally controlled by within-month daily regulated flow variability. Shortages in meeting instream flow targets and unappropriated flows are also affected by within-month stream flow variability.

Different strategies for employing the expanded WAM will be useful for different types of applications. With the methodology applied in this report, after SB3 EFS targets are determined with the daily WAM, routine 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. This strategy is valid and appropriate for monthly WAM modeling of the impacts of SB3 EFS on other more junior or senior water rights that appropriate stream flows for reservoir storage and water supply diversions.

However, as previously noted, shortages or capabilities for satisfying the instream flow requirements are modeled in the monthly simulation without consideration of within-month flow variability. A daily model will more accurately and appropriately model the extent to which SB3 EFS requirements are satisfied. Shortages in meeting daily SB3 EFS targets will be more accurate.

The daily WAM can be employed directly, without the monthly WAM, in various types of studies with input data varied in alternative daily *SIMD* simulations to explore alternative water management strategies and issues. The daily model can facilitate environmental flow studies in which assessments of capabilities for meeting environmental flow standards are important. Daily simulation modeling capabilities also support studies in which reservoir flood control operations are a significant concern.

Modeling Options Adopted for the Daily Colorado WAM

The following discussion deals with the daily Colorado WAM. However, the same issues are addressed in the Brazos, Trinity, and Neches WAM Reports [8, 9, 10]. Although river system hydrology, water demands, and water management capabilities vary significantly between the river basins modeled in these four daily WAMs as well as regionally within each river basin, the same modeling strategies are generally applicable for all four WAMs. These methods are also generally applicable to daily WAMs developed in the future for other river basins.

SIMD capabilities outlined in Table 9.1 are a series of optional modeling features that can be added singly or in combination to convert a monthly WAM to daily [1, 2, 4]. Much of the complexity of *SIMD* is due to the model containing multiple optional alternative methods for performing the same tasks. Several *SIMD* modeling tasks are listed in the first column of Table 9.2. Multiple alternative approaches are provided in *SIMD* for performing each of these tasks. Methods adopted for the daily Colorado WAM are listed in the second column of Table 9.2. The third column of Table 9.2 lists the other options that are not selected.

Table 9.1
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. Forecasting for Determining Stream Flow 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*.

Organizational modifications common to monthly *SIM* and daily *SIMD* input datasets are covered in Chapter 2. Information added to the monthly WAM in the conversion to a daily WAM is described in Chapters 3, 4, and 5. Impacts of daily modeling features on simulation results are explored in Chapter 7. Results from simulations with different features activated are compared. The transition from monthly to daily WAM in Chapter 7 begins with disaggregation of monthly naturalized flows to daily. Next routing and then forecasting are explored. Other related options and issues are discussed. Flood control operations of four reservoirs are added in the last section of Chapter 7. The SB3 EFS at 14 control points are added in Chapter 8. Alternative variations of the daily WAM with different options and input parameters are included in the simulation studies of Chapters 7 and 8. Table 9.2 refers fully to the WAM dataset finalized in Chapter 8 and labeled C3D and partially to alternative intermediate versions explored in Chapter 7.

Table 9.2
SIMD Simulation Options Adopted for Final WAM Labeled C3D

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	none adopted	*DW* and *DO* record daily options
routing flow changes	lag and attenuation, 30 sites	No routing or Muskingum routing
routing parameter calibration	*DAY* statistical method	*DAYH* optimization options
negative incremental flows	ADJINC option 7	ADJINC options 1, 2, 3, 5, 6
next month placement	beginning priority sequence	within priority sequence
flow forecasting	3-day forecast	no forecasting or a wide range of possible 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 continually 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 Texas WAM System is appropriately and effectively constructed based on a monthly computational time step. A monthly computational time step is generally optimal for water availability modeling. 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.

Flood control reservoir operations, high pulse environmental flows, and the interactions between environmental flow requirements and flood control operations are aspects of water management that clearly 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, particularly high flows resulting from major rainfall events.

