# CHAPTER 1
# INTRODUCTION

Although also providing a general overview of modeling capabilities covered in detail in the six WRAP manuals [1, 2, 3, 4, 5, 6], the primary purpose of this report is to supplement the manuals with additional practical guidance addressing various complexities of water management and associated water availability modeling. Knowledge and experience acquired from previous Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces daily WAM investigations [7, 8, 9, 10, 11, 12], further analyses thereof, and the overall WRAP/WAM experience base are synthesized. In addition to furthering understanding of water availability modeling, the report also provides insight regarding the hydrologic conditions and water management capabilities governing water availability in Texas. [Bracketed numbers refer to the list of references on pages 423-428.]

This "*Synthesis Report*" covers both monthly and daily modeling capabilities and complexities while focusing particularly on advancing implementation of newer daily modeling features. The routinely applied WRAP/WAM modeling system with continual development and application dating back to the 1990's is based on a monthly computational time step. The monthly modeling system has been routinely applied by the Texas water management community since 2000. Components of daily modeling capabilities were incorporated in August 2015, July 2018, and May 2019 versions of WRAP and further improved in January 2021 and August 2025 versions through TCEQ-sponsored research at TAMU [5, 13, 14]. Daily WRAP features are designed to supplement and extend rather than replace well-established, routinely-applied monthly modeling capabilities. The six case studies of Chapters 7-12 incorporate a strategy in which daily SB3 EFS instream flow targets are computed in a daily simulation and summed to monthly targets for input to a monthly WAM. Types of applications for daily WRAP/WAM modeling include:

- simulation of environmental flow standards (EFS) established through a process created by the 2007 Senate Bill 3 (SB3),
- simulation of reservoir flood control and surcharge storage operations, and
- support of integrated multiple-purpose water management that incorporates SB3 EFS and/or reservoir flood control or surcharge storage operations with water supply, hydroelectric power generation, and other aspects of water management.

## Generalized WRAP Modeling System and WAM Datasets

Water Rights Analysis Package (WRAP) software, manuals, other relevant publications, recorded training courses, and a link to the TCEQ Water Availability Modeling (WAM) website are available at the WRAP website (https://wrap.engr.tamu.edu/). The latest versions of the components of the generalized WRAP modeling system are documented by a set of manuals published as Texas Water Resources Institute (TWRI) technical reports [1, 2, 3, 4, 5, 6]. Development of the original WRAP at Texas A&M University (TAMU) was funded by a federal/state research program administered by TWRI. Extensive additions and improvements over the past 25 years were sponsored primarily by TCEQ, with certain modeling features and applications funded by other federal and state agencies [1, 13, 21].

The TCEQ Water Availability Modeling (WAM) System is comprised of the generalized WRAP, monthly WRAP simulation input datasets for all river basins of Texas called water availability models (WAMs), and related analysis tools and information [15]. The TCEQ WAM website (https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html) and TAMU WRAP website are interlinked. Monthly full authorization WAMs for all river basins of Texas are maintained at the TCEQ WAM website along with an array of information about water availability modeling, environmental flow standards established in accordance with the 2007 Senate Bill 3, and other related topics. A September 2023 WAM status report [15] accessible at the WAM website describes the past development and current status of the modeling system.

The WAM System was originally implemented by the Texas Natural Resource Conservation Commission (TNRCC), renamed TCEQ, and its partner agencies and contractors during 1998-2004 pursuant to water management legislation enacted by the Texas Legislature in 1997 known as Senate Bill 1 (SB1). The TNRCC was renamed the TCEQ in September 2002.

Scenarios of Water Resources Development, Allocation, Management, and Use

The initial WAM datasets were developed during 1998-2004 by consulting engineering firms working under contract with the TNRCC/TCEQ in collaboration with the Texas Water Development Board (TWDB), Texas Parks and Wildlife Department (TPWD), and stakeholder community [15, 16, 17]. About ten variations of water management scenarios were simulated in conjunction with the development of each initial WAM that reflected differing premises regarding water use, return flows, and reservoir sedimentation. The term "run" was adopted to refer to a defined variation of the WAM simulation input dataset for a particular modeling scenario. The full authorization and current conditions scenarios were called run 3 and run 8, respectively.

TCEQ full authorization monthly (run 3) WAMs available at the WAM website are used in the water use permitting process to assess water availability for proposed new and amended permits and impacts on existing water rights. Full authorization WAMs include diversion and storage amounts authorized by water rights. Return flows are generally not specified in water rights and the full authorization scenario WAMs. Reservoir storage capacities at the time of construction before losses to sedimentation are generally reflected in the full authorization WAMs. New water rights and amendments to existing water rights are added as they are approved by TCEQ.

Water rights for municipal, industrial, and other uses have sometimes included projected future needs associated with expected population and economic growth. Water right holders were not necessarily currently using the full amounts of water authorized. Current condition scenario (run 8) WAMs simulate actual recently reported water use, estimated return flows, and best available information regarding effects of sedimentation on reservoir storage capacities. The current condition WAMs have been used by TCEQ to assess short-term water availability for term water right permit applications for temporary water use over short periods of up to the next several years. TCEQ is no longer updating or maintaining current condition WAMs for river basins in which water right holders are actually using all or most of their authorized water [15].

The 1997 SB1 authorized both the TCEQ WAM system and a process administered by the TWDB for developing regional water plans and a statewide plan at five-year planning cycles, with a 50-year future planning horizon [18, 19]. Updated water plans were completed in 2002, 2007, 2012, 2017, and 2022. The current cycle is scheduled for completion in 2027. Updates of the sixteen regional plans and statewide plan are documented by reports available at the TWDB website along with rules governing the planning process and other information. The plans focus on water supply resources and future water needs and use. TCEQ approval of water use permit applications is contingent on consistency with relevant SB1 regional and statewide water plans.

TWDB staff, SB1 regional planning groups, and their consultants apply the WRAP/WAM modeling system in the regional and statewide planning studies. The WAMs reflect present and future water needs during drought conditions. The 2022 regional and statewide water plans assess water needs and supply capabilities for 2020, 2030, 2040, 2050, 2060, and 2070 under drought conditions. TWDB staff modify the TCEQ maintained WAMs as necessary to support the cyclic updating of the statewide and regional planning studies.

Applications of WRAP and the WAMs

WRAP/WAM simulation studies combine a specified scenario of river and reservoir system management and water use with hydrology represented by input datasets of sequences of naturalized stream flows and net reservoir evaporation less precipitation rates at pertinent locations for each month or day of a hydrologic period-of-analysis [1]. The WRAP monthly and daily simulation models *SIM* and *SIMD* allocate naturalized stream flows to meet specified water right requirements subject to instream channel losses and the losses or gains associated with evaporation from and precipitation onto reservoir water surfaces. A conventional application of the *SIM* or *SIMD* simulation model is based on:

- simulating capabilities for fulfilling specified river regulation and water use requirements for a specified scenario of water resources development infrastructure, water allocation and use requirements, and operating practices
- during an assumed hypothetical repetition of historical hydrology represented by sequences of naturalized stream flows and reservoir net evaporation-precipitation rates covering each monthly or daily time step of a specified hydrologic period-of-analysis.

Statistical water supply reliability and reservoir storage and stream flow frequency metrics are computed from simulation results. Historical stream flows adjusted to remove the effects of past water development/use and reservoir net evaporation-precipitation rates are adopted as being representative of the hydrologic characteristics that can be expected to continue in the future.

Applications of the modeling system range from relatively simple to very complex. Implementation of WRAP and the WAMs includes the following tasks.

- Compiling, updating, or accessing water management and hydrology input datasets,
- Simulating water resources development, allocation, regulation, management, and use scenarios based on the modeling premise of a repetition of past natural hydrology,
- Developing water supply reliability and streamflow and reservoir storage frequency metrics and otherwise organizing and analyzing simulation results.

Simulation input datasets for alternative water management and use scenarios have been developed and continue to be updated and maintained by the TCEQ and its contractors for all the river basins of Texas. Model users modify a simulation input dataset to reflect their proposed changes in water use, new projects to be constructed, and/or new or altered water management strategies. Applications of the WRAP modeling system outside of Texas require compilation of input datasets for the particular river/reservoir/water management/use systems of concern.

The WRAP/WAM modeling system based on a monthly computational time step has been routinely employed in Texas since about 2002 by:

- TCEQ staff and water use permit applicants or their consultants in administration of the statewide water rights system,
- TWDB staff and regional planning groups or their consultants in regional and statewide planning,
- river authorities and other water management entities in operational planning studies,
- university and agency researchers in investigating various water management issues,
- and other model users for various other types of applications.

TCEQ has sponsored research at TAMU over many years to expand and improve the WRAP modeling system. Research in recent years has included addition of features that employ a daily computational time step. The newer daily modeling features supplement, rather than replace, the routinely applied monthly modeling capabilities. Development of auxiliary daily modeling features was motivated primarily by the need to improve capabilities for incorporating environmental flow standards (EFS) established as mandated by the 2007 Senate Bill 3 (SB3). Addition of features for simulation of reservoir flood control operations was also facilitated by the daily time step computational capabilities.

The new and expanded capabilities associated with modeling with a daily computational time step support:

1. simulation of SB3 EFS comprised of subsistence flow, base flow, and high pulse flow components that vary seasonally and with hydrologic conditions and
2. simulation of reservoir flood control operations based on specified dam outlet release capacities and rules and nondamaging stream flow rates at downstream gage sites.

The daily computational features include *SIMD* simulation options for disaggregation of naturalized stream flows and other quantities from monthly to daily and flow routing and forecasting. Additional reservoir storage and stream flow frequency and supply reliability analysis options are incorporated in WRAP program *TABLES* for daily quantities. *HEC-DSSVue* provides comprehensive capabilities for managing and analyzing daily and monthly time series quantities.

<u>WRAP and WAM Publications</u>

The latest versions of WRAP are documented in detail by *Reference, Users, Fundamentals*, *Hydrology*, *Salinity*, and *Daily Manuals* published as TWRI technical reports [1, 2, 3, 4, 5, 6] available at both the TAMU WRAP and TWRI websites. A *WRAP Additions and Revisions Report* [13] tracks modifications from 1996 to the present. The "*Appendix A Bibliography of WRAP Related Publications*" of the *Reference Manual* lists 12 other TWRI technical reports, 16 WAM reports prepared during the original creation of the TCEQ WAMs, 31 academic thesis and dissertations, and 41 journal papers and book chapters. In addition to the WRAP manuals (TWRI

TRs), the publications cited below addressing the general topic areas indicated are accessible through the WRAP website as well as directly online from the publishers.

- A concise overview of WRAP including both monthly and daily features [14]
- Applications of WRAP and the WAMs in Texas [16, 17, 18, 19, 20, 21, 22]
- State-of-the-art reviews of generalized water management models and comparisons of other generalized models with WRAP [23, 24, 25, 26, 27, 28]

A book on managing water in river and reservoir systems in Texas [19] published in 2024 by ASCE Press (American Society of Civil Engineers) uses WRAP/WAM simulation results to explore hydrology and water management throughout the state. The Texas experience in managing river and reservoir system water management over the past 150 years, particularly over the past 30 years and continuing, is presented in the book as an experience base that can beneficially inform similar water management endeavors throughout the United States and world.

## River Basins of Texas and Associated WAMs

Climate, hydrology, economic development, water use, and water management vary dramatically across Texas from the arid and semiarid regions of West Texas to humid eastern forests, and from sparsely populated rural regions to the metropolitan areas of El Paso, San Antonio, Austin, Houston, Fort Worth, and Dallas shown in Figure 1.1. Mean annual precipitation varies from less than ten inches in far West Texas to over fifty-five inches in the Sabine River Basin in East Texas.

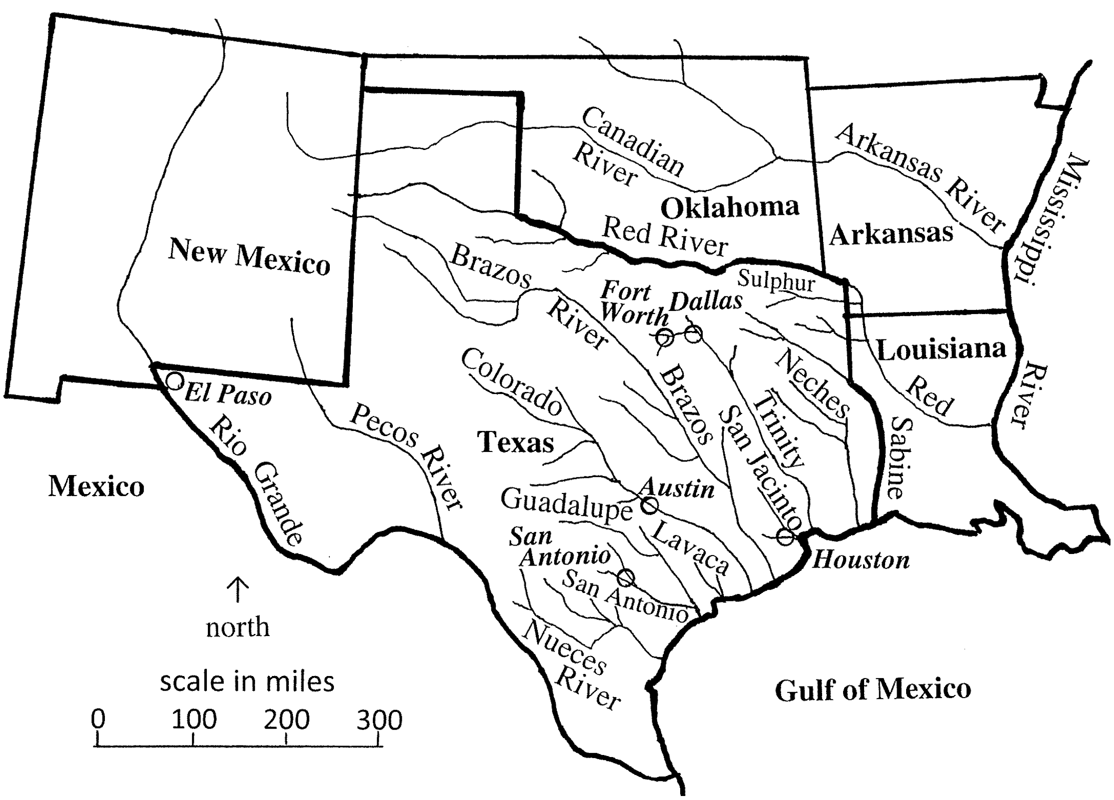


Figure 1.1 Major Rivers and Largest Cities of Texas

Fifteen Major River Basins and Eight Coastal Basins of Texas

Texas encompasses 268,600 square miles that includes fifteen major river basins and eight coastal basins located between the major rivers as delineated in Figure 1.2. The Arkansas and Red Rivers are tributaries of the Mississippi River as shown in Figure 1.1. The Canadian River is a tributary of the Arkansas River. Although the Sulphur River and Cypress Creek are tributaries of the Red River, their upper basins are treated as separate Texas river basins. With the exceptions of the Canadian and Red Rivers and their tributaries, the major river basins and coastal basins of Figure 1.2 discharge directly into the Gulf of Mexico.

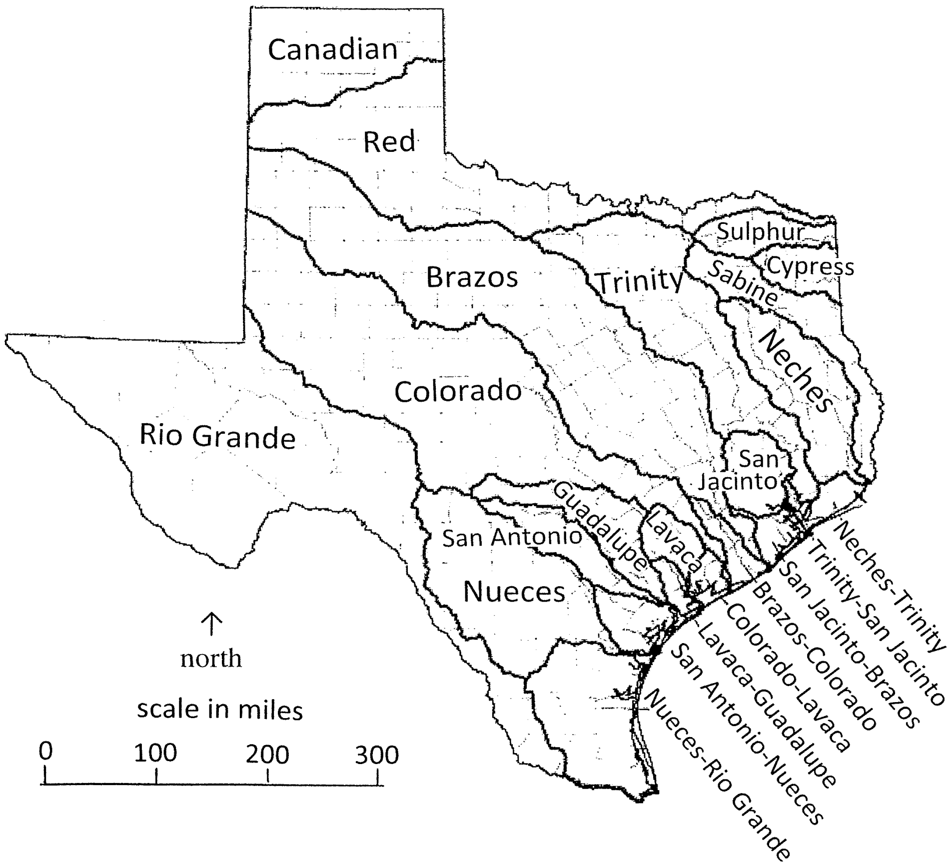


Figure 1.2 Fifteen Major River Basins and Eight Coastal Basins of Texas

The fifteen major river basins and eight coastal basins delineated by the TWDB as shown in Figure 1.2 are listed in Table 1.1 with watershed areas and reservoir storage capacities. The total area encompassed by each basin and the area in Texas tabulated in the second and third columns of Table 1.1 are from a TWDB website that also provides additional descriptive information (https://www.twdb.texas.gov/surfacewater/rivers/river_basins/index.asp). The 182,215 square mile area cited for the Rio Grande is exclusive of large additional noncontributing areas.

As noted earlier, management of river and reservoir systems throughout the fifteen major river basins and eight coastal basins of Texas is explored in a recently published book [19]. Selected results from the WRAP/WAM modeling system are employed in the book to support discussions of hydrology and water resources development, allocation, and management. Two appendices in the book summarize information describing the 195 existing major reservoirs located entirely or partially in Texas that have conservation storage capacities of at least 5,000 acre-feet or flood control pool storage capacities of at least 5,000 acre-feet [19]. The reservoirs are discussed by river basin in the book along with presentations of statewide information.