Within-Month Stream Flow Variability

Daily stream flow variability is the primary reason for the differences between monthly versus daily simulations. The plots of observed, naturalized, and simulated regulated stream flow found in this report illustrate the continuous variability and occasional extreme fluctuations that are characteristic of river flows throughout the Colorado River Basin and throughout Texas. Modeling within-month stream flow variability is the most significant aspect of adding the daily simulation capabilities to the WRAP/WAM modeling system. Developing the daily pattern hydrographs used by *SIMD* in converting monthly naturalized flows to daily while preserving monthly volumes 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.

DF record daily flow pattern hydrographs derived from observed daily flows at USGS gages were compiled at 45 control points for use in the *SIMD* simulation for disaggregating monthly naturalized flows to daily at over 2,200 control points as described in Chapter 3. In cases of gaps of missing gage records, daily flows were adopted from one or more other gages. The final pattern hydrographs were converted from observed daily flow rates in cfs to naturalized daily flow volumes in acre-feet/day that sum to the WAM monthly naturalized flow volumes.

The *DF* record daily pattern hydrographs are considered to provide a reasonably accurate representation of flow variability at most of the many individual control points. However, flows at over 2,200 sites are represented by flows developed for only 45 sites. The *DF* record flows do not capture the lag and attenuation effects of the reaches between the many control points for which the flows are repeated, which is relevant to the following discussion of routing and forecasting.

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 may be 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. 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 which 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 Colorado WAM with over 2,200 control points includes routing parameters at 30 control points.

Development of normal flow and high flow lag and attenuation parameters at 30 control points is described in Chapter 3. Lags vary with location but attenuation was determined to be 1.0 day for all 30 sites. Thus, the lag and attenuation method reduced to lag-only routing.

Routing parameter calibration employs a methodology of 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 in the Colorado River Basin as well as the Brazos, Trinity, and Neches River Basins were found to exhibit great apparently random variability. Calibrated values for the lag 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. Likewise, further improvements to the parameter calibration methodology would likely not further improve the accuracy of the model.

The daily as well as monthly versions of the Colorado WAM provide a valid simulation model without employing routing. Routing is approximate with inherent simplifications, uncertainties, inaccuracies, and variabilities. Routing may or may not improve the accuracy of various aspects of a simulation depending upon the particular application and circumstances. The effects of routing and variations in routing parameters on improving or worsening model accuracy is difficult to precisely assess. The simulation studies presented in Chapter 7 indicate reasonable results both with and without routing. Routing is included in the daily C3D WAM.

Forecasting of Effects of Flow Alterations on Future Stream Flows

The *SIMD* forecasting algorithm is applicable only in a daily, not monthly, simulation. 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) channel flow capabilities for releases from flood control pools. The following two purposes are served by forecasting in the model.

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.
2. Prevention of current day releases of water from flood control pools that contribute to flooding in future days.

The alternative simulations presented in Chapter 7 include alternative forecast periods of three and seven days. Forecast periods of significantly more than seven days were found to unrealistically over-constrain stream flow availability. The default forecast period of 41 days is computed by *SIMD* as twice the total lag time for the longest flow path plus one day and conceptually represents near-perfect protection of senior water rights from the adverse effects of junior streamflow depletions at upstream locations during preceding days.

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, perhaps many control points, in the future days of the forecast period as well as in the current day. 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 future days.

JU record parameters WRMETH and WRFCST control selection of next-day placement of routed flow changes within the next day priority sequence. Simulations presented in this report employ the default option of placing routed flows at the beginning of the priority sequence.

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 sequence simulation. Flow forecasting significantly magnifies these effects by considering all days of the forecast period.

In summary, 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.

Forecasting of future stream flow is also 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 approximate. 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.

Flood Control Operations

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 the 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 [4].

Reservoir flood control operations in the Colorado River Basin and the daily Colorado WAM are covered in Chapter 4 and the last section of Chapter 7. The daily Colorado WAM includes operation of designated flood control pools of Lakes Travis, Twin Buttes, O.C. Fischer, and Hords Creek. However, the full authorization scenario WAM simulation results show Lake Travis as being the only reservoir actually storing water in the flood control pool. Twin Buttes, O.C. Fischer, and Hords Creek Reservoirs are continuously drawn down below the top of conservation pool (bottom of flood control pool) throughout the simulation. Employing *SIMD* flood control pool features significantly affect the operation of Lake Travis but does not affect the operation of the three other flood control reservoirs.

The plots of historical storage levels in Twin Buttes, O.C. Fischer, and Hords Creek Reservoirs in Figures 4.2, 4.3, and 4.4 of Chapter 4 show frequent almost continuous severe drawdowns with only a few encroachments into flood control pools. Although actual storage levels have historically been notably low, the observed storage levels in these three reservoirs are generally a little higher than the simulated storage levels generated by the full authorization daily WAM. Draw-downs are much less severe and storage levels have frequently risen into the flood control pool of Lake Travis as shown in Figure 4.1. Likewise, water levels in Lake Travis encroach into flood control storage frequently in the daily WAM.

Flood control operation in *SIMD* refers specifically to managing releases from designated flood control pools in multiple-purpose reservoirs. Flood control pools are maintained empty except during and immediately following high flow events. Drawn-down conservation pools also incidentally reduce flood flows. Flood flows refill conservation pools used for water supply.

Stream Flow and Reservoir Storage Variability and Stationarity

Observed, naturalized, and simulated regulated stream flows in the Colorado River Basin are extremely variable as illustrated by time series plots and statistical frequency metrics presented throughout this report. Unappropriated flows are a small fraction of the corresponding naturalized and regulated flows. Unappropriated flows are zero or minimal the majority of the time throughout the basin, but particularly in the upper basin.

Hydrologic Stationarity and Variability

Monthly precipitation, evaporation, and naturalized stream flows are highly variable but essentially stationary as discussed in Chapter 6. The monthly basin-wide precipitation and reservoir evaporation rates plotted in Figures 6.1-6.4 provide a measure of long-term 1940-2020 climatic stationarity. Permanent changes or long-term trends in these monthly time series, if they exist, are hidden by the great continuous variability. This observation regarding hydrologic stationarity in the Colorado River Basin is consistent with similar statewide analyses [5, 22].

Observed stream flows at gage sites tend to be non-stationary due to water development, management, and use. Naturalized monthly flows in the Colorado WAM are generally stationary without detectable long-term alterations or trends. *SIM* and *SIMD* simulations adjust naturalized stream flow and reservoir storage for a specified constant set of water demand requirements. Therefore, simulated regulated and unappropriated flows and reservoir storage are also stationary.

Observed and simulated stream flow rates fluctuate continually, seasonally, and annually, and are subject to extremes of severe multiple year droughts and major intense floods. Conversion of the monthly WAM to daily focuses on within-month variability of daily flows. Time series plots and statistical frequency metrics presented in Chapters 6, 7, and 8 show the within-month variability to be very significant. Daily flows are much more variable than monthly flows.

Storage of water in reservoirs attenuates or dampens stream flow fluctuations, providing protection against severe multiple-year droughts and intense floods as well continual more gradual daily fluctuations. Water supply diversion needs are highly dependent on reservoir storage. Environmental instream flow requirements without access to reservoir storage, flood control, and run-of-river water supply diversions are sensitive to within-month daily stream flow fluctuations.

<u>Reservoir Storage</u>

Observed storage levels since initial impoundment of several selected reservoirs are plotted in Chapters 4 and 6. All simulations in this report are based on combining the full authorization scenario of water development, management, and use with 1940-2016 historical natural hydrology.