Table 1.1
Fifteen Major River Basins and Eight Coastal Basins of Texas

| Major River Basin or Coastal Basin | Basin Area (square miles) Total | Basin Area (square miles) Texas | Number of Major Reservoirs | Authorized Capacity (acre-feet) | Flood Control (acre-feet) |
|---|---|---|---|---|---|
| Major River Basins Listed in Order of Area in Texas | | | | | |
| Rio Grande | 182,215 | 49,387 | 7 | 3,023,656 | 2,235,730 |
| Brazos River | 45,573 | 42,865 | 42 | 5,050,716 | 4,102,667 |
| Colorado River | 42,318 | 39,428 | 28 | 5,270,565 | 1,526,397 |
| Red River | 93,450 | 24,297 | 24 | 4,568,916 | 3,270,726 |
| Trinity River | 17,913 | 17,913 | 31 | 7,815,297 | 1,767,592 |
| Nueces River | 16,700 | 16,700 | 3 | 1,047,017 | 0 |
| Canadian River | 47,705 | 12,865 | 2 | 1,478,892 | 589,630 |
| Neches River | 9,937 | 9,937 | 10 | 3,904,100 | 1,179,295 |
| Sabine River | 9,756 | 7,570 | 12 | 6,393,413 | 0 |
| Guadalupe River | 5,953 | 5,953 | 5 | 451,818 | 362,048 |
| San Antonio River | 4,180 | 4,180 | 4 | 367,028 | 12,600 |
| San Jacinto River | 3,936 | 3,936 | 6 | 637,190 | 409,214 |
| Sulphur River | 3,767 | 3,580 | 4 | 962,528 | 2,686,453 |
| Cypress Creek | 3,552 | 2,929 | 10 | 949,139 | 600,737 |
| Lavaca River | 2,309 | 2,309 | 1 | 265,247 | 0 |
| Coastal Basins from Southwest to Northeast | | | | | |
| Nueces-Rio Grande | 10,442 | all | 4 | 146,131 | 0 |
| San Antonio-Nueces | 2,652 | all | 0 | 3,548 | 0 |
| Lavaca-Guadalupe | 998 | all | 0 | 0 | 0 |
| Colorado-Lavaca | 939 | all | 0 | 9,666 | 0 |
| Brazos-Colorado | 1,850 | all | 0 | 30,959 | 0 |
| San Jacinto-Brazos | 1,440 | all | 1 | 51,042 | 0 |
| Trinity-San Jacinto | 247 | all | 1 | 18,633 | 0 |
| Neches-Trinity | 769 | all | 0 | 64,481 | 0 |
| Totals for the Fifteen Major River Basins and Eight Coastal Basins | | | | | |
| Totals | 508,601 | 263,186 | 195 | 42,509,984 | 18,743,089 |

The fourth column of Table 1.1 is the number of existing reservoirs with conservation or flood control storage capacities of 5,000 acre-feet or greater. The 195 major reservoirs are described in the book discussed above [19]. The fifth column is the total reservoir storage capacity authorized by TCEQ-administered water rights. Authorized reservoir capacity includes reservoirs licensed but not yet constructed and those smaller than 5,000 acre-feet as well as major existing reservoirs. Authorized storage does not include flood control. Flood control storage capacity in thirty-six reservoirs with designated flood control pools are reflected in the basin totals in the last column of Table 1.1. Reservoir storage capacity varies over time with sedimentation. Estimates of storage volume versus water surface elevation and storage capacities for many major reservoirs have been updated over time with site surveys that reflect accumulated sediment deposits. The storage capacity estimates in the last two columns of Table 1.1 do not necessarily reflect the latest update for sediment deposition or actual present storage volumes in each individual reservoir [19].

Twenty Water Availability Models (WAMs)

The fifteen major river basins and eight coastal basins of Figure 1.2 and Table 1.1 are modeled as twenty WAMs listed in Table 5.1 and discussed in Chapter 5. The Guadalupe-San Antonio (GSA) WAM includes both the San Antonio and Guadalupe River Basins. The San Antonio River is a tributary of the Guadalupe River. Their confluence is near the coast. The San Jacinto-Brazos Coastal Basin is included in the Brazos River Basin WAM. The Brazos-Colorado Coastal Basin is included in the Colorado River Basin WAM. The other major river basins and coastal basins are each modeled as individual WAM datasets.

The twenty WAMs simulate river system hydrology and operation of over 3,400 reservoir storage and other constructed facilities in accordance with 6,235 water use permits or certificates of adjudication, federal water supply storage contracts, a treaty and other agreements between the United States and Mexico, five interstate river compacts, and other institutional arrangements. Full authorization scenario versions of the twenty WAM datasets are available at the TCEQ WAM website. The full authorized scenario assumes all water right permit holders use the full amount of water to which they are legally entitled, subject to water availability.

TCEQ updates the full authorization WAMs to reflect new or amended water right permits and has extended (updated) the hydrology of several WAMs. Likewise, TWDB updates future water use projections and water supply capabilities in each planning cycle. TWDB employs TCEQ updates of hydrologic periods-of-analysis but also develops additional intermediate updates to support planning studies. WAM hydrology updates are discussed in Chapters 5 through 12.

## Daily and Monthly WAMs with SB3 EFS

This report focuses on daily and modified monthly WAMs for the Brazos River Basin and San Jacinto-Brazos Coastal Basin [7], Trinity River Basin [8], Neches River Basin [9], combined Colorado River Basin and Brazos-Colorado Coastal Basin [10], Lavaca River Basin [11], and Nueces River Basin [12] for which daily WAMs have been previously developed. These basins have contributing watershed drainage areas totaling 132,442 square miles which is 50 percent of the Table 1.1 statewide total contributing drainage area of 263,186 square miles. These basins with developmental daily WAMs reflect a broad range of climatic and hydrologic conditions, geography, population density, economics, and water management practices representative of the great statewide diversity. These six daily and modified monthly WAMs and associated river basins are further introduced in Chapter 6 and explored in Chapters 7 through 12.

TCEQ has contracted with the Texas Engineering Experiment Station (TEES) of the TAMU System over many years for research and development in expanding and improving the

WRAP modeling system. WRAP-related research and development performed at TAMU under the sponsorship of TCEQ in recent years has addressed the following along with other endeavors.

- Improvements in capabilities of the WRAP modeling system for modeling SB3 EFS.
- Addition of capabilities for simulation of reservoir flood control operations that were made possible by the addition of daily modeling capabilities developed primarily to support simulation of Senate Bill 3 (SB3) environmental flow standards (EFS).
- Features for disaggregating naturalized stream flows and other quantities from monthly to daily and options for flow forecasting and routing daily stream flow changes.
- Application of expanded WRAP capabilities to convert monthly Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces WAMs to daily.
- Incorporation of SB3 EFS and reservoir flood control operations in the daily WAMs.
- Simulation studies with the daily WAMs that include aggregation of simulated daily instream flow targets to monthly for the SB3 EFS for incorporation in monthly WAMs.

Development of daily and modified monthly WAMs for the Brazos and adjoining coastal, Trinity, Neches, Colorado and adjoining coastal, Lavaca, and Nueces Basins and associated simulation studies are documented in detail by technical reports [7, 8, 9, 10, 11, 12]. The following strategy was employed in the research studies documented by these six daily WAM reports to develop modified monthly WAMs incorporating SB3 environmental flow standards (EFS).

1. Daily WAMs were developed by converting the latest TCEQ monthly WAMs to daily. SB3 EFS modeled using older methods were removed from the monthly WAMs.
2. The SB3 EFS were added to the daily WAMs using more recently developed methods. Daily instream flow targets were computed for the SB3 EFS in daily simulations within the WRAP daily simulation model *SIMD*. The daily EFS instream flow targets were summed to monthly by *SIMD* within the daily simulation.
3. The monthly WAMs were then modified by inserting monthly SBS EFS instream flow targets into the monthly *SIM* simulation model input dataset that were computed within the daily *SIMD* simulation by summing simulated daily targets to monthly.

The daily and modified monthly versions of the six WAMs were further reviewed and refined along with preparation of this report. Intermediate approximate hydrology updates through 2023 are also developed. This synthesis report provides an overview compilation of experience and knowledge gained through the six developmental case studies and other investigations.

## **Scope and Organization of this Synthesis Report**

The monthly and daily WRAP simulation models *SIM* and *SIMD* combine:

1. A specified scenario of river/reservoir system development and water allocation, management, and use (for brevity called water management or WAM water rights)
2. Hydrologic period-of-analysis sequences of monthly naturalized stream flows and net reservoir evaporation less precipitation rates (for brevity called WAM hydrology)

This technical report provides an overview of water availability modeling in Texas focusing on key practical complexities. The following general broad subjects are covered.

- River system hydrology in Texas.
- Water resources development and management in river/reservoir systems in Texas.
- WRAP/WAM modeling of river system hydrology.
- WRAP/WAM modeling of the management of water in river and reservoir systems.

This first chapter provides a general introductory overview of the generalized WRAP modeling system and the WAM datasets. The remainder of this report focuses on river system hydrology and modeling thereof, transformations of monthly WAMs to daily, application of daily WAMs, and combining of monthly and daily WAMs. Lessons learned and knowledge acquired from earlier research in developing and preforming simulation studies with Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces daily and modified monthly WAMs are synthesized in this report along with reliance on the broader experience base spanning over two decades in creation and implementation of the WRAP/WAM modeling system.

Chapter 2 provides an overview of WRAP followed by a discussion of daily modeling capabilities including converting monthly WAMs to daily, routing flow changes, flow forecasting, daily simulation of flood control reservoir operations, and simulation of SB3 EFS in daily and monthly WAMs. Other practical complexities of WRAP/WAM modeling are also highlighted.

Chapter 3 provides an overview of surface water development and management in Texas focusing on reservoir system development and operations, water allocation, environmental flow standards created pursuant to the 2007 SB3, statewide water planning, and comprehensive water management. Observed storage plots presented in Appendix A are discussed in Chapter 3.

Chapter 4 explores river system hydrology statewide, focusing on variability and stationarity of precipitation, reservoir evaporation, stream flow, and reservoir storage. Chapter 5 covers WRAP/WAM capabilities for modeling river system hydrology including methods for compiling and updating hydrologic data. Hydrologic variability includes droughts and floods along with less extreme fluctuations. Stationarity deals with permanent long-term changes or trends in hydrologic characteristics. Observed reservoir storage and stream flow plots discussed in Chapter 4 are presented in Appendices A and B.

The first half of Chapter 6 consists of a series of analyses with a simple hypothetical example WAM for the Upper Neches River designed to illustrate the basics of WRAP/WAM modeling. The second half of Chapter 6 introduces the six case studies presented in Chapters 7-12. Developmental daily and modified WAMs documented by six previous reports [7, 8, 9, 10, 11, 12] and further analyses thereof are described in Chapters 7-12. Extension of the period-of-analysis through 2023 is included in each of the six case studies. Plots and statistical metrics of monthly and daily reservoir storage and stream flows are presented in the chapters. Plots of SB3 EFS instream targets and shortages discussed in Chapters 7 through 12 are presented as Appendix C.

Lessons from the six case studies and additional analyses performed in conjunction with preparation of this report are summarized and conclusions and recommended guidelines presented as Chapter 13. Strategies and methods for dealing with water availability modeling complexities explored throughout this report along with lessons learned in the six simulation studies are synthesized and summarized in the last chapter. Guidance for WRAP/WAM modeling is outlined. This report, including Chapter 13, reflects experience gained during the past 25 years of expanding and applying the monthly WRAP/WAM modeling system as well as research in daily modeling.

## Datasets Discussed in this Report

This report is accompanied by a compilation of datasets that include the following.

- DSS file of daily observed reservoir storage volumes discussed in Chapters 3 and 4.
- DSS file of monthly precipitation and reservoir evaporation depths discussed in Chapter 4.
- DSS file of daily and monthly observed stream flow rates discussed in Chapter 4.
- WRAP program *HYD* input HIN files discussed in Chapter 6.
- Daily and monthly WAM datasets and simulation results discussed in Chapters 7-12.

Appendices A, B, and C of this report are comprised of time series plots of observed reservoir storage, observed stream flow, and simulated SB3 EFS targets that are discussed in Chapter 3-4, Chapter 4, and Chapters 7-12, respectively. These and other relevant time series datasets are stored in DSS files that can be conveniently accessed with *HEC-DSSVue* for viewing, manipulation, and analysis. Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces WAMs are a central focus of this report. The daily and monthly WAM simulation input datasets are executed with the WRAP programs *SIM* and *SIMD*. Simulation results are recorded in DSS files.

### Files Containing Time Series Data Discussed in Chapters 3 and 4

The time series of observed reservoir storage volumes discussed in Chapters 3 and 4 and plotted in Appendix A are from a Texas Water Development Board (TWDB) reservoir storage online database. These datasets were downloaded from the TWDB database into a csv (comma-separated values) file read with *HEC-DSSVue* and stored as a DSS file with filename extension ObservedStorage.DSS used for data plotting and analyses.

Monthly precipitation and reservoir evaporation depths for ninety-two quadrangles encompassing Texas from a database maintained by TWDB staff are employed in Chapter 4 and Chapters 7-10. The TWDB monthly precipitation and reservoir evaporation data were downloaded as a CSV file and stored in a DSS file with filename PrecipEvap.DSS read by *HEC-DSSVue* and the WRAP program *HYD*. These same datasets also are stored in text files with filenames Precipitation and Evaporation.EEE that are also read by *HYD*.

Daily observed flows were downloaded from the National Water Information System (NWIS) website maintained by the U.S. Geological Survey (USGS) directly into a DSS file using an import feature of *HEC-DSSVue*. All analyses of the USGS daily flow dataset presented in Chapter 4 and Appendix B were performed with *HEC-DSSVue*.

### Program *HYD* Input HIN Files Discussed in Chapter 6

WRAP program *HYD* input files controlling intermediate hydrology extensions for four of the six WAMs are described in Chapter 6. These *HYD* input files have the following filenames.

| | |
|---|---|
| BrazosFlow.HIN | BrazosEvapPrecip.HIN |
| TrinityFlow.HIN | TrinityEvapPrecip.HIN |
| NechesFlow.HIN | NechesEvapPrecip.HIN |
| ColoradoFlow.HIN | ColoradoEvapPrecip.HIN |

Daily and Modified Monthly WAMs Presented in Chapters 7 through 12

The following filename roots for the official TCEQ full authorization (run 3) WAMs date back to their original creation: bwam3 (Brazos), trin3 (Trinity), Neches3 (Neches), C3 (Colorado), lav3 (Lavaca), and N_Run3 (Nueces). The following filename roots are adopted in this report for the WAM datasets with hydrology converted to DSS and extended through 2023 but no other modifications: Brazos3, Trinity3, Neches3, Colorado3, Lavaca3, and Nueces3. The original FLO, EVA, FAD, and HIS files are combined into a single DSS input file and updated through 2023.

The full authorization (run 3) daily and monthly WAMs with modified SB3 EFS described in Chapters 7 through 12 are comprised of sets of files with the filenames listed in Table 1.2. File types are identified by filename extensions. The DAT files are different for the daily versus monthly versions of the WAMs. Daily input DIF files are employed only with *SIMD*. *SIM* and *SIMD* share the same flow distribution DIS and hydrology time series DSS files.

Table 1.2
Simulation Input Data Files for the WAMs of Chapters 7 through 12

| Daily WAM | Shared Files | Monthly WAM | Daily WAM | Shared Files | Monthly WAM |
|---|---|---|---|---|---|
| BrazosD.DAT | Brazos.DIS | BrazosM.DAT | TrinityD.DAT | Trinity.DIS | TrinityM.DAT |
| Brazos.DIF | BrazosHYD.DSS | | Trinity.DIF | TrinityHYD.DSS | |
| NechesD.DAT | Neches.DIS | NechesM.DAT | ColoradoD.DAT | Colorado.DIS | ColoradoM.DAT |
| Neches.DIF | NechesHYD.DSS | | Colorado.DIF | ColoradoHYD.DSS | |
| LavacaD.DAT | Lavaca.DIS | LavacaM.DAT | NuecesD.DAT | Nueces.DIS | NuecesM.DAT |
| Lavaca.DIF | LavacaHYD.DSS | | Nueces.DIF | NuecesHYD.DSS | |

WRAP programs *SIM*, *SIMD*, and *WinWRAP* by default allow all input files to share the same filename root, with the exception of the required HYD inserted in the filename root for the DSS input file. DIS and DIF files are treated as hydrology input files which, like FLO and EVA files, can optionally be assigned a different filename root than the DAT file. For example, when executing the daily Brazos WAM within *WinWRAP*, the default root is BrazosD, but Brazos.DIS and Brazos.DIF can be opened by specifying Brazos as the hydrology filename root.

Although the WRAP monthly *SIM* and daily *SIMD* simulation models also generate several different types of output files in text format, this report focuses primarily on time series simulation results recorded in data storage system (DSS) files identified by their filename extension DSS. Selected simulation results are stored in DSS files assigned descriptive filenames to serve as auxiliary information supporting and supplementing the presentations found in the report.

# CHAPTER 2
# WATER RIGHTS ANALYSIS PACKAGE

The Water Rights Analysis Package (WRAP) is a framework and set of tools for computer modeling and analysis of the development, allocation, management, and use of the water resources of river/reservoir systems located any place in the world. Applications of WRAP in Texas employ simulation input datasets called water availability models (WAMs) created and maintained by the Texas Commission on Environmental Quality (TCEQ). For applications outside of Texas, WRAP users develop simulation input datasets for their local river and reservoir systems of concern.

WRAP executable software, manuals, other relevant publications, and training courses are accessible at a website (https://wrap.engr.tamu.edu/) maintained at Texas A&M University. The WRAP website and the water availability modeling (WAM) website maintained by the TCEQ are interlinked. The TCEQ WAM website provides an array of information including WRAP simulation model *SIM* input datasets (called WAMs) covering all the river basins of Texas.

## WRAP Software

The WRAP modeling system consists of the following computer programs and manuals that document these computer programs. The computer programs have evolved through multiple versions over many years [1, 13]. The dates of the latest versions of the software are shown in parenthesis. For programs updated in 2025, the date of the latest preceding version is also shown.

*WinWRAP* (July 2022, August 2025) provides an interface for executing the WRAP programs within the Microsoft Windows environment along with other Microsoft software and *HEC-DSSVue*.

*SIM* (July 2022, August 2025) simulates a specified water development/allocation/management/use scenario for input hydrologic period-of-analysis sequences of monthly naturalized stream flows and reservoir net evaporation less precipitation rates representing river system hydrology.

*SIMD* (July 2022, August 2025) is an expanded version of *SIM* for daily simulations that additionally include monthly-to-daily disaggregation, routing flow changes, flow forecasting, reservoir flood control operations, and environmental requirements for preserving high pulse flows.

*TABLES* (July 2022, August 2025) develops water supply or hydropower reliability tables, flow and storage frequency metrics, volume budgets, and various summaries or listings for organizing, summarizing, and displaying *SIM*, *SIMD*, and *SALT* input data and simulation results.

*HYD* (May 2019, August 2025) is a set of routines for developing monthly naturalized stream flow and reservoir net evaporation-precipitation rate datasets for input to *SIM*/*SIMD* simulations, extending hydrologic periods-of-analysis, and/or analyzing hydrologic time series data.

*DAY* (July 2018) and *DAYH* (August 2013) assist in calibrating parameters for routing daily stream flow changes and compiling other daily hydrology input data for *SIMD*.

*SALT* (July 2010) reads a conventional *SIM* simulation output file and a salinity input file and tracks salt constituent loads and concentrations through the river and reservoir system being simulated.

The data storage system (DSS) and DSS interface program *HEC-DSSVue* developed and maintained by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) are also integral components of WRAP. The WRAP programs listed above are executable computer programs coded in the Fortran programming language [29, 30]. The Fortran programs include HEC-DSS library routines developed by the USACE HEC using a combination of programming languages for use with programs coded in various programming languages. HEC-DSS is designed primarily for managing time series data. The WRAP programs read and create DSS files. WRAP users work directly with the WRAP executable programs and *HEC-DSSVue*.

## WRAP Manuals and Training

The WRAP programs are documented in detail by *Reference* [1], *Users* [2], *Fundamentals* [3], *Hydrology* [4], *Daily* [5], and *Salinity* [6] *Manuals* published as Texas Water Resources Institute (TWRI) technical reports (TRs). The TWRI is a component of the Texas A&M University System ( https://twri.tamu.edu/ ). The manuals are available for download as PDFs at both the TWRI and WRAP websites. Input data files for the examples in the *Reference*, *Fundamentals*, *Hydrology*, *Daily*, and *Salinity Manuals* are available at the WRAP website.

The *Reference Manual* [1] outlines the overall organizational framework of the modeling system and explains the computational and data management algorithms implemented within the monthly simulation model *SIM* and pre- and post-simulation utility program *TABLES*. The daily simulation model *SIMD* includes all capabilities of the monthly *SIM* plus additional daily modeling features. The *Daily Manual* [5] explains the daily-only features of *SIMD* and *TABLES* and also documents the programs *DAY* and *DAYH* which provide optional methods for compiling certain daily-only *SIMD* input, primarily calibration of routing parameters.

The *Users Manual* [2] explains the detailed logistics for creating and modifying *SIM*, *SIMD*, and *TABLES* input files and the input records contained in the input files. *SIM* and *SIMD* share sixty-one types of input records. *SIMD* has an additional sixteen types of input records used only in daily simulations. Most types of input records are optional, used only where relevant. Some are required. The *Users Manual* contains detailed instructions regarding the input data entered on each of the input records in each of the input files read by programs *SIM*, *SIMD*, and *TABLES*.

All information and instructions in the *Fundamentals Manual* [3] are also found in the comprehensive *Reference* and *Users Manuals*. Like many generalized modeling systems, WRAP is a complex package of tools built upon a relatively simple set of core concepts and procedures. The *Fundamentals Manual* focuses on basics that are essential for most applications and sufficient for many applications. New WRAP users should typically study the *Fundamentals Manual* and its example dataset in their early efforts in becoming proficient with the modeling system.

The *Fundamentals Manual* is organized around an illustrative example. The *SIM* and *TABLES* input files for the *Fundamentals Manual* example are available at the WRAP website along with input files for the examples in the other manuals. Some of the examples in the *Reference* and *Daily Manuals* build upon and extend the example in the *Fundamentals Manual*.

The *Hydrology Manual* [4] is a combined reference and user's manual for the set of computation and data management routines in *HYD*. Program *HYD* provides various options supporting compilation of monthly naturalized flows (*IN* records) and evaporation-precipitation depths (*EV* records) for *SIM* and *SIMD* input datasets. *HYD* also includes routines for analyzing precipitation, evaporation, stream flow, and other hydrologic time series datasets.

The *Salinity Manual* [6] documents the WRAP program *SALT* which combines a salinity input file with *SIM* simulation results to track salinity loads and concentrations through a river and reservoir system. The *Salinity Manual* serves as both a reference and user's manual for *SALT*.

The five TCEQ-sponsored online courses accessible at the WRAP website are comprised of a 301-page document (PDF) dated June 2021 entitled *Water Rights Analysis Package (WRAP) Modeling System Online Training Courses* and audio/video recordings (MP4 files) of 21 lectures totaling 32 hours of instruction. The PDF contains various information including copies of 592 PowerPoint slides for the twenty-one modules comprising the following five courses. The textbook for each course is shown in parenthesis in the following list of five courses.

1. Basics of Water Availability Modeling with WRAP (*Fundamentals Manual*)
2. WRAP Program *HYD* Capabilities for Compiling, Analyzing, and Updating *SIM* Hydrology Input Datasets (*Hydrology Manual*)
3. Simulating Water Resources Development, Allocation, Management, and Use as Water Rights (*Reference and Users Manuals*)
4. Short-Term Conditional Reliability Modeling (*Reference Manual Chapter 8 Short-Term Conditional Reliability Modeling* and *Chapter 5 of Users Manual*)
5. WRAP Daily Modeling System (*Daily Manual* and Chapter 4 of *Users Manual*)

## Modeling and Analysis Framework

The evolution of the generalized WRAP modeling system over many years has been driven by the needs of the Texas water management community. Water management practices and issues in Texas are diverse and often complex. The overall purposes and organization of the modeling system are outlined in this section. The previously cited manuals cover the details of understanding and applying each of the WRAP programs individually and in combination.

### Small to Large and Simple to Complex

WRAP applications vary greatly both in simulation input dataset size and other modeling complexities. The *SIM* simulation model may be employed to estimate the firm yield and/or the yield versus reliability relationship for a single water supply reservoir, which could perhaps represent a relatively simple endeavor. Conversely, the modeling system may be used to explore interactions between numerous water users, types of water use, and complex operations of extensive constructed facilities including multiple-purpose, multiple-reservoir systems in a large region encompassing multiple river basins and inter-basin water transfers.

Referring to the list of twenty TCEQ WAMs in Table 5.1 of Chapter 5, the number of reservoirs range from zero in the Colorado-Lavaca Coastal WAM to 699 reservoirs in the Trinity WAM. The number of control point locations range from 53 control points in the San Antonio-Nueces Coastal Basin WAM to 4,468 control points in the Brazos WAM.

Most water rights are relatively simply to model. Multiple-reservoir water supply system operations with firm and interruptible supply commitments such as those of the Lower Colorado River Authority (LCRA) and Brazos River Authority (BRA) are much more complex to model.

Conservation pools of several USACE multipurpose reservoirs are shared by two or three nonfederal water supply sponsors. The United States share of the storage capacity of International Amistad and Falcon Reservoirs is allocated among well over a thousand Texas water right holders. Allocation of stream flow and reservoir storage between the United States and Mexico by treaty and between Texas and neighboring states through interstate river compacts add to water management and associated modeling complexities. Multiple-purpose river/reservoir/conveyance operations combining water supply, hydroelectric power generation, environmental instream flow requirements, and flood control further add to modeling and analysis complexities.

Multiple options for accomplishing the same computation or data management task further complicate the modeling system while providing greater flexibility. Multiple options for dealing with negative incremental flows is one of many examples of multiple options for performing simulation computations. As discussed in the next section, all *SIM* and *SIMD* time series input data can be stored in a single binary DSS file or alternatively stored in multiple text files.

WRAP includes a flexible array of optional modeling capabilities necessitated by diverse water management practices found throughout Texas. Many WRAP applications require only the basics outlined in the *Fundamentals Manual* [3]. However, an array of optional modeling capabilities may be selectively activated to address a variety of water management complexities.

WRAP Programs, HEC Data Storage System (DSS), and Program *HEC-DSSVue*

The generalized WRAP modeling system includes the following.

- user interface (*WinWRAP*) employed in Microsoft Windows,
- simulation model (*SIM*) with a monthly computational time step,
- daily computational time step version of the simulation model (*SIMD*) with additional capabilities for modeling reservoir flood control operations, high pulse components of instream flow standards, and other aspects of hydrology and water management,
- salinity tracking simulation model (*SALT*) combined with *SIM*,
- table-building program called *TABLES* for organizing simulation results and performing supply reliability, flow and storage frequency, and other types of analyses,
- and program for compiling and analyzing hydrology time series datasets (*HYD*).

The computer program *HEC-DSSVue* is also an integral component of WRAP. WRAP programs *SIM*, *SIMD*, *HYD*, and *TABLES* include file management options for creating and reading binary DSS files. The WRAP programs also include options for creating and reading ordinary text files. Thus, WRAP programs can be employed either with or without DSS files. The program *HEC-DSSVue* is designed for managing, organizing, manipulating, and tabularly or graphically displaying data in DSS files but can also read and create Microsoft Excel and other types of files.

The USACE Hydrologic Engineering Center (HEC) has developed and continues to maintain, improve, and expand probably the most extensively applied inventory of many generalized water resources engineering software packages in the United States and world. For example, the *HEC-HMS Hydrologic Modeling System* and *HEC-RAS River Analysis System* are routinely applied in floodplain management studies in most of the over 20,000 communities participating in the National Flood Insurance Program as well as in the design of stormwater facilities, bridges and culverts, dams and appurtenant structures, and other hydraulic structures throughout the United States and abroad. The many generalized simulation models, supporting documentation, and other software products developed by the Hydrologic Engineering Center are available for download free-of-charge at the HEC website (https://www.hec.usace.army.mil/).

The Hydrologic Engineering Center (HEC) developed a system for managing time series data called HEC-DSS (Data Storage System) that is incorporated in almost all HEC simulation models and several non-HEC modeling systems including WRAP. Both the DSS library routines coded into simulation computer programs and the *HEC-DSSVue* user-interface and data management and analysis program are available from the HEC. *HEC-DSSVue* can be downloaded from the HEC website (https://www.hec.usace.army.mil/software/hec-dssvue/) and is documented in detail in a July 2009 Version 2.0 User's Manual [31] downloaded as a PDF and a December 2024 Version 3.4 User's Manual viewed online.

(https://www.hec.usace.army.mil/software/hec-dssvue/documentation.aspx)

DSS files store data in a binary format written and read only by software with DSS capabilities. HEC-DSS dates back to 1979. During 2021, the Hydrologic Engineering Center released new versions of both HEC-DSS {Version 7 (DSS7) replacing the 1991 Version 6 (DSS6)} and *HEC-DSSVue* {Version 3 replacing Version 2}. DSS6 and *HEC-DSSVue* Version 2 efficiently manage extremely large time series datasets. DSS7 and *HEC-DSSVue* Version 3 more efficiently manage even much larger time series datasets and provide certain additional more advanced data management features [30]. HEC has continued to refine and improve DSS7 during 2021-2025.

Only software with DSS capabilities read and write binary DSS files. Simulation models or other software with version DSS7 library routines can read DSS files created with either versions DSS6 or DSS7. Software incorporating DSS6 library routines can read files created with DSS6 but cannot read files created with software with the later version DSS7 library routines.

*HEC-DSSVue* Version 3 can read DSS files created with software employing either DSS versions DSS6 or DSS7. *HEC-DSSVue* Version 3 can create either DSS6 or DSS7 files. *HEC-DSSVue* Version 2 is limited to working with only DSS6 files.

The WRAP programs were updated during 2021-2022 from DSS6 to DSS7 [30]. WRAP applications of DSS files and *HEC-DSSVue* are explained in "*Chapter 6 HEC-DSS Data Storage System and HEC-DSSVue*" of the WRAP *Users Manual* [2]. The WRAP programs include options for reading time series input datasets from DSS files and outputting simulation results time series variables to DSS files. The WRAP programs also include options for reading any or all input data from text files and storing all output in text files.

Most past applications of the WRAP/WAM modeling system have been limited to monthly simulations without use of DSS. However, DSS files and *HEC-DSSVue* significantly enhance monthly modeling applications and are practically essential for managing daily *SIMD* simulation studies with large input and output datasets. DSS files and *HEC-DSSVue* are employed in development and application of the daily WAMs in Chapters 7 through 12. All *SIM* and *SIMD* time series input datasets for the six daily and modified monthly WAMs are stored in DSS files. Simulation results are written to DSS files. Data manipulations are performed within *HEC-DSSVue*. All of the time series plots presented throughout this report were prepared with *HEC-DSSVue*.

Computer Programs, Data Files, and Input Records

The WRAP computer programs and the manuals that explain their conceptual basis, computational algorithms, and application are listed and described earlier in this chapter. Each of the computer programs is an individual executable file that can be executed within the Microsoft Windows operating system environment in the same manner as other executable software. Each individual program can be executed and connected to input and output files individually. However, the *WinWRAP* user interface makes coordination of program execution and connection to data files more convenient and quicker. The *Fundamentals Manual* explains the logistics of executing the computer programs and connecting programs with input and output data files through *WinWRAP*.

Model-users cannot modify the executable computer programs. Model creation and revision consists of creating and/or modifying input data files. The programs create output files upon execution. Input and output data files have fixed filename extensions that identify the type of data contained in the file. For example, program *SIM* input files have filename extensions DAT, DIS, FLO, EVA, and DSS. *SIM* output files have filename extensions OUT, MSS, YRO, and DSS. The files are referenced by their filename extensions. Input data files are comprised of records. The first characters of the input records or lines of data label the record type in text files. Part C of the pathname of DSS input records contains the record type identifier. *SIM* and *SIMD* share sixty-one different types of input records. *SIMD* has an additional sixteen types of input records used only in *SIMD*. The format and content of each type of input record and the organization of input and output data files are explained in the *Users Manual* [2].

The water availability models (WAMs) maintained by TCEQ are sets of input files for the simulation model *SIM*. All twenty of the WAMs listed in Table 5.1 of Chapter 5 include DAT, DIS, FLO, and EVA files. Several also include FAD and HIS files. FLO and EVA files contain naturalized flow *IN* and evaporation-precipitation *EV* records. FAD and HIS files contain flow adjustment *FA* and hydrologic index *HI* records. Flow distribution DIS files contain flow distribution *FD* and watershed parameter *WP* records. The many other types of input records describing water resources development/management/allocation/use (water rights) are stored in a *SIM* input data file with filename extension DAT. The time series input records (*IN*, *EV*, *FA*, and *HI* records) in the FLO, EVA, FAD, and HIS simulation input files are combined into a single DSS file for the daily and modified monthly WAMs described in Chapters 7 through 12.

General Modeling and Analysis Framework

Model application includes the following tasks.

- Compiling, updating, or modifying water management and hydrology input datasets for the simulation model components *SIM* or *SIMD* of the WRAP modeling system.
- Executing *SIM* or *SIMD* with WAM input datasets to simulate specified water development, allocation, regulation, management, and use scenarios based on the premise of a hypothetical repetition of historical hydrology adjusted to represent stationary natural conditions.
- Employing programs *TABLES* and/or *HEC-DSSVue* to develop water supply reliability and streamflow and reservoir storage frequency metrics and otherwise organizing, analyzing, summarizing, and displaying *SIM* or *SIMD* simulation results.

A specified water management scenario is combined with historical natural hydrology in a WRAP monthly *SIM* or daily *SIMD* simulation. Historical natural hydrology is adopted to capture the hydrologic characteristics of a river system. The water management and use scenario and modifications thereto may reflect the premise that all water right holders use their full authorized amounts, actual current or recent water use, projected future conditions, or some other scenario. The specified water management scenario is simulated during a hypothetical repetition of hydrologic period-of-analysis sequences of naturalized stream flows and reservoir net evaporation less precipitation rates. Simulation results are organized, and frequency and reliability metrics are computed with *TABLES* and/or *HEC-DSSVue* from the simulation results.

Simulation results consist of values for 43 time series variables listed with the *OF* record instructions in the *Users Manual* [2] or user-selected subsets thereof. The forty-three simulation results variables are defined in Chapter 5 of the *Reference Manual* [1]. Sixteen, fifteen, and twelve of the variables are associated with control points, water rights, and reservoirs, respectively. *SIM* and *SIMD* both compute values for the same time series variables. *SIM* generates values for each variable for each month of the hydrologic period-of-analysis. *SIMD* generates values for each variable for each day of the simulation and also aggregates daily quantities to monthly values which can also be included in the simulation results output files. The *SIM/SIM* main simulation results OUT and DSS files include only time series quantities. Other quantities can be recorded in other optional files. A message (MSS) file provides information tracking the simulation.

Simulation results datasets may be very large. For example, Table 5.1 of Chapter 5 indicates that the Brazos WAM has 4,468 control points, 3,213 water rights (2,470 *WR* and 743 *IF* records), 695 reservoirs, and a hydrologic period-of-analysis of 1940-2018. The 79 year 1940-2018 simulation extends through 948 months or 28,855 days. With both daily and aggregated monthly values for all forty-three simulation results variables included in a *SIMD* output file, the output would consist of 121,365,804 monthly quantities and 3,694,103,665 daily quantities.

| | | | |
|---|---|---|---|
| number of daily control point quantities | = | (4,468)(16)(28,855) = | 2,062,786,240 |
| number of daily water right quantities | = | (3,213)(15)(28,855) = | 1,390,666,725 |
| number of daily reservoir quantities | = | (695)(12)(28,855) = | 240,650,700 |
| total number of daily quantities in simulation results | | | 3,694,103,665 |

Massive output datasets are inconvenient to manage. Normally, only relevant time series are included in the recorded simulation results. Input parameters on *JD*, *CO*, *WO*, and *RO* records in the DAT file control the selection of control points, water rights, and reservoirs for which variables are included in OUT and DSS simulation results output files. The *OF* record controls the selection of simulation results variables to include in the DSS output file as well as other options associated with DSS input and output files.

*HEC-DSSVue* and the WRAP program *TABLES* provide flexible options for organizing, analyzing, summarizing, and displaying *SIM* and *SIMD* simulation results. *HEC-DSSVue* and *TABLES* can be used in combination. *TABLES* includes water supply reliability analyses and other optional capabilities not included in *HEC-DSSVue*. Similar statistical frequency analysis computations are performed by both *TABLES* and *HEC-DSSVue*, though the analysis results are displayed in different formats. *HEC-DSSVue* provides comprehensive, flexible, and efficient capabilities for managing and analyzing time series datasets, including extremely large datasets. *HEC-DSSVue* also has comprehensive, convenient capabilities for plotting time series.

Various water supply reliability and stream flow and reservoir storage frequency metrics representing likelihood, probability, or percent-of-time are adopted in WRAP/WAM modeling. Volume reliability is computed as the percentage of the volume of water demand that is supplied during a simulation. Period reliability is the percent-of-time that a specified percent of a target is supplied in a simulation. For example, TCEQ applies the following criteria in evaluating water right permit applications. For approval of a proposed permitted increase in agricultural water use, at least 75% of the proposed new diversion target should be supplied at least 75% of the time based on the premises reflected in the model. For proposed increases in authorized municipal water use, 100% of the water demand should be supplied 100% of the time during the simulation. The Texas water rights permit system and the WRAP simulation model protect senior water right holders from having their water supply reliabilities adversely affected by junior water rights.

*Water Volume Accounting Framework of a SIM or SIMD Simulation*

The monthly *SIM* or daily *SIMD* simulation model allocates water to meet requirements specified in the water rights input dataset for each sequential time period (month or day) of naturalized stream flows and net evaporation-precipitation rates. Water supply diversion, instream flow, and hydroelectric power generation requirements are met and reservoir storage is filled to the extent allowed by the water remaining in storage from the previous time period, diversion return flows from the previous time period, and stream inflows during the current time period. Water supply diversion, instream flow, and/or hydroelectric energy shortages are declared whenever insufficient stream flow and/or storage are available to fully satisfy the target demands.