SIM and *SIMD* include a count of 526 reservoirs in the message file. However, 42 of these reservoirs are designated as artificial as explained in Chapter 2. The *SIM/SIMD* count of 484 actual reservoirs cited throughout the report is somewhat approximate. Some existing reservoir storage facilities and authorized but not yet constructed projects may be reasonably counted as either multiple reservoirs or one combined reservoir.

End-of-day storage contents for the 28,125 days of the 1940-2016 hydrologic period-of-analysis computed with the C3D dataset and end-of-month storage contents for the 924 months computed with the C3M datasets are compared in Figures 8.43, 8.44, and 8.45 for summations of all 484 reservoirs, six Highland Lakes, and three largest CRMWD reservoirs, respectively. The full authorization scenario monthly *SIM* and daily *SIMD* simulations result in severe reservoir draw-downs as illustrated by the C3M and C3D storage plots in Figures 8.43, 8.44, and 8.45 on pages 175-176 and other similar storage plots and storages frequency tables presented in Chapters 2, 7, and 8. Reservoirs in the upper basin stay dramatically at or near empty much of the time during the full authorization scenario simulations.

The 1940-2016 daily reservoir storage contents from a *SIMD* simulation with the C3D WAM dataset and monthly storage contents from a *SIM* simulation with the C3M dataset are very close to each other in Figures 8.43, 8.44, and 8.45. The greatest difference between *C3D* and *C3M* simulated storage contents is storage in the Lake Travis flood control pool during floods.

Most Hydrologically Severe Droughts in the Colorado River Basin Since 1940

Simulated reservoir storage for a specified water development/management/use scenario is among the various metrics that can used as indices of hydrologic drought severity. The full authorization scenario reservoir storage plots of Figures 2.9, 2.10, 8.43, 8.44, and 8.45 are adopted in this discussion as a basin-wide drought index. Since a specified fixed level of economic development is combined with historical natural hydrology in the simulation, reservoir storage depletions are a measure of hydrologic drought severity rather than economic drought severity.

Using full authorization simulated storage as a measure of drought severity, the two most severe droughts in the Colorado River Basin since 1940 occurred during 1950-1957 and 2008-2015. The 1950s drought begin gradually in 1950 and ended with a major flood in May-April 1957. The 2008-2015 drought began in 2008 and ended with extremely high rainfall during 2015. The minimum of the daily summation of storage contents of the 484 reservoirs in the C3D simulation of Figure 8.43 is 8.97 percent of the total authorized storage capacity. This minimum storage level occurs on March 6, 2015 of the hydrologic period-of-analysis. The minimum total volume of water stored in the 484 reservoirs in the C3D simulation during the 1950s drought is 15.9 percent of capacity on August 31, 1952.

The storage summation for the 484 reservoirs of Figure 8.43 never totally refills to capacity after the 1950s drought. Thus, the severe storage deletion during the 1950s drought can affect storage in some reservoirs in future years. The 2008-2015 drought began with less water in storage than the amount in storage at the beginning of the 1950-1957 drought.

The WAMs for all the river basins reflect the premise that all reservoirs are full to capacity at the beginning of the simulation. Reservoirs are significantly drawn-down most of the time in the full authorization scenario Colorado WAM. Figures 7.7, 7.8, and 7.9 address the issue of beginning-of-simulation storage. An alternative simulation with the beginning storage in each reservoir set equal to its end-of-simulation storage is compared with the conventional full-to-capacity premise. Full authorization scenario simulated storage levels were found to be essentially the same after the 1940s with either alternative premise. Rainfall and stream flows were extremely high during 1941 and several other years of the decade of the 1940s preceding the 1950s drought.