For each month or day of the simulation, *SIM* or *SIMD* performs the water accounting computations for each water right, in turn, in priority sequence. The computations proceed by time step and, within each time step, by water right with the most senior water right in the WAM being considered first. Water allocation computations are performed for each water right in priority order.

As *SIM* or *SIMD* considers each water right, pertinent computational algorithms are activated to make water management decisions and perform volume balance accounting computations. Diversion targets and diversion shortages are computed. Environmental instream flow targets are computed. Reservoir storage capacity is filled to the extent allowed by available stream flow. Reservoir net evaporation-precipitation volume is incorporated in an iterative water balance algorithm. Return flows re-enter the stream at user-specified control points. An accounting is maintained of storage levels in each reservoir and stream flow still available at each control point.

WRAP views a water right as a set of water development/allocation/management/use capabilities and requirements. Considerable flexibility is provided for specifying water right capabilities and requirements. The following features of the computational algorithms are fundamental to representing water right components in the monthly time step *SIM* or daily time step *SIMD* simulation [1]. As discussed in the *Daily Manual* [5] and later in this chapter, *SIMD* also has flow forecasting and routing routines connecting time steps.

- The simulation progresses sequentially by time step. The following model features connect a time step with the preceding time step. The computed end-of-period reservoir storage becomes the beginning-of-period storage for the next time period. An option allows return flows from diversions in a period to be returned to the stream the next period. Hydropower releases may be made available at downstream locations optionally either the same or following time step. Targets may be based on reservoir storage or cumulative stream flows. Options limit annual or seasonal diversions, withdrawals from storage, and stream flow depletions.

- A water rights priority loop is embedded within the monthly or daily computational loop. In a particular month or day, the water rights are considered in priority order. Thus, in general, each water right is affected only by more senior rights, with the following exceptions. Reservoir storage is affected by computations for previous months. Next-month return flow options allow senior rights access to junior return flows. Instream flow requirements may be considered in an optional second-pass loop within the water rights loop, allowing junior return flows or releases to affect stream flow constraints on water availability for more senior rights.

The simulation progresses through each monthly or daily time step of the hydrologic period-of-analysis and, within each time step, by water right in priority order with the most senior right in the WAM being considered first. Thus, if supplies are insufficient to meet all demands in a given time step, the water available to a particular water right is not adversely affected by other rights that are more junior in priority. Most of the system simulation computations are performed within the water rights priority loop. For each individual water right in turn, the computations are performed in the following four stages.

1. The diversion, instream flow, or hydropower generation target is set based on specifications read from water right *WR*, instream flow *IF*, water use coefficient *UC*, supplemental options *SO*, target options *TO*, operating rules *OR*, flow switch *FS*, time series *TS*, and drought or storage index *DI/IS/IP* records. Environmental standard *ES*, hydrologic condition *HC*, and *SIMD*-only pulse flow *PF* records have been added for modeling *IF* record instream flow rights in SB3 environmental flow standard format. These target setting records are included in the DAT file.

2. The amount of stream flow available to the right is determined. Stream flow availability is determined as the lesser of stream flow availability array amounts at the control point of the water right and at each of the control points located downstream. Thus, negative incremental naturalized flows and options for dealing with negative incremental flows affect water availability.

3. Water volume balance computations are performed to compute the stream flow depletion, net reservoir evaporation-precipitation, end-of-period reservoir storage, return flow, diversion volume and the volume of diversion shortage, and hydroelectric energy generated and energy shortage. The interrelationships between the variables necessitate an iterative algorithm.

4. The stream flow availability array values at the control point of the water right and at downstream control points are decreased by a stream flow depletion and increased by a return flow or hydropower release, with adjustments for channel losses or loss credits. Upon completion of the water rights computation loop, regulated and unappropriated flows are determined from the stream flow availability array as adjusted for the effects of the water rights.

## Simulation and Analysis Modes

Various types of WRAP/WAM simulation features are used in different types of modeling and analysis applications. The same basic WAM simulation input datasets are used in all the following simulation modes. Parameters on records in the DAT file control selections between the following alternative strategies for applying the *SIM* or *SIMD* simulation models [1, 2].

## Conventional Long-Term Monthly or Daily Simulation

Conventional planning and water right permitting applications are based on simulating a specified scenario of water development, management, and use during a hypothetical repetition of natural hydrology during a long hydrologic period-of-analysis such as perhaps 1940-2023. The majority of applications of the WRAP/WAM modeling system over the past 25 years have been in this conventional single long-term hydrologic period-of-analysis hydrology simulation mode using a time step of a month. This report also deals with long-term simulations using a daily time step. A *SIM* or *SIMD* simulation includes hydrology for a long time-series sequence. With a 1940-2023 period-of-analysis, the hydrology sequence includes 1,008 months or 30,681 days.

Water supply reliability metrics are usually computed from the simulation results. Hydroelectric energy reliability metrics and reservoir storage and stream flow frequency metrics can likewise be computed. The simulation results may be organized as a variety of other metrics in a variety of other formats as well. Simulation results are displayed as stream flow and reservoir storage time series plots throughout this report.

Routine WRAP/WAM applications are based on a monthly computational time step. An extensive experience base of monthly simulation applications focused largely on water supply has been established since 2000 by TCEQ, TWDB, other agencies, universities, and engineering consulting firms. More recently developed WRAP/WAM modeling features employing a daily computational time interval add capabilities for simulating reservoir flood control operations and more complex environmental instream flow requirements including high flow pulse components.

Either *SIMD* or *SIM* can be employed to perform a monthly simulation with an input dataset prepared for a monthly simulation that contains no input records that are applicable only to *SIMD*. The monthly *SIM* can also be employed to perform a monthly simulation with an input dataset prepared for a daily simulation that contains input records that are applicable only to *SIMD*. The monthly *SIM* simply skips over daily-only *SIMD* input records. However, a monthly simulation with the daily *SIMD* terminates with an error message if a daily-only *SIMD* input record is found in the DAT file. A daily *SIMD* simulation optionally outputs post-simulation monthly aggregations of daily quantities as well as the daily quantities computed in the daily simulation.

With activation of dual simulation options explained in the *Reference* and *Users Manuals* [1, 2], two simulations are performed automatically during a single execution of *SIM* or *SIMD*. The dual-simulation option feature is designed primarily for applications where multiple rights with different priorities divert water from the same reservoir. Without the dual simulation, reservoir draw-downs associated with junior diversions may be inappropriately refilled in subsequent months by senior rights at the same reservoir. The set of dual simulation options allow stream flow depletions computed during an initial simulation to serve as upper limits constraining depletions during a second simulation. Selected water rights may be switched on or off as specified by input record parameters during either the initial or second simulations.

The twenty TCEQ WAMs adopt the premise of all reservoirs being full to their authorized storage capacity at the beginning of the hydrologic period-of-analysis (such as beginning of January 1940). *SIM* and *SIMD* include a beginning-ending-storage (BES) option that allows conveniently setting the beginning-of-simulation storage contents of all or selected reservoirs equal to their storage contents at the end of the simulation. This is conceptually equivalent to assuming that the hydrologic period-of-analysis is repeated cyclically an infinite number of times. The effects of the BES option is explored in Chapters 7 and 12 with Brazos and Nueces WAMs.

Firm Yield Analysis

Firm yields are routinely computed in planning studies. Firm yield is the maximum annual diversion rate, which varies seasonally during the year, supplied continuously without shortage through a conventional long-term simulation while maintaining a specified minimum non-zero or zero reservoir storage reserve. The *SIM* and *SIMD* simulation models include an optional iterative firm yield analysis mode activated by inserting a *FY* record in the input DAT file. The model adjusts specified water supply or hydropower targets while automatically repeating the entire hydrologic period-of-analysis simulation in an iterative search for the firm yield. The iteratively repeated *SIM* or *SIM* simulations produce a YRO file with a yield versus reliability table that includes the firm (100% reliability) yield if such a firm yield is possible.

The alternative strategy for computing firm yield is to execute *SIM* or *SIMD* many times while manually changing the annual water supply target of interest between executions in a trial-of-error search for the maximum target amount that can be supplied without shortage. The automated iterative simulation procedure activated by the firm yield *FY* record is much quicker.

Short-Term Conditional Reliability Modeling

The WRAP short-term conditional reliability modeling (CRM) mode is designed for developing frequency and reliability statistics for a future period typically ranging from a month to a year but optionally longer than a year that are conditioned on present or beginning known reservoir storage levels. This simulation mode supports real-time actual drought management operations or operational planning for future drought.

CRM allows development of estimated exceedance probability versus reservoir storage level relationships for future times over the next several months, year, or longer, conditioned upon given present storage contents [1, 2, 32]. Many short-term forecast simulations with different hydrology sequences begin with the same beginning reservoir storage contents. The probabilities of reservoir storage contents equaling or exceeding various levels at various future times such as one year from now, at the end of the irrigation season, or several months later in the drought are conditioned on present volumes of water in storage. Likelihoods of supplying diversion targets and maintaining stream flow levels over the specified short-term future period can also be included in the CRM assessments conditioned on present storage levels.

As an example, with a WAM 1940-2023 hydrology dataset, *SIM* may perform 83 (starting in February-December) or 84 (starting in January) annual automated simulations with each of the twelve-month hydrology sequences beginning at the same selected date with the same specified beginning reservoir storage contents. Water supply reliability and reservoir storage and stream flow frequency metrics are computed from the results of the 83 or 84 short-term simulations.

CRM is activated and CRM options are selected by inserting a *CR* record in the DAT file. Different options reflecting varying levels of computational complexity include weighting each alternative hydrologic forecast simulation sequence the same or alternatively weighting each of the hydrology sequences differently as a function of known beginning reservoir storage contents.

Salinity Simulation

Development of the WRAP salinity simulation program *SALT* was motivated by natural salt pollution in the Permian Basin geologic region in the upper watersheds of the Pecos, Colorado, Brazos, and Red River Basins in Texas, Oklahoma, Kansas, and New Mexico. Natural salt pollution from this region severely affects water quality in major reservoirs and streams further downstream such as Possum Kingdom, Granbury, and Whitney Reservoirs on the Brazos River, Lakes Texoma and Kemp in the Red River Basin, Red Bluff Reservoir on the Pecos River, and multiple reservoirs in the upper Colorado River Basin [33]. The only application of the *SALT* component of WRAP to date has been research studies at TAMU on effects of natural salt pollution and proposed salt control projects in the upper Brazos River Basin on water supply capabilities of Possum Kingdom, Granbury, and Whitney Reservoirs and the overall Brazos system [34, 35].

Application of *SALT* salinity tracking capabilities begins with a conventional simulation performed with *SIM*. Program *SALT* reads simulated regulated monthly stream flow volumes and end-of-month reservoir storage volumes from a *SIM* simulation results output file. *SALT* also reads an input file of salinity loads or concentrations entering the river system, which for the Brazos studies included total dissolved solids, sulphate, and chloride. The *SALT* simulation computations consists of tracking the salt loads and concentrations throughout the river and reservoir system.

Time series of monthly salt inflows are required for applying *SALT*. The USGS collected measurements of salinity concentrations of flows from salt source watersheds in the upper Brazos River Basin during the 1960's-1980's in support of USACE natural salt pollution control studies. WRAP was used in research studies at TAMU to assess the effects of proposed salt control projects on reducing total dissolved solids, chloride, and sulfate concentrations throughout the river and reservoir system [34, 35].

## 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 continuously 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 daily *SIMD* and monthly *SIM* simulations 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.

Types of Modeling and Analysis Applications

The effects of computational time step choice on simulation results vary with different water management modeling situations and applications. Flood control reservoir operations, high flow pulse environmental flow requirements, and the interactions between environmental flow requirements, flood control operations, and other aspects of multiple-purpose integrated water management are key considerations that can be modeled much more accurately with a daily WAM than with a monthly WAM. Daily models are required for modeling both the high flow pulse components of environmental flow standards and reservoir operations during floods due to the great variability characteristic of stream flow, particularly in response to intense rainfall events.

A monthly computational time step is generally optimal for water availability modeling of water supply capabilities in traditional applications supporting regional and statewide planning and administration of the water rights system. The accuracy of modeling water supply capabilities may or may not be improved in various situations by converting from a monthly to a daily WAM. A daily model better captures within-month variability. However, a monthly WAM may be more accurate than a daily WAM in accessing water supply capabilities due to: the complexities of streamflow translation and attenuation modeled by routing and forecasting; disaggregation and associated limitations on available stream flow and water use data; and other aspects of daily modeling. Daily modeling also requires significant additional input data compilation efforts.

Conventional water availability modeling is appropriately and effectively based on a monthly computational time step. The month generally is the optimum time interval for assessing water supply capabilities. 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 represents a particularly significant advantage of daily modeling.

Conversion from a monthly to daily model is also essential for meaningfully simulating reservoir flood control operations. Simulation of integrated water management strategies considering interactions between environmental instream flow requirements, reservoir flood control operations, water supply, hydroelectric power generation, recreation, and other water management objectives may also benefit from more detailed daily simulations.

Stream Flow Variability

The great variability of stream flow is the primary factor responsible for the differences between monthly versus daily simulations. Plots of observed and naturalized stream flow presented later in this report illustrate the continuous variability and occasional extreme fluctuations that are characteristic of river flows throughout Texas. Modeling within-month stream flow variability is the most significant aspect of the daily *SIMD* simulation model. Developing daily pattern stream flow hydrographs is the most important aspect of converting from a monthly to daily WAM.

Refilling reservoir storage and supplying diversion targets in a daily simulation depends on the volume of stream flow available each day. A monthly simulation averages stream flow availability, balancing high and low flows during the month analogously to reservoir storage. Timing of flows within the month does not constrain availability for storage or diversion. Effects of reservoir storage also somewhat diminish the effects of within-month timing of daily flows.

Run-of-river diversion and instream flow targets and shortages in meeting targets are significantly affected by within-month stream flow variability. Environmental high flow pulse standards are essentially completely defined by stream flow variability including within-month.

## **Daily *SIMD* Simulation Model**

Components of the daily modeling system are outlined in Table 2.1. The daily *SIMD* simulation model includes all the modeling capabilities of the monthly *SIM* simulation model, adjusted if and as necessary for a daily computational time step. *SIMD* includes additional disaggregation, routing, and forecasting features needed and/or relevant for dealing with complexities in a daily model that do not occur in a monthly simulation. The daily computational time step provides opportunities not possible with a monthly time step to add reservoir flood control operations and high flow pulse components of environmental flow standards to the model.

Table 2.1
Daily WRAP Modeling System

Simulation of River/Reservoir Water Management/Use System with *SIMD*

- All *SIM* monthly simulation capabilities are replicated in *SIMD*
- Additional *SIMD* capabilities that are not available in *SIM*
  1. Monthly-to-daily disaggregation of naturalized stream flows
  2. Monthly-to-daily disaggregation of other quantities
  3. Routing flow changes caused by water rights
  4. Stream flow forecasting for assessing water availability
  5. Additional negative incremental flow option and other adjustments
  6. Simulation of reservoir operations for flood control
  7. Tracking high flow pulse events for environmental flow standards

Compilation/Management/Analysis of *SIMD* Input Datasets with *HEC-DSSVue*

Management/Analysis of *SIMD* Simulation Results with *TABLES* and *HEC-DSSVue*

Calibration of Routing Parameters Using Program *DAY*

The *SIMD* simulation model is the central component of the daily modeling system. *TABLES* and *HEC-DSSVue* provide a variety of capabilities for managing, organizing, and analyzing *SIM* or *SIMD* input datasets and simulation results. Methods for calibrating flow routing parameters are implemented in the WRAP program *DAY*. The concepts and methodologies employed in the WRAP modeling system are documented by the *Reference Manual* [1] and auxiliary *Daily Manual* [5]. The logistics of preparing input records shared by *SIM* and *SIMD* are explained in Chapter 3 and additional *SIMD*-only records are explained in Chapter 4 of the *Users Manual* [2]. Instructions for using *TABLES* and *HEC-DSSVue* with either daily or monthly input or output datasets are found in Chapters 5 and 6, respectively, of the *Users Manual*. The daily WRAP program *DAY* is documented in Appendix A of the *Daily Manual*.

### General Guidelines Regarding Selection of *SIMD* Simulation Options

The Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces daily WAMs and simulation studies performed with these daily WAMs are documented by previous reports [7, 8, 9, 10, 11, 12] and further explored in Chapters 7 through 12 of this report. These six daily WAMs represent very different river basins reflecting the diversity of hydrology and water management throughout Texas. However, basic findings regarding modeling strategies and methods from the six different simulation studies are similar and complementary. The options adopted and lessons learned provide a significant experience base for developing guidance for daily WAM modeling in general.

*SIMD* capabilities listed in Table 2.1 are a series of optional modeling features that can be added singly or in combination to convert a monthly WAM to daily. Much of the complexity of *SIMD* is due to the model containing multiple optional alternative methods for performing the same tasks. A choice of optional methodology leads to another list of choices of options for implementing that selected methodology.

*SIMD* modeling tasks are listed in the first column of Table 2.2. Alternative approaches are provided in *SIMD* for performing each of these tasks. Methods generally adopted for the six daily WAMs are listed in the second column of Table 2.2. The third column lists other *SIMD* daily simulation options. The alternatives in the third column are concluded to generally not be the optimal choice of method or their usefulness is limited to particular types of modeling situations.

Table 2.2
*SIMD* Simulation Options

| 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 & attenuation or none | Muskingum |
| routing parameter calibration | *DAY* statistical method | *DAYH* optimization options |
| negative incremental flows | NEGINC options 4, 6, or 7 | NEGINC options 1, 2, 3, 5, 8 |
| next month placement | beginning priority sequence | within priority sequence |
| flow forecasting | no forecasting | wide range of forecast periods |

Methods listed in the second column of Table 2.2 are generally recommended for typical applications. Alternative methods listed in the third column may be relevant in some applications. A key concept highlighted later in this chapter is that routing, forecasting, and other optional modeling features may result in sub-optimal daily WAMs that are unnecessarily complicated.

*SIM* has sixty-one types of input records, almost all of which have been beneficially adopted for use in at least some of the twenty TCEQ WAMs. Many of these *SIM* record types are found in all of the WAMs. All of the record types in *SIM* are also applicable in *SIMD*. Sixteen other types of input records listed in Table 2.3 are used only for *SIMD* daily simulations.

Most of the records in Table 2.3 are used in the daily Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces daily WAMs. The following daily records are included in these daily WAMs: *JT* and *JU* (simulation options), *FR*, *FF*, *FV*, *FQ* (flood control), *RT* (routing), *DF* and *DC* (daily flows), and *PF* (pulse flow component of SB3 environmental flow standards). The *DW*, *DO*, and *SC*, and *PO* records in Table 2.3 have not been adopted for actual applications to date.