Reservoir storage is still severely depleted at the end of the 1940-2016 hydrologic period-of-analysis simulation due to the 2010-2015 drought. Information in Chapter 6 indicates that relatively normal hydrologic conditions followed after 2016. For example, the 2017-2020 basin-wide mean precipitation of 26.9 inches/year is close to the 1940-2020 mean of 26.3 inches/year. Plots of actual observed storage contents in the five largest reservoirs in the basin presented in Figures 6.12-6.16 show significant refilling of storage during the period 2017 to near the present.

Data Files

This final section of this last chapter provides a summary inventory of the data files that accompany this report. The accompanying data files include *SIM* and *SIMD* input files, *SIM* and *SIMD* simulation results, and auxiliary datasets discussed in the various chapters. Data storage system (DSS) files can be viewed and edited with *HEC-DSSVue*. *SIM/SIMD* input files in text format can be viewed and edited with Microsoft WordPad, NotePad, or Word or other editors.

Latest TCEQ *SIM* Input Dataset

The full authorization scenario Colorado WAM last updated by the TCEQ in February 2020 is described in Chapter 2. The monthly WAM consists of the following *SIM* input files.

C3.DAT –The DAT file contains the many types of *SIM* simulation input records that are not contained in the following five other *SIM* simulation input files.

C3.DIS – The flow distribution (DIS) file contains 2,240 flow distribution (*FD*) records and 2,285 watershed parameter (*WP*) records employed in the *SIM* simulation to distribute monthly naturalized stream flows from 45 primary to over 2,200 secondary control points.

C3.FLO – The FLO file contains 3,465 *IN* records with 1940-2016 monthly naturalized flow volumes in acre-feet/month at 45 primary control points.

C3.EVA – The EVA file contains 3,696 *EV* records with 48 sequences of 1940-2016 monthly net reservoir evaporation minus precipitation depths in feet.

C3.FAD – The flow adjustment (FAD) file contains 1,001 flow adjustment (*FA*) records with 1940-2016 monthly adjustments at 13 control points. The quantities on the *FA* records are used to adjust the *IN* record naturalized stream flows for the effects of spring flows.

C3.HIS – The hydrologic index series (HIS) file contains 77 hydrologic index (*HI*) records for a 1940-2016 monthly index at control point G50000 at USGS gage 08148500 on the North Llano River near Junction referenced by target options (*TO*) records in the DAT file.

Daily C3D and Monthly C3M Simulation Input Datasets

The full authorization daily *SIMD* input dataset labeled C3D and modified monthly *SIM* input dataset labeled C3M are described in Chapter 8. These WAM files are listed in Table 9.3. The same DSS and DIS files are used with both monthly *SIM* and daily *SIMD* simulations. The DIF file is applicable only with *SIMD*. The contents of each file are described below.

Table 9.3
Filenames of Data Files for WAMs Described in Chapter 8

Daily C3D WAM	C3D and C3M	Monthly C3M WAM
C3D.DAT C3D.DIF	C3HYD.DSS C3.DIS	C3M.DAT

C3HYD.DSS − The 166 DSS records of 1940-2016 time series data include 45 *IN* records of monthly naturalized flows, 48 *EV* records of reservoir evaporation less precipitation depths, 45 *DF* records of daily flows, 13 *FA* records of flow adjustments, one *HI* record hydrologic index, and 14 *TS* records of monthly SB3 EFS instream flow targets. *SIM* and *SIMD* input DSS record pathnames are defined in Table 6.6 of the *Users Manual* [2].

C3.DIS − The flow distribution DIS file contains the flow distribution *FD* and watershed parameter *WP* records used to distribute monthly naturalized flows from 45 primary to over 2,200 secondary control points the same with the daily versus monthly versions of the WAM. The *FD* and *WP* records and DIS file are the same in all WAM versions discussed in this report.

C3D.DIF − The daily input file (DIF) contains flow disaggregation specifications on three *DC* records and lag and attenuation routing parameters on 30 *RT* records. A daily *SIMD* simulation can be performed optionally with or without routing of flow changes using the *RT* records.