Table 2.3
*SIMD* Input Records for Daily Simulations [2]

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

The Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces daily *SIMD* input datasets are each composed of DAT, DIS, DIF, and DSS files. The original flow distribution DIS files (*FD* and *WP* records) are used without modification in both the daily and expanded monthly versions of the WAMs. The DSS hydrology input file is shared by both the expanded monthly and daily versions of the WAM. The DIF file is relevant only with the daily *SIMD*. *SIMD* will execute without the 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 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, *SIMD* has no option for skipping daily-only records in the DAT file, other than the model-user manually commenting (**) them out. *SIMD* can perform a monthly simulation if and only if no daily-only records are included in the input dataset. *SIMD* can also aggregate daily simulation results to monthly.

<u>DAT File Input Records with Simulation Control Option Parameters</u>

Additional "daily-only" input records are added in the conversion of an existing monthly WAM to daily. The daily-only *SIMD* input records listed in Table 2.3 are explained in Chapter 4 of the *Users Manual* [2]. Input records applicable to both *SIM* and *SIMD* are covered in Chapter 3 of the *Users Manual*. The only record absolutely 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. 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*.

*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. The following simulation control options activated on *JT*, *JU*, *JO*, and *OF* records contribute to the conversion of a monthly WAM to daily.

- ADJINC option 7 selected in *JD* record field 9 is the recommended standard negative incremental flow adjustment option for daily simulations with forecasting as explained in *Daily Manual* Chapter 3. *ADJINC* options 4 or 6 are the recommended standards for monthly simulations or daily simulations without forecasting.
- TL in *JD* record field 11 increases the number of entries allowed in the *SV/SA* record storage-area table and *DI/IS/IP* drought indices above the default of 12. TL is usually relevant when the *SV* and *SA* records are extended to encompass flood control pools.
- INEV option 6 in *JO* record field 2 instructs *SIM* and *SIMD* to read *IN* and *EV* records from a DSS input file. DSS(5) in *OF* record field 6 activates a routine that converts FLO and EVA files to a DSS file. Options activated in *JO* record fields 4, 5, 6, and 7 transport other types of time series input data from text files to the DSS input file.
- DSS(3) options selected in *OF* record field 4 instruct *SIM* or *SIMD* to record daily and/or monthly simulation results in a DSS output file. DSS(4) in *OF* record field 5 controls the selection of variables to be included in the simulation results output files.
- The DSS input filename root is entered in *OF* record field 12 for DSSROOT. With field 12 blank, by default the filename of the DSS input file is the same as the DIS file which by default is the same as the DAT file.
- The *JT* record is only absolutely required record for a daily simulation, but all fields may be blank. Defaults are activated for blank fields or entries of zero on the *JT* and *JU* records.
- Fields 8, 9, 10, 11, and 12 on the *JT* record 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 *JT* record field 13 (column 52) activates the daily output SUB file.
- The *JU* record controls disaggregation and forecasting options. A blank (or zero) *JU* record field 3 (column 12) activates the default DFFILE option 1, meaning daily flow *DF* records are read from the DSS file for the control points listed on the DAT file *DF* records.
- 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 that have actual naturalized flows.
- 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. Blank fields result in defaults being adopted.
- Forecasting is activated by FCST option 2 in *JU* record field 6. The forecast period FPRD set in *JU* record field 7 can be easily set or changed. If FCST=2 is entered in *JU* record field 6 and field 7 is blank, the forecast period FPRD is automatically computed within *SIMD*. The default forecast period is generally unreasonably too long and should normally not be used. The default forecast period represents a maximum upper limit rather than optimal choice.

Monthly-to-Daily Disaggregation

*SIMD* simulations can be performed directly with daily naturalized stream flows without using monthly flows, as illustrated by research projects at TAMU. However, daily applications of Texas WAMs to date have always been based on disaggregating monthly naturalized flow to daily. Disaggregation of monthly naturalized flow volumes to daily volumes is the basic key component of converting a monthly WAM to daily. Disaggregation of monthly naturalized flows to daily is the focus of this section and is further discussed in Chapter 5. However, other variables are also disaggregated from monthly to daily in a *SIMD* simulation, normally by default uniformly.

Monthly water supply diversion targets are uniformly disaggregated to daily. Daily diversion targets in acre-feet/day are computed within *SIMD* by dividing monthly diversion target volumes by the number of days in the month. *SIMD* knows the number of days in each month and which years are leap years. *SIMD* includes options for non-uniformly disaggregating monthly diversion targets to daily, activated by input parameters on *JU*, *DW*, and *DO* records, but these options are not employed in the six daily WAMs discussed in this report.

Releases from flood control pools and targets for environmental flow standards (EFS) established pursuant to the 2007 Senate Bill 3 (SB3) are computed by *SIMD* on a daily basis. *SIMD* directly computes daily *IF* record instream flow targets for SB3 EFS based on *HC*, *ES*, and *PF* record specifications rather than disaggregating computed monthly targets to daily. However, for other *IF* record instream flow requirements, computed monthly target volumes are uniformly sub-divided to daily volumes. Non-uniform *IF* target distribution options provided by *SIMD JU*, *DW*, and *DO* records are not employed in the six daily WAMs discussed in this report.

Selection between alternative options for disaggregating monthly naturalized flows to daily is made with input parameter DFMETH on the daily simulation options *JU* record. The default DFMETH option 4 is the standard alternative for almost all cases. DFMETH option 4 consists of employing *DF* record flow pattern hydrographs with automatic repetition. DFMETH option 1 consisting of uniformly distributing the monthly naturalized flows to the days of each month requires no *DF* record daily flows. Option 1 is relevant if daily variability is not relevant or important. The six daily WAMs employ primarily the standard DFMETH option 4, with option 1 used in special cases discussed in later chapters. The other disaggregation options are not used.

The *DF* records for one control point could conceptually be repeated for all control points. Adding different *DF* records for as many control points as practical increases the accuracy of capturing the differences in variability at different locations in the stream system. DFMETH option 4 employs *DF* record flow pattern hydrographs with automatic repetition. The automatic repetition algorithm employed within *SIMD* to repeat the same *DF* record pattern flows at any number of control points is explained in Chapter 2 of the *Daily Manual* [5].

Monthly naturalized stream flows are input for all primary control points and synthesized for all other control points (called secondary) in exactly the same manner in both *SIM* monthly and *SIMD* daily simulations. Daily flow pattern hydrographs are assigned within *SIMD* to all control points, both primary and secondary. Monthly naturalized flows at many control points are disaggregated to daily naturalized stream flows using *DF* record daily flow pattern hydrographs input for a much smaller number of control points.

With the standard default DFMETH option 4 activated, *SIMD* disaggregates monthly naturalized flow volumes to daily volumes in proportion to the flows in the daily pattern hydrographs while preserving the monthly volumes. Although monthly and daily flow volumes in a *SIMD* simulation are in units of acre-feet, flow rates in cubic feet per second (cfs) or other units can be used for the *DF* record flow sequences defining patterns since only relative within each month, not absolute, quantities are relevant. However, the final daily flows adopted for the pattern hydrographs for the six daily WAMs are daily naturalized flow volumes in acre-feet/day.

Daily flows on *DF* records are initially compiled in units of cubic feet per second (cfs) for the daily WAMs of Chapters 7-12. A *SIMD* simulation is performed with *DF* records for flows in cfs stored in the *SIMD* hydrology input DSS file. *SIMD* simulation results including daily naturalized flows in acre-feet are recorded by *SIMD* in its simulation results DSS output file. The daily naturalized flows in acre-feet in the *SIMD* simulation results DSS file are converted to *DF* records within *HEC-DSSVue* and copied to the *SIMD* hydrology input DSS file.

Compilation of *DF* record daily flows for the six daily WAMs is described in general in Chapter 5 and Chapters 7-12 and in greater detail in previous reports [7, 8, 9, 10, 11, 12]. Most of the *DF* record flows are derived from daily observed flows at USGS gage sites downloaded with *HEC-DSSVue* from the National Water Information System (NWIS) discussed in Chapter 4.

### Other Groups of Input Records

Flood control reservoir operations are modeled by adding *FR* and *FF* records to the DAT file as discussed later in this chapter. Senate Bill 3 (SB3) environmental flow standards (EFS) are modeled by adding *IF*, *ES*, *HC*, and *PF* records as described later. *SV/SA* and *IS/IP* record tables in the DAT file may be extended to include flood control pools. TL in *JD* record field 11 increases the number of entries allowed in the *SV/SA* record storage-area and *IS/IP* record drought index tables above the default of 12. Lag and attenuation routing coefficients developed as discussed later in this chapter are recorded on *RT* records stored in a file with filename extension DIF.

## ***SIMD* Routing and Forecasting**

Streamflow depletions for diversions and refilling reservoir storage, reservoir releases, and return flows result in stream flow changes that propagate through river reaches to downstream control points. 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. Likewise, hydropower releases in a monthly simulation may be released to the river in the next month. Otherwise, a monthly *SIM* simulation has no routing. Flow changes are assumed to propagate to the river system outlet within the current month. This is an approximation since, in reality, the effects of diversions and refilling reservoir storage late in a particular month may still be propagating downstream during the first week or two of the next month.

Flow changes in a *SIMD* daily simulation can also be assumed to propagate through river reaches to the outlet within the current day. The assumption of complete propagation in a single time period is significantly more approximate or inaccurate in a daily *SIMD* simulation than in a monthly *SIM* simulation. *SIMD* includes routing options to lag and attenuate the flow changes. However, as noted in the following discussion, routing computations are also approximate and inaccurate. Forecasting is relevant only if routing is activated. Forecasting is also approximate and inaccurate. In general, routing and forecasting computations should be activated in *SIMD* simulations only if the particular characteristics of the modeling application warrant their use.

The alternative methods for routing, calibration of routing parameters, forecasting, and related computations listed in Table 2.2 on page 27 of this chapter are explained in the *Daily Manual* [5]. Recommended options are listed in the second column of Table 2.2. The following discussion focuses on the methods adopted for the case study daily WAMs and recommended for future applications. Experience with the six case study daily WAMs is explored in Chapters 7 through 12 and summarized with conclusions and general guidance for dealing with complexities in Chapter 13 of this report. Basic considerations regarding routing and forecasting in daily *SIMD* simulation are outlined in the following subsections of this chapter.

Routing of Flow Changes

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 or attenuation, in a daily *SIMD* simulation in essentially the same manner as in 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* [5]. The routing parameters are stored on *RT* records in the daily input DIF file as 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 *SIMD* routing computations for the river reaches between all control points are not feasible for large WAMs. Routing parameters are determined for only selected river reaches defined by upstream and downstream flow gages. Routing computations are typically performed for only a sub-reach of each selected gaged reach.

The *SIMD* routing algorithm simulates lag and attenuation of flow changes in free flowing stream reaches, not reservoirs. However, surcharge storage in reservoirs either with or without flood control pools can be modeled in the flood control routines using reservoir storage volume versus outflow tables input on *FV* and *FQ* records.

Routing of flow changes through downstream control points is incorporated in a *SIMD* simulation by a DIF file with routing parameters on *RT* records. Routing can be switched off with the NORT parameter in *JU* record field 9, commenting out *RT* records, or if the DIF file has no other records, removing the DIF 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.

Lag and attenuation routing is activated as RTYPE(cp) option 1 in *RT* record field 3. Lag (LAG and LAGF) and attenuation (ATT and ATTF) routing parameters in units of days are provided on *RT* records in a DIF file. Separate values for lag and attenuation are provided for normal water right operations (LAG and ATT) and flood control operations (LAGF and ATTF). The parameters are for the river reach below the control point in *RT* record field 2.

Routing Parameters

The lag and attenuation routing algorithm in *SIMD* is explained in detail in Chapter 3 of the *Daily Manual* [5]. Methods for calibrating routing parameters are explained in Chapter 4 of the *Daily Manual*. 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 USGS gage sites for normal flows and high (flood) flows. 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.

The Brazos, Trinity, Neches, and Colorado daily WAMs have lag and attenuation routing parameters for 67, 39, 19, and 30 control points [7, 8, 9, 10]. No routing parameters were developed for the Lavaca and Nueces daily WAMs based on the conclusion that incorporation of routing would not beneficially contribute to accuracy of the models [11, 12]. Relevant stream lengths in the Lavaca and Nueces river basins are much shorter than in the other four larger river systems.

Routing parameters for the Brazos, Trinity, Neches, and Colorado River Basins were developed in a research study that tested the then newly created statistical analysis calibration methodology described in Chapter 4 of the *Daily Manual* [5] along with exploring stream flow characteristics relevant to routing [37]. The routing parameters incorporated in the daily Brazos, Trinity, Neches, and Colorado WAMs were derived primarily from this previous investigation [37]. The following discussion is based largely on the previous research study [37], even earlier research [36], and the daily WAM simulation studies [7, 8, 9, 10].

The optimal values for the attenuation parameters ATT and ATTF were determined to be 1.0 day for all 67, 39, 19, and 30 stream reaches in the four daily WAMs. 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. Thus, with ATT and ATTF values of 1.0, the lag and attenuation routing method is essentially simplified to lagging flow changes. LAG and LAGF reflect travel times that vary between reaches with differences in reach lengths, stream characteristics, and discharge rates that affect mean flow velocity, velocity profiles, and wave celerity.

Simulation studies with the Brazos, Trinity, Neches, and Colorado daily WAMs included comparative analysis of simulation results with and without routing. Calibration of routing parameters requires significant effort, time, and expertise. However, routing is easily activated or deactivated in various ways including selection or deselection of the no routing NORT parameter on the *JU* record. The *RT* records in the DIF file are easily manipulated.

In general, simulation results with the four daily WAMs were found not to be overly sensitive to routing strategies and the values of routing parameters. Reasonable and similar simulation results can be obtained with or without routing and, with routing, results vary only minimally with significant changes to routing parameter values and selections of routing reaches.

As discussed in Chapters 8 and 9, routing is deactivated in the final adopted daily Trinity and Neches WAMs. The *RT* records remain in the DIF file for future use as desired, but the final adopted daily Trinity and Neches WAMs were concluded to be better without routing [9, 10].

The Brazos and Colorado River Basins are larger with longer river reaches than the Trinity and Neches River Basins. As discussed in Chapters 7 and 10, routing is employed in the final adopted daily Brazos and Colorado WAMs in some reaches but with a relatively short forecast period [7, 10]. The daily Brazos and Colorado WAMs are concluded to be valid models with little difference in simulation results either with or without routing as long as the selected forecast period is relatively short. Simulation results become unreasonable if the forecast period is long. Forecasting is activated in any of the daily WAMs only if routing is activated.

Forecasting of 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* [5], are designed specifically to deal with the effects of water management actions in a particular day on downstream stream flows in future days, as reflected in routing computations. With routing (lag and attenuation), stream flow depletions, return flows, and reservoir releases in the current day can affect both (1) stream flow availability for downstream senior water rights in future days and (2) flood flow capabilities for releases from flood control pools. The following two purposes are served by forecasting in the *SIMD* 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 from flood control pools that contribute to flooding in future 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 available flows at the control point of the water right and all downstream control points. The reason for considering all downstream control points is to assure that a water right does not appropriate stream flow that has already been appropriated by other more senior water rights. With forecasting in a daily *SIMD* simulation, water availability depends on flows at downstream control points in future days as well as in the current day. The amount of streamflow available for refilling reservoir storage and supplying diversion targets for a water right at a particular control point in a particular day is set as the minimum available flow at that control point and many downstream control points in that day and, with forecasting, during the multiple days of the forecast period. Stream flow variability, routing inaccuracies, and other complexities may result in water availability being over-constrained by the consideration of many downstream control points and additional future days.

Flood control operations are based on making no releases from flood control pools that contribute to increases in flows above specified nondamaging levels at downstream gage sites. Without forecasting, releases from flood control pools in the current day may inappropriately contribute to exceedance of specified flow levels at downstream locations in future days.

Other Modeling Features that Interact with Routing and Forecasting

Negative incremental naturalized stream flows are a significant issue in monthly *SIM* simulations and have a much greater effect in a daily *SIMD* simulation. Negative incremental flows refer to time periods (days or months) during which the naturalized flow at the downstream end of a river reach are smaller than the flow at the upstream end. Negative incremental flows during the forecast simulation is a consideration in the determination to not activate forecasting and in the selection of routing and forecasting parameters and negative incremental flow adjustment options. Without proper ADJINC adjustments, negative incremental naturalized flows may significantly contribute to over-constraining water availability in the simulation computations.

The several alternative negative incremental flow adjustment options including the recommended standard options for monthly and daily simulations are explained in Chapter 3 of the *Reference Manual* and Chapter 3 of the *Daily Manual*. ADJINC option 4 is generally the recommended best option for monthly simulations. ADJINC option 6 conceptually achieves the same results as option 4 with less computations, but the reduction in computer run time is negligible. Option 5 has been activated in the past in several of the monthly WAMs. However, options 4, 5, and 6 are 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. ADJINC options 4 or 6 are recommended for daily simulations without forecasting.

The selection parameters WRMETH and WRFCST in *JU* record fields 4 and 5 control the choice of next-day placement of routed flow changes. The simulations presented in the four daily WAM reports employ the default option of placing the routed flows at the beginning of the water right priority sequence in the next day of the simulation, rather than within the priority sequence.

Routing and Forecasting Complexities

Routing parameter calibration is based on statistical analyses of flow changes detected in observed flows between USGS gages. Observed actual lag and attenuation characteristics of flow changes in actual gaged river reaches were found to exhibit significant variability that is difficult to describe or explain [5, 36, 37]. Calibrated values for the lag and attenuation parameters for the *SIMD* routing algorithm also exhibit significant unexplained variability and associated uncertainty.

Lag or travel time of a flow change is related to the mean stream flow velocity, stream flow velocity profiles across the stream cross-section and along the river reach, and wave celerity. These hydraulic parameters vary with discharge rates, which vary greatly over the range from low flows to high flows, between main channel flows and overbank flows, and between increasing flows rates and decreasing flow rates. *SIMD* routing does not capture all relevant hydraulic relationships.

One- and two-dimensional hydraulic routing based on numerical solution of differential equations representing conservation of mass and momentum is implemented in the *HEC-RAS River Analysis System* available from the USACE Hydrologic Engineering Center. Input data required in hydraulic modeling of flows in river reaches with *HEC-RAS* include detailed cross-sectional geometry along the stream reach and roughness parameters as well as time-varying flow rates of inflows to stream reaches. *HEC-RAS* hydraulic routing provides better estimates of lag and attenuation effects but is not practicable for WRAP/WAM water availability modeling.

The routing algorithm incorporated in the *SIMD* simulation is a very simplistic model of a complex phenomenon. 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 WAMs provide a valid simulation model without employing routing. Routing is very approximate with inherent simplifications, uncertainties, inaccuracies, and variabilities. Routing may or may not improve the accuracy of a simulation depending upon the particular application and circumstances. The effects of routing and variation in routing parameters on improving or worsening model accuracy is difficult to precisely assess. Simulation studies presented in this report and previous reports [7, 8, 9, 10] indicate reasonable results without routing and perhaps better results without than with routing.