C3D.DAT − The daily version of the full authorization scenario DAT file with filename C3D.DAT expands the monthly DAT file with filename C3.DAT as described in this report.

C3M.DAT − The version of the monthly full authorization scenario DAT file with filename C3M.DAT reflects addition of SB3 EFS to the monthly DAT file with filename C3.DAT.

A monthly simulation can be performed with *SIM* with a DAT file containing input records for a daily simulation. *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* can perform a monthly simulation if and only if no daily-only records are included in the input dataset.

SIM and *SIMD* Results for the C3D and C3M WAMs (ColoradoSimulationResults.DSS)

Simulation results generated with the C3D and C3M datasets are described in Chapter 8. Results from multiple simulations recorded in output files with filenames C3D.DSS and C3M.DSS are consolidated into a file labeled ColoradoSimulationResults.DSS. Pathnames for DSS records of *SIM* and *SIMD* simulation results are defined in Table 6.5 of the *Users Manual* [2]. Units are acre-feet/day or acre-feet/month for flows and acre-feet for storage. The compilation of 1940-2016 series of C3D daily results and monthly summations thereof on 714 and 244 DSS records, respectively, and C3M monthly results on 632 DSS records contains the following quantities.

- C3D daily volumes and monthly summations of daily volumes of naturalized, regulated, and unappropriated flows at the 45 primary control points.
- C3D daily volumes and monthly summations of *ES* record and *PF* record components of SB3 EFS targets (IFT-WR & TIF-WR) and shortages (IFS-WR) for 28 *IF* water rights.
- C3D daily volumes and monthly summations of final SB3 EFS targets (IFT-CP) and associated shortages (IFS-CP) at 14 control points.
- C3D daily reservoir storage volumes for all control points with non-zero storage volumes.
- C3M naturalized, regulated, and unappropriated flows at the 45 primary control points.
- C3M monthly SB3 EFS targets (IFT-CP) and shortages (IFS-CP) at 14 control points.
- C3M reservoir storage volumes for all control points with non-zero storage volumes.

Auxiliary Datasets (ColoradoAuxiliaryData.DSS)

A DSS file with filename ColoradoAuxiliaryData.DSS contains the following selected datasets from Chapters 3, 6, 7, and 8. Pathname part A includes the chapter of this report in which the datasets are discussed. Other pathname parts are assigned labels descriptive of the datasets.

Chapter 3 – Period-of-record observed daily flows in cfs at 45 USGS gages listed in Table 3.3.

Chapter 6 – Monthly and annual precipitation and evaporation in inches in Figures 6.1-6.4.

Chapter 7 – Summations of 1940-2016 monthly and daily storage volumes in acre-feet in Tables 7.11-7.13 for the three groups of reservoirs described in Table 7.10.

Chapter 8 – Summations of 1940-2016 monthly and daily storage volumes in acre-feet with frequency statistics in Table 8.4 and plots in Figures 8.2-8.4 and 8.43-8.45.

REFERENCES

1. R.A. Wurbs, *Water Rights Analysis Package Modeling System Reference Manual*, Texas Water Resources Institute (TWRI) Technical Report (TR) 255, 13th Edition, 464 pages, Jan. 2021.

2. R.A. Wurbs, *Water Rights Analysis Package Modeling System Users Manual*, TWRI TR-256, 13th Edition, 270 pages, January 2021.

3. R.A. Wurbs, *Fundamentals of Water Availability Modeling with WRAP*, TWRI TR-283, 9th Edition, 116 pages, May 2019.

4. R.A. Wurbs and R.J. Hoffpauir, *Water Rights Analysis Package Daily Modeling System*, TWRI TR-430, 4th Edition, 342 pages, January 2021.

5. R.A. Wurbs, *Water Rights Analysis Package River System Hydrology*, TWRI TR-431, 3rd Edition, 241 pages, May 2019.

6. R.A. Wurbs, *Salinity Simulation with WRAP*, TWRI TR-317, 87 pages, July 2009.

7. R.A. Wurbs, *WRAP Additions and Revisions*, Texas Commission on Environmental Quality, Contract 582-15-50298, 92 pages, January 2021.