Calibration of routing parameters is a major endeavor requiring significant time and expertise. Upon completion of the compilation of routing parameters, routing is easily activated or deactivated in the daily WAMs. In general, simulation results appear to not be overly sensitive to routing strategies and the values of routing parameters. Reasonable simulation results can be obtained with or without routing. With routing, results vary relatively minimally with significant changes to routing parameter values.

Developing monthly SB3 EFS instream flow targets from daily simulation results is the primary application considered in this report and the six previous daily WAM reports. Routing could possibly be more beneficial in other types of daily modeling applications.

Forecasting is switched on or off with parameter FCST on *JU* record field 6. The forecast period in days is entered as FPRD in *JU* record field 7. With no value entered for FRPD, the forecast period is computed within *SIMD* as twice the longest flow path measured in lag time days plus one day. This default option is conceptually based on preventing any impact of actions of junior water rights today on senior water rights in future days. Simulation studies with the Brazos, Trinity, Neches, and Colorado daily WAMs demonstrated that the default forecast periods were excessively long resulting in severe decreases in the stream flow available to water rights.

Simulations with large monthly WAMs have computer run times of several seconds. Simulations with daily versions of these WAMs without forecasting have computer run times of perhaps one or two minutes. Simulations with daily versions of these WAMs with forecasting with the default forecast period have computer run times varying from several hours to many hours.

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

<u>Concluding Observations Regarding Daily *SIMD* Routing and Forecasting</u>

Previously noted research investigations [36, 37] and daily WAM simulation studies [7, 8, 9, 10] and other analyses support the following general observations.

1. Routing is very approximate, generally does not dramatically affect simulation results, and may or may not contribute to model validity. Routing may be most beneficial without forecasting in situations in which precise preservation of water right priorities is not required.

2. Forecasting significantly affects simulation results and may adversely affect accuracy/validity. Forecasting can be easily be switched on and off. The forecast period represents the number of days into the future considered in determining water availability constrained by downstream senior water rights and downstream nondamaging flows governing releases from reservoir flood control pools. The forecast period is an input parameter that is difficult to accurately estimate.
3. Interactions between negative incremental flow adjustments, routing, forecasting, and other flow adjustments are complex. Negative incremental flow adjustment options in particular significantly affect stream flow availability in the water rights priority simulation. Flow forecasting significantly magnifies these effects by considering all days of the forecast period rather than just the current day.

## Reservoir Flood Control Operations

Flood control reservoir operations are treated as a type of water right in *SIMD*. In WRAP terminology, a water right is a set of water control requirements, reservoir storage 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. Flood control features of *SIMD* may simulate any number of reservoirs operated as a multiple-reservoir system based on outlet capacities and specified allowable nondamaging stream flow rates at any number of downstream gage sites (control points).

Procedures for operating the flood control pools of U.S. Army Corps of Engineers (USACE) multiple-purpose reservoirs are outlined in Chapter 3. Flood control pool operations are guided by two sets of operating rules called regular operations and emergency operations. Regular operations are based on maximum allowable discharge rates specified at the dams as functions of storage and at USGS stream gage sites located downstream of the dams. Allowable downstream flow limits may vary with storage contents of one or more upstream reservoirs. If the flood control pool storage capacity is exceeded, emergency operations are activated to protect the dam following release rules that assure that a designated maximum design water surface is never overtopped, even though the releases from the flood control pool contribute to downstream flooding.

Regular flood control operations based on criteria regarding stream flow at downstream control points are modeled in *SIMD* with a flood control reservoir *FR* record for each reservoir and flood flow *FF* record for each of the downstream control points that govern upstream reservoir releases. A *FV/FQ* record pair describes a relationship between reservoir storage volume and outflow rates for a particular reservoir. The *FV/FQ* table of reservoir storage volume versus outflow represents the hydraulics of the outlet structures. *FV* and *FQ* records and/or FCMAX on the *FR* record can be used to model outlet structure capacities for flood control operations. These 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.

*SIMD* creates an optional AFF output file with annual series of peak flows and reservoir storage volumes. 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 analyses specified by a 7FFA record based on the log-normal or log-Pearson Type III probability distribution functions.

In a monthly *SIM* simulation, outflow equals inflow with no flow attenuation (storage) whenever the reservoir is full to the top of conservation (authorized) storage capacity. *SIMD* includes comprehensive capabilities for modeling the flood pool operations of single reservoirs or multiple-reservoir systems with releases controlled by a combination of dam outlet capacities and specified allowable non-damaging flow levels at any number of gaging stations located at downstream sites. Flood control operations affect reservoir storage contents and downstream river flows only during high flow periods when the reservoir conservation storage is full to capacity.

## Senate Bill 3 Environmental Flow Standards

Hydrologic condition *HC*, environmental standard *ES*, pulse flow *PF*, and pulse flow options *PO* records are designed to express instream flow *IF* record water rights in the format of environmental flow standards (EFS) established following the process created by the 2007 Senate Bill 3 (SB3). *ES* records model subsistence and base flow components of SB3 EFS for either a monthly *SIM* or daily *SIMD* simulation. Pulse flow *PF* and pulse options *PO* records are applicable only in a daily *SIMD* simulation, not a monthly *SIM* simulation. The high flow pulse components of SB3 EFS consist of requirements for preserving high flow or flood events. The *PF* record is designed for tracking high flow or flood events which generally are rapidly varying, requiring a daily rather than monthly computational time interval to realistically model.

### Simulation of SB3 EFS in a Daily *SIMD* Simulation

*HC*, *ES*, *PF*, and *PO* records provide flexible generic capabilities that can be employed in various combinations with other types of records. However, the *HC*, *ES*, *PF*, and *PO* records are designed specifically to model *IF* record instream flow rights in the format of environmental flow standards developed following the process established by the 2007 Senate Bill 3 (SB3 EFS). An *IF* record is followed by an optional *HC* record, optional set of *ES* records, and for a daily *SIMD* simulation an optional set of *PF/PO* records. The hydrologic conditions defined by the *HC* record may be applicable to any or all of the *ES* and/or *PF* records. *PF* records can be used either with or without the additional options activated by *PO* records.

The same *HC* and *ES* records are used for both monthly *SIM* and daily *SIMD* simulations. The multiple alternative sequences of twelve monthly minimum flow limit quantities are the same in either a monthly or daily simulation. Monthly volume limits are uniformly subdivided into daily volume limits in a daily simulation. The selection between subsistence, base, and high flow limits each day depends upon daily regulated (default) or naturalized (optional) stream flows in a *SIMD* simulation. Instream flow targets based on regulated flows depend on regulated flow at the particular point in the water rights priority sequence computations. Stream flow rates in cubic feet per second averaged over a month versus averaged over a day will differ, sometimes greatly.

A daily simulation more accurately models the *ES* record subsistence and base flow standards due to better representing within-month daily stream flow fluctuations. The characteristics of high flow pulse events necessitate a daily simulation for modeling the *PF*/*PO* record components of SB3 EFS. Modeling subsistence and base flow components of SB3 EFS with *ES* and *HC* records is explained in *Reference Manual* Chapter 4 and *Users Manual* Chapter 3. Modeling high pulse flows with *PF*, *PO*, and *HC* records is described in Chapter 4 of the *Users Manual* [2] and Chapter 6 of the *Daily Manual* [5].

SB3 environmental flow standards (EFS) set minimum instream flow limits at a control point based on the following considerations which are modeled in a *SIM* or *SIMD* simulation based on a selected flow variable ESV, which by default is the computed regulated flow, and target setting specifications input on sets of *IF*, *HC*, *ES*, *PF*, and *PO* input records.

- *ES* records model subsistence and base flow components of flow standards. Subsidence flow limits control if the regulated flow is below base flow limits. Base flow limits control if the regulated flow is between base flow limits and high flow limits. High flow limits control if the regulated flow is at or above high flow limits.
- *PF* and *PO* records model high pulse flow components of an EFS.
- Any or all components of the flow standards may vary seasonally or monthly.
- Any or all components of the flow standards may vary with hydrologic conditions as specified on *HC* records, which are defined based on preceding stream flow or reservoir storage content, hydrologic index input on *HI* records, or other hydrologic time series variables.

Environmental flow standards may vary as a function of hydrologic condition and season of the year. Sets of *ES* records and *PF* records contain separate records for the various combinations of seasons and hydrologic conditions. For example, the environmental flow standards at a control point could be defined based on four seasons (Spring, Summer, Fall, and Winter) and three hydrologic conditions (dry, average, and wet). The flow standards would be modeled with a set of twelve *ES* records and a set of twelve *PF* records along with a *HC* record to define the hydrologic conditions.

Incorporating Daily Instream Flow Targets in a Monthly WAM

A strategy for incorporating monthly instream flow targets for SB3 EFS computed in a daily *SIMD* simulation is demonstrated in the previous six daily WAM reports [7, 8, 9, 10, 11, 12] and Chapters 7 through 12 of this report. Daily *IF* record instream flow targets for SB3 EFS are computed and summed to monthly quantities within the daily *SIMD* simulation for input to the monthly *SIM* simulation input dataset. The monthly *SIM* simulation model is applied with the SB3 EFS modeled as *IF* record water rights with targets defined as target series *TS* records.

Monthly instream flow targets for the SB3 EFS are computed and converted to *TS* records, which are copied to the time series DSS input file. The *IF* records incorporated in the DAT file for the monthly simulation access the *TS* record targets in the DSS input file. The conversion of *SIMD* simulation results to *SIM* input data is accomplished efficiently within *HEC-DSSVue*.

With the strategy outlined here, conventional monthly applications of the WAMs can continue generally with no additional complexity imposed upon model-users. The daily WAMs can be applied independently of conventional monthly applications to adjust the WAM datasets somewhat analogously to occasional updates to extend the hydrologic period-of-analysis. Many model-users can be employing the same monthly WAMs updated by the TCEQ or its contractors.

This adopted 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.

Different strategies for employing expanded WAMs will be useful for different types of applications. With the strategy applied in this report, after SB3 EFS targets are established with the daily WAM, routine modeling applications employ the monthly WAM. SB3 EFS set-asides are incorporated in the monthly WAM appropriately reducing the quantities of stream flow available for further appropriation by junior appropriators. This strategy is relevant for evaluating water right permit applications and various types of planning studies. However, as noted in the preceding paragraph, shortages or capabilities for satisfying the instream flow requirements are not accurately modeled due to the basic within-month stream flow variability issue.

Daily WAMs can be employed directly in many other types of studies with input data varied in alternative daily *SIMD* simulations to explore various water management strategies and issues. The daily model can facilitate environmental flow studies in which assessments of capabilities for meeting environmental flow standards are important. Daily simulation modeling capabilities also support studies in which flood control operations are a significant concern.

## Modeling Other Water Management Complexities

A "model" water right is defined in the WRAP/WAM modeling system as a water right *WR* record or instream flow *IF* record followed in the DAT file by a set of auxiliary records. Multiple *WR* records with multiple other supporting input records may be used to represent a single actual water right permit. Most of the over 6,200 actual water rights simulated in the twenty WAMs listed in Table 5.1 are modeled simply by using a *WR* record and water right storage *WS* record, with the *WR* record connected to a use coefficient *UC* record with a set of twelve monthly water use coefficients for distributing an annual water supply diversion target over the twelve months of the year. Any number of *WR* records can reference the same *UC* record. Likewise, minimum instream flow targets are modeled simply with an *IF* and *UC* record. However, more complex water rights can be modeled by creatively combining any number of options controlled by any number of other types of input records associated with one or multiple *WR* or *IF* records.

### Water Right Target Building and Operating Rule Options

In each time step, as each *WR* or *IF* record water right is considered in priority sequence, a target and amount of water available to supply the target are computed. Rules are specified for determining water availability and supplying the water supply or hydroelectric energy generation target (*WR* record right) or setting the instream flow target to be protected (*IF* record water right).

*WR* record field 6 allows selection among eight alternative types of water rights that simulate different water management tasks. The default type 1 water right supplies diversion targets and refills reservoir storage. A type 5 right generates hydroelectric energy and refills reservoir storage. The other *WR* record water right type options define variations in water supply, hydropower, and reservoir operations. Reservoir operations are also defined by entries on water supply storage *WS*, operating rules *OR*, and monthly-varying storage *MS* records. *OR* records define multiple-reservoir system operations. *MS* records define seasonal rule curve operations.

Flexible options for setting targets are controlled by input parameters on various types of auxiliary input records connected to a *WR* or *IF* record including target options *TO*, supplemental options *SO*, flow switch *FS*, cumulative volume *CV*, and back-up *BU* records. *HP* records define hydroelectric power generation targets and rules for supplying the energy targets. Drought index *DI/IS/IP* records allow diversion, hydropower, or instream flow targets to be specified as a function of reservoir storage. Target building options controlled by entries on these input records can be employed individually or in various combinations to model unique and complex water management situations. Series of monthly targets can also be developed independently of *SIM* and *SIMD* and incorporated into the *SIM* and *SIMD* input dataset as target series *TS* records. Certain options on the target building records allow specification of the amount stream flow that can be appropriated which may represent pumping or conveyance capacities. Limits or capacities may also be set by parameters on limit options *LO* and monthly varying limits *ML* records. Each of these type of records can be found in many or at least some of the monthly TCEQ WAMs.

The DAT file input records noted in the three preceding paragraphs have been employed to model minimum instream flow requirements and more recently the more complex SB3 EFS. However, the *ES* and *HC* records added to both *SIM* and *SIMD* and the *PF* and *PO* records added only to *SIMD* are designed specifically for more efficiently modeling SB3 EFS in the structured format in which the SB3 EFS are actually defined. *ES*, *HC*, *PF*, and *PO* records greatly simplify modeling SB3 EFS and can also be used to model other types of instream flow requirements.

*FR*, *FF*, *FV*, and *FQ* input records were added to *SIMD* to model flood control operations and/or surcharge storage. The monthly *SIM* includes no features for simulating flood control operations or surcharge storage. With conservation storage full to capacity, outflow equals inflow.

Hydroelectric Energy Generation

Hydroelectric power production is simulated similarly to water supply diversions. Water right types 5 or 6 are specified on the *WR* record for hydropower rights with or without storage refilling analogously to types 1 and 2 rights for water supply. An annual energy generation target in kilowatt-hours per year is entered on the *WR* record instead of water supply diversion target in acre-feet. The conventional hydroelectric power equation employed in *SIM/SIMD* computations expresses energy as a function of both energy head and discharge through the turbines. A hydropower *HP* record with the *WR* record provides data regarding energy conversion efficiency and the tailwater elevation which is combined with a reservoir surface (headwater) elevation to determine head. *PE/SV* input records relate reservoir storage volume to water surface elevation.

Twenty-six hydropower plants are in operation in Texas [19]. Most or all water released through most hydroelectric power turbines in Texas is diverted downstream for water supply. Hydropower operations are secondary or incidental to water supply operations. The large USACE Lake Texoma on the Red River is a notable exception in that water is released to generate hydroelectric energy without necessarily always also being diverted downstream for water supply.

Water rights for hydroelectric energy generation in Texas are generally treated as components of water supply diversion rights. Reservoir releases for hydropower are typically modeled in the WAMs as diversions with 100 percent return flow. The 100% diversion return flow representing hydropower releases can be returned in the same month or the next month as the hydropower (diversion) target. The next-month return flow option allows senior water rights access to return flows or hydropower releases of other *WR* record water rights that are more junior.

Water Right Priorities

Preserving the prior appropriation water rights concept based on relative seniority is a key fundamental aspect of the WRAP/WAM modeling system. The water management priority system simulated in *SIM* and *SIMD* is based on the relative seniority of water rights. Priorities are normally set by integers entered in field 5 of *WR* and *IF* records, usually but not necessarily always representing appropriation dates from water use permits or certificates of adjudication. Priorities are defined by the relative magnitude of the integer numbers. For example, the number 19520516, representing May 16, 1952, is senior to the number 19681103, representing November 3, 1968.

The *SIM* and *SIMD* simulation models are designed to preserve relative priorities but also include optional features for modifying priorities. With NPOPT option 1 selected in *JO* record field 13, the regular Texas prior appropriation priority system defined by priority numbers assigned on the *WR* and *IF* records is automatically replaced with a natural upstream-to-downstream priority system that simulates riparian water rights or no water rights system at all. NPOPT options 2 and 3 facilitate other water right priority strategies defined by the model-user. Factors entered on the use priority *UP* record allow modifications to priorities set in field 5 of *WR* and *IF* records to be applied to selected types of water rights identified by the use type identifier in field 4 of the *WR* and *IF* records and field 2 of the *UP* record. For example, municipal water use could be assigned a higher priority than agricultural use. These supplemental options for changing the conventional priority system have been employed little or not at all in actual WRAP/WAM applications to date.

Simulation Features for Addressing Water Allocation Priority Issues

An assortment of *SIM/SIMD* options for dealing with a variety of water management modeling complexities are highlighted in this section, beginning with the following two issues that are fundamental to a WRAP/WAM prior appropriation water rights priority-based simulation.

1. Senior water rights do not have access in the current time step to water made available in the current time step by junior water rights through diversion return flows or hydropower releases.
2. Junior reservoir releases for diversions at downstream locations may not be properly credited for contributing to meeting senior instream flow requirements at intermediate locations between the dam and water supply diversion site.

Next-month return flow and next-month hydropower options are normally activated in the TCEQ WAMs by parameter RFD on the *JO* record or RFMETH on *WR* records to deal with the first issue. A second-pass instream flow option controlled by input parameters PASS2 on the *JO* record and IFM(if,3) on the *IF* record activates a second-pass through the water rights priority loop as needed to deal with the second issue. This second-pass simulation option can result in perhaps unnecessary complications and should be used judiciously and only if actually needed.

The dual-simulation option has been activated in several of the TCEQ WAMs to preserve reservoir storage aspects of the Texas water rights priority system. The dual-simulation option feature activated by DUALD in *JO* record field 16 or DUAL(wr) in *PX* record field 2 is designed primarily for applications where two or more water rights with different priorities are supplied water from the same reservoir and refill the same reservoir. Reservoir draw-downs resulting from junior water supply diversions may be inappropriately refilled in subsequent months by senior rights at the same reservoir. The dual simulation allows stream flow depletions computed during an initial simulation to serve as upper limits constraining depletions during a second simulation.

Multiple water right holders may be supplied water from the same reservoir under various contractual arrangements. For example, two or more nonfederal water supply sponsors may contract with the federal government for water supply storage capacity in the same USACE multiple-purpose reservoir. The portions of the total storage capacity allocated to each of the nonfederal water supply entities may be modeled essentially as separate component reservoirs. Evaporation-precipitation allocation *EA* and *EF* records may be used to allocate net evaporation-precipitation between the component reservoirs. Stream flow availability allocation factors on an *AF* record may be used to allocate available streamflow between the component reservoirs.

The issue of allowing or curtailing refilling of reservoir storage during drought and non-drought conditions versus supplying current water supply diversion needs is illustrative of various water management complexities related to water allocation. A water right is typically assigned the same seniority date in a certificate of adjudication or water use permit for both refilling reservoir storage and water supply diversions. However, risks and potential consequences of curtailing present refilling of depleted storage capacity of a half-full or almost-full reservoir will be very different than curtailing present water supply diversions for municipal, industrial, or agricultural use. Any number of model water rights can be associated with a particular reservoir in a WRAP simulation. Storage-only rights allow a different priority (seniority) to be assigned to refilling storage relative to withdrawals or releases of water for water supply. Modeling flexibility is provided for simulating various strategies. Storage refilling versus supply diversion priorities represent a water allocation policy issue rather than available modeling capability issue.

With the exception of DUAL(wr) in *PX* record field 2, the several other parameters on the *PX* and *AX* records control alternative priority sequence circumvention options. Subordination agreements are the primary motivation for these priority sequence circumvention options. Use of *PX* and *AX* records to circumvent the normal water rights priority sequence should be employed very cautiously if at all. As noted in the next paragraph, the fundamental difficulty is that other water rights can be affected other than those directly included in the subordination agreement.

Subordination agreements have been executed in various river basins of Texas that allow selected upstream junior rights to access stream flow that should otherwise be passed through to a downstream senior water right. The objective of a subordination agreement, and modeling thereof, is to circumvent the water rights seniority system. The difficulty in both the real-world and the simulation model is that these water management agreements may have unintended consequences for third party water rights holders that are not included in the subordination agreements. Schemes for implementing and/or modeling agreements that achieve the intended subordination without affecting and/or being affected by other third-party water rights may not be possible.

<u>Artificial Reservoirs, Control Points, and Water Rights</u>

Use of artificial reservoirs, water rights, and/or control points to model water management complexities dates back to compilation of the original WAMs during 1998-2002 and has continued with subsequent WAM updates. The term "*dummy*" reservoirs, control points, and water rights has been used in the past rather than the term "*artificial*". 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. Creatively devised water accounting computational schemes using "*dummy*" reservoirs, control points, and/or water rights are formulated to simulate various water management complexities.

Artificial (dummy) control points, water rights, and reservoirs can complicate the interpretation of the input dataset and the simulation results. The following labeling features added in the July 2022 versions of *SIM*, *SIMD*, and *TABLES* are designed to provide greater clarity in analyzing the *SIM* or *SIMD* input DAT file and simulation results. Actual numerical values of individual input and simulation results 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.

Modifications introduced in the July 2022 versions of *SIM* and *SIMD* allow reservoirs, water rights, and control points to categorized as artificial by a new optional input parameter added to control point output *CO* and water right output *WO* records. *SIM* and *SIMD* automatically define 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 artificial 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.

# CHAPTER 3
# MANAGEMENT OF WATER IN THE RIVERS AND RESERVOIRS OF TEXAS

Computer simulations performed with the WRAP/WAM modeling system combine:

- river system hydrology
- institutional practices for managing water resources
- operation of reservoirs and other constructed infrastructure

Chapter 3 briefly describes institutional practices and constructed facilities for managing surface water resources in Texas. Chapter 4 explores relevant characteristics of river system hydrology in Texas. Chapter 2 and Chapters 5 through 12 address WRAP/WAM capabilities for modeling and analysis of the actual real-world hydrologic, institutional, and physical infrastructure systems discussed in Chapters 3 and 4. WRAP/WAM simulation and analysis tools are applied within the framework of the water management endeavors outlined in Chapter 3.

## Water Management Community

People and organizations manage water resources within an institutional framework of laws, policies, programs, practices, traditions, professional disciplines, and administrative processes [19]. The water management community consists of many people and organizations with different concerns and responsibilities working together on collaborative endeavors. Several key agencies with responsibilities for planning, development, and management of river and reservoir systems in Texas and associated WRAP/WAM modeling applications are highlighted as follows.

### State Agencies with Statewide Jurisdictions

Information describing the programs and responsibilities of the Texas Water Development Board (TWDB), Texas Commission on Environmental Quality (TCEQ), and Texas Parks and Wildlife Department (TPWD) is found at their websites. These three agencies play key roles in statewide river and reservoir system water management. TWDB has both planning and financing responsibilities. TCEQ has water allocation, public health and safety, and environmental protection responsibilities. TPWD responsibilities for recreation and conservation of natural resources intersect with TWDB and TCEQ endeavors.

TCEQ has about 2,800 employees in a main Austin office and sixteen regional offices, making it the largest state environmental regulatory agency in the United States. TCEQ administers the National Pollutant Discharge Elimination (NPDES) in Texas under the oversight of the federal Environmental Protection Agency as well as other water quality and environmental protection programs. TCEQ has a dam safety program for inspecting nonfederal dams and enforcing safety regulations. TCEQ administers two versions of a water rights system, one for the Texas side of the Rio Grande downstream of Fort Quitman and the other version for the remainder of Texas. TCEQ also provides administrative and technical staff support for the Texas commissioners of the commissions responsible for five interstate river compacts with neighboring states.

TWDB with about 400 employees is responsible for statewide and regional planning which includes working with sixteen regional planning groups pursuant to the 1997 Senate Bill 1 (SB1) to periodically update regional water plans which are consolidated into a statewide plan. TWDB also administers multiple grant and revolving fund loan programs to assist local and regional entities in financing water projects. For example, the State Water Implementation Fund for Texas (SWIFT) administered by TWDB provides low-interest loans with favorable terms for any political subdivision of Texas or nonprofit water supply corporation for implementation of projects included in the most recently adopted regional and state water plans. Projects may include developing reservoirs or well fields, building new pipelines, desalination treatment plants, purchasing water rights, or other endeavors recommended in the state and regional water plans.

The 3,500 employees of the Texas Parks and Wildlife Department (TPWD) are responsible for management of ninety-five state parks, fifty-one wildlife management areas, eight fish hatcheries, and numerous field offices. State park lands, wetlands, and recreation facilities are described in a periodically updated Texas Outdoor Recreation Plan. Many of the state parks and wildlife management areas are located at reservoirs. The TPWD mission is to manage and conserve the natural and cultural resources of Texas and to provide hunting, fishing, and outdoor recreation opportunities for the use and enjoyment of present and future generations.

River Authorities and Water Districts

Texas has over a thousand water management jurisdictions organized as river authorities, municipal water districts, irrigation districts, groundwater conservation districts, soil and water conservation districts, and drainage or flood control districts. River authorities are jurisdictions of state government created by the Texas Legislature to manage the water resources of all or a major portion of a river basin. Municipal water districts are created to develop and operate regional water supply and wastewater management facilities for multiple member cities. The regional approach is often more efficient than each city owning and operating its own individual facilities. Irrigation districts supply water to multiple farmers. Groundwater conservation districts regulate or support in various ways the development and use of groundwater in their jurisdictional counties.

The approximately twenty river authorities in Texas are agencies created by the Texas Legislature to manage the water resources of all or a major portion of a river basin. Some water management districts may be categorized as either regular water districts or smaller river authorities. River authorities have no taxing authority or regular legislative appropriations. They are funded through the sale of water and other services. The different river authorities vary in size and types of activities. The three largest are the Lower Colorado River Authority (LCRA), Brazos River Authority (BRA), and Trinity River Authority (TRA).

LCRA is a major provider of both electricity and water, operating four thermal-electric power plants and six water supply reservoirs while also generating hydropower. LCRA operates the six Highland Lakes on the Colorado River to supply water for Austin, other cities, and farmers in the lower basin. These six reservoirs also generate hydropower and are extremely popular for recreation. LCRA also owns and operates reservoirs for supplying water for producing and condensing (cooling) steam for its thermal electric power plants.

BRA created in 1930 manages the water resources of the 45,600 square mile Brazos River Basin, which is larger than many states and nations. The BRA constructed and now operates three water supply reservoirs, contracts for the conservation storage capacity of nine USACE reservoirs, and operates a regional water supply system and three regional wastewater treatment systems.

TRA is the water supply sponsor for four USACE reservoirs in the upper Trinity River Basin and owns and operates Lake Livingston on the lower Trinity River in partnership with the City of Houston. Water is conveyed by pipeline from Lake Livingston to Houston located in the San Jacinto River Basin. TRA also owns and operates regional water and wastewater treatment facilities serving Dallas, Fort Worth, Houston, and smaller cities.

River authorities, water districts, and cities contract for conservation storage capacity in U.S. Army Corps of Engineers (USACE) reservoirs as well as develop and maintain their own reservoirs. River authorities, water districts, and cities contract for water supply storage capacity of twenty-seven USACE multipurpose reservoirs in Texas and reimburse the federal government for all construction, operation, and maintenance costs allocated to water supply pursuant to the Water Supply Act of 1958 and amendments thereto [19].

Nonfederal sponsors contract for the use of storage capacity in USACE multiple-purpose reservoirs. The USACE provides nonfederal sponsors a volume of reservoir storage capacity but is not responsible for the supply or delivery of water. Nonfederal water supply sponsors, not the USACE, are responsible for water rights. River authorities sell water to cities and other customers under agreements that commit delivered water rather than reservoir storage. The river authorities or in some cases their municipal or industrial customers obtain and hold water use permits.

U.S. Army Corps of Engineers (USACE)

The U.S. Congress assigned the U.S. Army Corps of Engineers (USACE) responsibility for navigation improvements of the rivers of the nation during the 1800's. The USACE Civil Works Program has since grown to encompass nationwide multiple-purpose water resources development and management endeavors [19]. With the exception of executive-level military leadership, most of the administrative and technical staff of the division, district, project, and other USACE offices across the nation are comprised of civilian federal employees. The USACE Southwestern Division Civil Works Program is comprised of the Fort Worth, Galveston, Tulsa, Little Rock, and Albuquerque Districts. The entire river basin land area assigned to the Fort Worth and Galveston Districts and a portion of the Red River Basin component of the Tulsa District are encompassed within Texas.

The Flood Control Act of 1936 and amendments thereto established the nationwide flood control responsibilities of the Corps of Engineers [19]. The Water Supply Act of 1958 authorized inclusion of water supply storage in federal reservoirs subject to all costs allocated to water supply being reimbursed to the federal government by nonfederal project sponsors [38]. Under authority of Section 404 of the Clean Water Act of 1972 and amendments thereto, USACE administers a permit program regulating construction and other activities involving dredging and/or filling in rivers, streams, and wetlands. The National Environmental Policy Act (NEPA) of 1970 articulated the policy of protecting the environment and established requirements for evaluating the environmental impacts of federal actions. Although NEPA is applicable only to federal actions, USACE section 404 permitting of nonfederal construction activities is a federal action subject to NEPA [19].

The USACE, through its Civil Works Program, has constructed and now owns and operates more reservoir projects nationwide and in Texas than any other entity. The USACE has constructed and now owns and operates twenty-seven multiple-purpose lakes in Texas that contain both water supply and flood control storage, two flood control reservoirs that have no water supply storage, and a brine control dam. Twenty-five of the multiple-purpose reservoirs are in the Fort Worth District, and the other two are in the Tulsa District. The Truscott brine control dam is in the Tulsa District. The Addicks and Barker flood control dams in Houston are in the USACE Galveston District. Corps of Engineers reservoirs contain about 27.9%, 78.3%, and 44.0%, respectively, of the conservation, flood control, and total storage capacity of the major reservoirs of Texas [19]. The USACE is responsible for flood control operations. Nonfederal entities contract for water supply storage.

Other Federal Water Agencies

The U.S. Bureau of Reclamation (USBR) of the Department of Interior was created by the Reclamation Act of 1902 to develop water projects needed to support population and economic growth in 17 states in the West. An initial focus on agricultural irrigation later grew into multiple purpose water resources development. USBR has constructed many large reservoir projects in the 17 western states, which includes Texas. Lakes Mead and Powell impounded by Hoover and Glen Canyon Dams, constructed and operated by USBR, are the two largest reservoirs in the United States.

USBR performed planning and design studies and constructed the following five reservoir projects in Texas: Lakes Travis, Twin Buttes, Texana, Choke Canyon, and Meredith. The five reservoirs were turned over to local sponsors to own, maintain, and operate. All costs allocated to water supply are the responsibility of the local sponsors following the provisions of the Water Supply Act of 1958. The USACE has oversight responsibility for flood control operations at the three USBR-constructed reservoirs that contain designated flood control storage capacity (Travis, Twin Buttes, Meredith). The USBR also constructed several water conveyance and distribution facilities for irrigation, municipal, and industrial water use in the Rio Grande, Colorado, and Canadian River Basins in western regions of Texas that are now operated by local sponsors.

The Natural Resource Conservation Service (NRCS) of the U.S. Department of Agriculture has constructed 11,850 flood retarding dams in rural tributary watersheds nationwide including 2,040 dams in Texas. NRCS flood retarding dams have ungated outlet structures that do not require operation by people. After construction on private land with federal funding, these projects are maintained by nonfederal sponsors at nonfederal expense.

The Environmental Protection Agency (EPA) was established in 1970 to consolidate in one agency a variety of federal research, monitoring, standard-setting, and enforcement activities to ensure environmental protection. EPA's mission is to protect human health and safeguard the natural environment (air, water, and land) upon which life depends. EPA has over 18,000 employees. Regional offices in each of ten regions of the US are responsible for execution of EPA's programs within the states in that region. The EPA Office of Research and Development operates fourteen national laboratories. The EPA Office of Water, working through the EPA regional offices in collaboration with state environmental agencies is responsible for implementing the Clean Water Act, Safe Drinking Water Act, and other federal laws pertaining to protection of water quality, public health, and environmental resources.

The National Pollution Discharge Elimination System, safe drinking water programs, and an array of other regulatory activities are accomplished through issuance and enforcement of permits by state regulatory agencies that meet requirements outlined by the federal EPA. The TCEQ implements national EPA administered programs in Texas.

The US Fish and Wildlife Service (USFWS) created in 1939 is responsible for enforcing wildlife laws, protecting endangered species, and conserving wildlife and habitat on public and private lands nationwide. These responsibilities significantly affect the activities of other agencies in developing and managing water projects. USFWS also manages a system of 520 national wildlife refuges, thousands of wetlands and other special management areas, and many national fish hatcheries and fishery and ecological services offices. The Fish and Wildlife Conservation Act of 1958 established the policy that fish and wildlife conservation be coordinated with other reservoir project purposes and receive equal consideration. Requirements for conservation of endangered species, pursuant to the 1973 Endangered Species Act as amended in 1978 and 1979 and other legislation, are administered by USFWS in coordination with other agencies. Endangered species are officially identified, and they and their habitat are protected from actions that could cause their destruction. Endangered species protection requirements have significantly impacted water management nationwide and in Texas.

The nationwide mission of the Federal Emergency Management Agency (FEMA), created in 1979, is to reduce loss of life and property and protect infrastructure from all types of hazards through a comprehensive, risk-based, emergency management program of mitigation, preparedness, response, and recovery. Two major water management programs of FEMA are (1) managing emergency response to the full spectrum of disasters including hurricanes, floods, and droughts, and (2) administration of the National Flood Insurance Program (NFIP) which includes both local governmental floodplain management and private flood insurance components. The Flood Insurance Administration of FEMA administers the flood insurance component of the NFIP. The Mitigation Directorate of FEMA oversees the floodplain management aspect of the NFIP.

The Federal Energy Regulatory Commission (FERC) of the US Department of Energy regulates the transmission and sale of natural gas, oil, and electricity in interstate commerce and licenses and inspects private, municipal, and state hydroelectric projects. Hydroelectric power regulation includes issuing permits, project licenses, and exemptions from licensing; ensuring dam safety; performing project compliance activities; and coordinating with other agencies.

The Western Area Power Administration (WAPA) and Southwestern Power Administration (SWPA) are two of four US Department of Energy agencies that market and transmit wholesale electricity generated by hydroelectric plants at federal multipurpose reservoirs. The four regional electric power marketing agencies sell and transmit the electricity generated at hydropower plants at federal multipurpose reservoirs to other agencies, cities, rural electric cooperatives, and electric utility companies that distribute the power to retail customers. SWPA is responsible for a six-state area that includes the hydroelectric plants at the USACE reservoirs in Texas. WAPA has a fifteen-state service area that includes fifty-seven hydropower plants operated by the USBR, USACE, and IBWC, which includes International Amistad and Falcon Reservoirs.

International Boundary and Water Commission (IBWC)

The United States and Mexico Sections of the International Boundary and Water Commission (IBWC) are federal agencies of the two nations. IBWC owns and operates International Amistad and Falcon Reservoirs on the Rio Grande. Initial impoundment of water in these two reservoirs constructed pursuant to a 1944 international treaty occurred in 1953 and 1968, respectively. The waters of the Rio Grande are allocated between the two countries in accordance with the 1944 treaty and other agreements. The TCEQ water master office is responsible for allocating the Texas share of Amistad and Falcon reservoir storage and releases.

Water management in the Rio Grande Basin is notably different than the other river basins of Texas hydrologically, economically, and institutionally [19]. The water rights system for the Texas portion of the Rio Grande Basin below Fort Quitman is very different than the water rights system for the rest of Texas [19]. Likewise, the Rio Grande water availability model (WAM) is notably different than the WAMs for the other river basins of Texas.

Other Government, Stakeholder, Academic, and Professional Entities

Water supply, wastewater management, and stormwater management facilities are constructed and maintained by numerous cities, local governmental entities, electric utilities and commercial enterprises. Many of the private reservoirs are owned by electric power utilities and used for producing and condensing steam in thermal electric power plant operations.

Civil engineering firms and other consultants provide technical support for the water management agencies. The many consulting firms active in the Texas water management community range in size from a single registered professional engineer to many thousands of employees. Professional services are employed in planning studies, preparing water right permit applications, delineating floodplains, designing facilities, and various other activities.

Water users, recreationists, environmentalists, residential and commercial developers, and property owners are integrally involved in a full spectrum of water-related activities. Everyone uses water. Public involvement is an important aspect of water management. Advisory groups and local, state, and federal elected and appointed political officials play key fundamental roles in water management. University research and education are important in addressing water issues.

## Water Allocation

The institutional framework for water resources management includes a hierarchy of water allocation systems. Water resources are allocated between nations by treaties and other agreements. In the United States, water is allocated among states through interstate river compacts. Within individual states, water is shared by regional water authorities, municipal utility districts, cities, irrigation districts, farmers, and private companies through water right systems. Water supply entities service their customers in accordance with contracts and other commitments.

Water allocation systems (1) equitably apportion water resources among users, (2) protect existing water users from having their supplies diminished by new users, (3) govern the sharing of limited water resources during droughts when supplies are inadequate to meet all needs, (4) facilitate efficient use of water resources, and (5) protect against wasteful over-exploitation. Effective water allocation becomes particularly important as demands exceed reliable supplies.

Surface Water and Groundwater

Ground and surface water are different from the perspectives of both hydrologic processes and water management [20, 40]. Although potential benefits of conjunctive ground and surface water management have long been recognized, combining and coordinating the use of water from surface and groundwater sources is difficult due to various factors including differences in water rights associated with surface water versus groundwater.

Water in the rivers and lakes of Texas is owned by the state, and its use is regulated through a statewide water rights system administered by TCEQ. Like most states in the western United States, surface water is regulated through a prior appropriation permit system that protects senior water users from junior (more recent) appropriators diminishing their supply reliability. Seniorities (priorities) are based on the dates that water is first used or water rights are requested.