8. R.A. Wurbs, *Daily Water Availability Model for the Brazos River Basin and San Jacinto-Brazos Coastal Basin*, TCEQ Contract 582--18-80410, TWRI TR-513, 238 pages, May 2019.

9. R.A. Wurbs, *Daily Water Availability Model for the Trinity River Basin*, Texas Commission on Environmental Quality, Contract 582-18-80410, 193 pages, December 2019.

10. R.A. Wurbs, *Daily Water Availability Model for the Neches River Basin*, Texas Commission on Environmental Quality, Contract 582-18-80410, 199 pages, June 2020.

11. Texas Commission on Environmental Quality, Texas Administrative Code, *Chapter 298 Environmental Flow Standards, Subchapter D Colorado and Lavaca Rivers, and Matagorda and Lavaca Bays*, August 2012.

12. R.J. Brandes Company, *Water Availability Modeling for Colorado and Brazos Colorado Basin Water Availability Assessment – Final Report*, Prepared for Texas Natural Resource Conservation Commission, December 2001.

13. Lower Colorado River Authority, *Lakes Buchanan and Travis Water Management Plan and Drought Contingency Plan*, Submitted to Texas Commission on Environmental Quality February 2019, Approved by Texas Commission on Environmental Quality February 2020.

14. Lower Colorado River Authority, *2020 Water Management Plan*, 4 pages, March 2020.

15. M.A. Pauls, R.J. Hoffpauir, and R.A. Wurbs, *Hydrologic Period-of-Analysis Extension for the Colorado River Basin and Brazos-Colorado Coastal Basin Water Availability Model*, TCEQ Contract 582-12-10220, 455 pages, August 2013.

16. R.J. Hoffpauir, M.A. Pauls, and R.A. Wurbs, *Application of Expanded WRAP Modeling Capabilities to the Colorado WAM*, TCEQ Contract 582-12-10220, 153 pages, September 2013.

17. R.A. Wurbs and Ankit Bista, *Comparative Analysis of Naturalized Stream Flow in Colorado River Basin*, TCEQ Contract 582-15-50298, 155 pages, October 2014.

18. M.A. Pauls, *Incorporating and Evaluating Environmental Instream Flows in Priority Order Based Surface Water Allocation System*, M.S. Thesis, Texas A&M University, May 2014.

19. M.A. Pauls and R.A. Wurbs, "Environmental Flow Attainment Metrics for Water Allocation Modeling", *Journal of Water Resources Planning and Management*, ASCE, 142(8), 2016.

20. R.J. Hoffpauir, *Daily Time Step Simulation with a Priority Order Based Surface Water Allocation Model*, Ph.D. Dissertation, Texas A&M University, December 2010.

21. M.A.R. Siddiqui, *Lag and Attenuation Parameters for Routing Daily Flow Changes through Large River Systems*, M.S. Thesis, Texas A&M University, August 2017.

22. R.A. Wurbs, *Storage and Regulation of River Flows by Dams and Reservoirs*, Texas Water Journal, Vol. 12, No. 1, February 2021.

23. R.A. Wurbs, *Water Rights Analysis Package Modeling System*, Texas Water Journal, Vol. 12, No. 1, July 2021.

24. Colorado and Lavaca Rivers and Matagorda Bays Basin and Bay Expert Science Team, Environmental Flow Regime Recommendations Report, 497 pages, Submitted to the Colorado and Lavaca Basin and Bay Area Stakeholder Committee, Environmental Flows Advisory Group, and Texas Commission on Environmental Quality, March 1, 2011.

25. Colorado and Lavaca Basin and Bay Area Stakeholder Committee, *Environmental Flows Recommendation Report*, 347 pages, August 2011.