Groundwater rights in Texas have historically been based on the common law rule allowing landowners to pump as much water as they wish from under their land [39, 40, 41, 42]. Increased state regulation of groundwater has evolved primarily through establishment of local groundwater conservation districts. The Legislature passed laws in 1949 and 1985 authorizing creation of groundwater conservation districts with county-level voter approval. Twelve districts existed prior to 1985. As of 2024, ninety-eight groundwater districts have been created covering about seventy percent of the land area of the 254 counties of the state. The primary purposes of the districts are to encourage water conservation and protect water quality. Legislatively mandated duties of groundwater conservation districts include permitting water wells, developing management plans, and adopting necessary rules to implement management plans. The districts tread a narrow path between private ownership of groundwater and state responsibility to protect water resources.

Surface Water Rights in Texas

Texas has a rich heritage of developing water allocation strategies as a central thrust of its water resources management efforts [39, 41, 43]. Water rights in Texas evolved over several centuries into an unmanageable assortment of poorly recorded and often conflicting rights. A severe drought during 1950-1957 motivated a massive lawsuit in the Lower Rio Grande Valley that resulted in allocation of the Texas share of the waters of the Rio Grande below Fort Quitman, which is 90 miles below El Paso. The judicial proceedings extended over several years and demonstrated the impracticality of a purely judicial adjudication of water rights statewide.

The Water Rights Adjudication Act was enacted by the Texas Legislature in 1967 to create a unified water rights system for all of Texas except the Rio Grande below Fort Quitman which already had a recently (1960's) established allocation system. The Water Rights Adjudication Act required a recording of all claims for water rights, limited the exercise of claims to actual use, and provided for the adjudication and administration of water rights. The adjudication process required for transition to a water use permit system was initiated in 1968 and completed by about 1990.

Between 1968 and 1990, riparian water rights dating back centuries were merged into variations of prior appropriation rights dating back to the 1800’s [19]. Two water right systems now exist. One water allocation approach is designed for managing use of the Texas share of waters of the Rio Grande stored in International Amistad and Falcon Reservoirs owned and operated by IBWC. The other water rights system is applicable to the remainder of Texas.

Some type of water rights system has been administered statewide since 1913 by a centralized agency, but that agency has changed over time. The Board of Water Engineers was established in 1913; reorganized as the Texas Water Commission in 1962; and renamed the Texas Water Rights Commission in 1965 with non-water rights functions being transferred to the TWDB. In 1977, the Texas Department of Water Resources was created by combining the Water Rights Commission, TWDB, and Water Quality Board. In 1985, the TDWR was dissolved, and the TWC and TWDB became separate agencies. The Texas Natural Resource Conservation Commission (TNRCC) was created in 1993 by merging the TWC and Texas Air Quality Board. The TNRCC was renamed the Texas Commission on Environmental Quality (TCEQ) effective September 2002. The TCEQ consists of three full-time commissioners appointed by the governor and a professional and administrative staff of about 2,800 employees. Water rights for use of stream flow and reservoir storage are one of many regulatory responsibilities of the TCEQ.

Surface water rights in Texas are in the forms of certificates of adjudication or permanent or term permits. Water rights resulting from adjudication of pre-existing rights pursuant to the Water Rights Adjudication Act of 1967 are recorded as certificates of adjudication. Rights created after completion of the adjudication process are documented as water use permits. Modifications to water rights are recorded by permit amendments. Most water rights are permanently in effect as long as the holder continues to use water as specified by the water right. The TCEQ also issues term permits valid for only a specified period, typically from one to several years, to deal with emergencies or special situations. Water rights include water conservation plans. Complex rights include water management plans outlined in auxiliary documents that are periodically updated.

As of late 2023, a total of 6,235 water rights were documented as 4,892 certificates of adjudication and 1,343 water use permits. Typically, over 100 pending applications for new or amended water rights are in the TCEQ review and approval process at any time. Water rights are granted by a state license (certificate of adjudication or water use permit), which authorizes the license holder to divert a specified amount of water annually at a specific location, for a specific purpose, and to store water in reservoirs of specified capacity. A water right holder has no actual title of ownership of the water but only a right to store water in reservoirs and withdraw the water for beneficial use. However, water rights can be sold, leased, or transferred, subject to TCEQ approval.

Any organization or person may apply to the TCEQ for a new water right or to change an existing water right at any time. The TCEQ will approve the application if unappropriated water is available, the proposed beneficial need for water will be supplied at an acceptable level of reliability, existing water rights are not impaired, efficient water conservation will be practiced, and proposed actions are consistent with relevant SB1 statewide and regional water plans. During the 1968-1990 adjudication process, priority dates were established based on historical water use. Since then, priorities are based on the dates that the water use permits are administratively approved. The generalized WRAP modeling system and WAM datasets are employed to access water availability.

Most surface water rights are held by cities, river authorities, municipal water districts, and irrigation districts. Some water rights are held by electric utilities or other large private companies. Most of the thirty million residents of Texas and most private businesses are provided water by water utilities of the cities within which they reside. The cities and/or water districts or river authorities that supply water to the cities hold water right permits.

Diffuse surface runoff from precipitation belongs to the landowner until the runoff reaches a stream. Landowners can capture surface water in reservoirs with storage capacities of less than 200 acre-feet without obtaining a water use permit. The Texas Water Code also allows a person to divert water from a stream for domestic and livestock purposes on land adjacent to the stream owned by the person without obtaining a permit. Water used for wildlife management on private land is also exempt from water right permit requirements.

Several western states have water-master operations, but other states do not. The TCEQ Lower Rio Grande Water Master Office, established during the 1970’s, administers a relatively precise accounting of water use, working closely with irrigators, cities, and the IBWC. Water-master operations and associated monitoring and accounting procedures have been established more recently for several South Texas River Basins and the Brazos River Basin. For the remainder of the state for which water-master offices have not yet been created, the TCEQ administers curtailment actions during drought and takes enforcement action anytime to stop reported unauthorized water use but does not otherwise closely monitor water use other than through periodic water use reports. Water right holders throughout Texas are required to submit annual reports recording their water use.

Effective water management requires an understanding of the reliabilities that water needs can be supplied and the effects of actions of each water user on other water users. Pursuant to the 1997 SB1 the water availability modeling (WAM) system was developed by the TCEQ as lead agency in collaboration with the TWDB and TPWD and contractors consisting of consulting firms and university researchers [15]. Water use permit applicants, or their consultants, and TCEQ staff employ the WAM system to assess water supply reliabilities for proposed new or revised water use permits and impacts on other water rights. The TWDB and regional planning groups apply the modeling system to assess water supply capabilities and consequences of proposed management plans in the regional and statewide planning studies discussed later in this chapter.

Explanations of TCEQ procedures for submitting water right permit applications are available at a TCEQ webpage (https://www.tceq.texas.gov/permitting). Information for each active water right is publicly accessible at the TCEQ Water Rights Viewer website that includes a user guide for navigating the database (https://www.tceq.texas.gov/gis/water-rights-viewer). TCEQ also maintains a webpage with information for pending water right applications currently in the review process. Each water holder is required to submit an annual report of water use following instructions provided online. A database of reported annual water use data is also publicly available online.

Interstate River Compacts

Texas participates in five interstate river compacts that have been executed by member states and approved by the US Congress and are administered by compact commissions. Many similarly administered interstate river compacts have been established throughout the United States, especially in the western states. The rivers and the dates that compacts between Texas and neighboring states became effective are Rio Grande, 1939; Pecos, 1948; Canadian, 1952; Sabine, 1954; and Red, 1980. The compacts for each of the five rivers are published as Chapters 41, 42, 43, 44, and 45, respectively, of "Title 3 River Compacts" of the Texas Water Code. The compacts represent both state and federal law. The purposes of the compacts are to provide for equitable allocation of water between the states and to facilitate cooperative planning and management.

The water apportionment rules are structured differently between the five compacts though general administrative procedures are the same. Each compact is administered by a commission with representatives from each member state and a representative of the federal government appointed by the President of the United States. The commissioners rely on state water agencies for staff support. The Texas compact commissioners rely upon TCEQ staff for technical and administrative support.

A website (https://www.tceq.texas.gov/permitting/compacts/interstate.html) maintained by TCEQ provides convenient access to copies of the compacts and related documents and contact information for Texas commissioners and TCEQ technical and legal advisory staff. The website also provides a brief history of each of the five compacts.

Allocation of the Waters of the Rio Grande

The Rio Grande Basin is the fifth largest river basin in the US. The Mississippi, Yukon, Columbia, and Colorado (western states, not the Texas Colorado) River Basins are larger. The waters of the Rio Grande are shared by Mexico and the United States, and the river serves as an international boundary. International Amistad and Falcon Dams and Reservoirs are operated jointly by the two nations through the IBWC. Within the United States, the waters of the Rio Grande are allocated between Texas, New Mexico, and Colorado by interstate compacts. The Rio Grande is different from the other rivers in Texas both institutionally as discussed here in Chapter 3 and hydrologically as discussed in Chapter 4. Two countries, several states in each country, farming enterprises, and cities manage water resources of this large dry river basin with water demands, largely agricultural irrigation, exceeding available reliable supplies.

The share of the waters of the Rio Grande allocated to Texas is further allocated to water right holders through a water allocation system administered by TCEQ. As discussed earlier in this chapter, TCEQ administers a surface water rights permit system for all of Texas. However, water rights in the Rio Grande Basin below Fort Quitman are significantly different than surface water rights everywhere else in Texas [19].

Fort Quitman is a key location in both the international and state water allocation systems. Fort Quitman was established in 1858 as a US Army installation but is now an abandoned historical site. The site is located about 90 river miles downstream of the City of El Paso and 1,150 river miles upstream of the Gulf of Mexico.

The international boundary between the United States and Mexico follows the middle of the Rio Grande from its mouth at the Gulf of Mexico 1,255 miles to a point just upstream of El Paso, Texas. From there, the boundary follows an alignment westward overland for 533 miles to the Colorado River, follows the middle of that river for 24 miles, and then extends overland for 140 miles to the Pacific Ocean. The governments of the two countries through the Convention of 1889 established the International Boundary Commission to settle questions arising regarding the location of the boundary when the two meandering rivers changed their course.

A 1944 treaty allocating the waters of the Rio Grande and Colorado River between the two nations also changed the name of the International Boundary Commission to International Boundary and Water Commission (IBWC). The Mexico Section and US Section of the IBWC are headquartered in Ciudad Juarez, Chihuahua, Mexico and City of El Paso, Texas, which are separated by the Rio Grande. IBWC administers the allocation of the waters of the Rio Grande and Colorado River between the two nations and operates a multipurpose reservoir system on the Rio

Grande for water supply, flood control, hydroelectric power, and recreation. International Amistad and Falcon are the second and fifth largest reservoirs located partially or wholly in Texas. Diversion dams facilitate pumping releases from Amistad and Falcon from the river at downstream locations. IBWC also conducts planning studies and implements projects for border water supply and sanitation, salinity mitigation, local flood control, and stream bank stabilization.

A 1906 Convention between the US and Mexico provides for delivery of 60,000 acre-feet/year of Rio Grande water to Mexico in the El Paso-Juarez Valley above Fort Quitman. Elephant Butte Reservoir in New Mexico, operated by the USBR, and the American and International diversion dams near El Paso, operated by the IBWC, are used to implement the water allocation provisions of the 1906 Convention.

The Water Treaty of 1944 provided for the distribution of waters of the Rio Grande from Fort Quitman to the Gulf of Mexico between the two nations and authorized construction of the International Amistad and Falcon Reservoir projects. The 1944 treaty also allocates the waters of the Colorado River between the upstream and downstream countries. The Colorado River flows through Lakes Powell and Mead, the two largest reservoirs in the US, impounded by Glen Canyon and Hoover Dams, before flowing from the US through Mexico to the Gulf of California. The Colorado River and its tributaries drain the fourth largest river basin in the US encompassing portions of seven western states, which jointly administer interstate river basin compacts.

The Rio Grande Compact approved by the legislatures of Colorado, New Mexico, and Texas in 1939 allocates the remaining waters of the Rio Grande above Fort Quitman that are not committed to Mexico by the 1906 Convention. The Pecos River Compact adopted in 1949 allocates the waters of that tributary of the Rio Grande between Texas and New Mexico. The 307,000 acre-feet Red Bluff Reservoir is located on the Pecos River in Texas just downstream of the border with New Mexico. Construction of the project was completed in 1936. The Red Bluff Water Control District operates the reservoir for agricultural irrigation and hydroelectric power.

Differences Between the Rio Grande and Rest of Texas

All of Texas except the Rio Grande below Fort Quitman has a consistent surface water rights permit system which is different than the system for the lower Rio Grande. The TCEQ administers both systems. Water allocation in the Rio Grande Basin is significantly different than the other river basins of Texas from various perspectives. The differences listed below focus specifically on water rights in Texas.

- The water rights system in the Rio Grande was established judicially during 1956-1971 in response to litigation. The water rights system for the rest of Texas was established administratively pursuant to the Water Rights Adjudication Act of 1967.
- Priorities for the Rio Grande are based on three categories: municipal, irrigation Class A, and irrigation Class B. Priorities for the rest of Texas are based on the dates that water right holders initially requested rights to appropriate water.
- Storage accounting by the IBWC tracks the storage volume in Amistad and Falcon Reservoirs allocated to each of the two nations. The Rio Grande is the only international river in Texas.

- Storage accounting by the TCEQ water master tracks the US storage contents in Amistad and Falcon Reservoirs allocated to each of well over a thousand individual Texas water right accounts. One or at most several cities, river authorities, water districts, or other entities hold water rights for storing water in each of the other individual reservoirs in Texas.
- TCEQ water master operations have been well established for the Rio Grande for several decades. Establishment of water master operations for the other river basins has been slowly progressing over the past several decades. The water accounting system is much more detailed for the Rio Grande than other river systems of Texas.

## Environmental Flow Standards Established Pursuant to 2007 Senate Bill 3

The importance of policies and practices to protect instream flows for fish, riverine ecosystems, wetlands, and freshwater inflows to bays and estuaries has been recognized in Texas since the 1980's and earlier. Efforts to formulate and implement environmental flow standards intensified pursuant to legislation enacted by the Texas Legislature in 2001 as Senate Bill 2 (SB2) and in 2007 as Senate Bill 3 (SB3).

SB2 enacted in 2001 created the Texas Instream Flow Program (TIFP) jointly administered by the TWDB, TCEQ, and TPWD to improve capabilities for understanding and protecting aquatic ecosystems [44]. The TIFP is described and reports documenting studies performed under the TIFP are compiled at a TWDB website (https://www.twdb.texas.gov/surfacewater/flows/index.asp).

### SB3 Process for Establishing EFS

Recognizing that many years will be required to perform detailed studies for all reaches of all streams under the SB2 TIFP, the Legislature enacted SB3 in 2007 creating an accelerated process for establishing instream flow standards for selected priority river systems using the best available information and science. The SB3 process results in environmental flow standards (EFS) that are incorporated in the water availability modeling (WAM) system maintained by the TCEQ [45]. The SB3 process also includes periodically reevaluating and updating the EFS. The EFS and an array of related information are available the following TCEQ website.

(https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/e-flows).

The flow standards consist of metrics and rules that vary with location, season, and hydrologic condition that govern curtailment of diversion and/or storage of stream flows by junior water rights. Environmental flow standards (EFS) are defined in terms of regimes with subsistence, base, and high pulse flow components required to maintain a sound ecology.

TCEQ, TWDB, and TPWD provide administrative leadership and technical and funding support for the SB3 process. A stakeholder committee reflecting an equitable balance of interest groups is appointed for each priority river system. An expert science team is also appointed for each priority river system to develop a recommended flow regime considering only environmental needs. The stakeholder committee reviews the science team recommendations and develops environmental flow requirements based on a comprehensive consideration of all water needs. The TCEQ evaluates and adopts flow standards based on the recommendations of the science teams and stakeholder committees, along with public review and comment.

The environmental flow standards are incorporated in the WAMs with a priority based on the date that TCEQ receives the environmental flow regime recommendations from the applicable science team. Thereafter, the TCEQ may not issue a permit for a new appropriation or amendment to an existing water right permit that increases the amount of water authorized to be stored or diverted if any environmental flow standard requirement would be impaired. However, holders of existing senior water rights are not required to curtail appropriations of water to maintain junior environmental instream flow requirements.

TCEQ has established environmental flow standards (EFS) through the process mandated by the 2007 Senate Bill 3 (SB3) that are published as the following subchapters of Chapter 298 of the Texas Administrative Code [98]. The EFS are listed in Table 3.1.

TCEQ, Chapter 298 – Environmental Flow Standards
Subchapter A: General Provisions, Effective May 2011.
Subchapter B: Trinity and San Jacinto Rivers, and Galveston Bay, Effective May 2011.
Subchapter C: Sabine and Neches Rivers, and Sabine Lake Bay, Effective August 2012.
Subchapter D: Colorado and Lavaca Rivers, and Matagorda and Lavaca Bays, Effective August 2012.
Subchapter E: Guadalupe, San Antonio, Mission, and Aransas Rivers, and Mission, Copano, Aransas, and San Antonio Bays, Effective August 2012.
Subchapter F: Nueces River and Corpus Christi and Baffin Bays, Effective March 2014.
Subchapter G: Brazos River Basin and Its Associated Bay and Estuary System, Effective March 2014.
Subchapter H: Rio Grande, Rio Grande Estuary, and Lower Laguna Madre, Effective March 2014.

Table 3.1
River Systems with Environmental Flow Standards (EFS)

| River Basin and Bay System | Effective Date | Priority Date | Number of Sites |
|---|---|---|---|
| Trinity and San Jacinto Rivers and Galveston Bay | May 2011 | Nov 2009 | 6 |
| Sabine and Neches Rivers and Sabine Lake Bay | May 2011 | Nov 2009 | 10 |
| Colorado and Lavaca Rivers and Matagorda and Lavaca Bays | Aug 2012 | Mar 2011 | 21 |
| Guadalupe, San Antonio, Mission, and Aransas Rivers, and Mission, Aransas, San Antonio Bays | Aug 2012 | Mar 2011 | 15 |
| Nueces River and Corpus Christi and Baffin Bays | Mar 2014 | Oct 2011 | 18 |
| Brazos River Basin and Bay and Estuary System | Mar 2014 | Mar 2012 | 19 |
| Rio Grande, Rio Grande Estuary, and Laguna Madre | Mar 2014 | Jul 2012 | 3 |

The river systems with EFS are listed in Table 3.1 with their effective and priority dates. The EFS are incorporated in the WAMs at the priority dates shown in Table 3.1. Water rights with priorities senior to these dates are not affected by the EFS in the WAM simulations. The EFS are established at the sites of USGS stream gages. The number of sites with EFS are tabulated in the last column of Table 3.1. Incorporation of SB3 EFS into the Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces WAMs is a major focus of Chapters 7 through 12 of this report.

Structure of SB3 Environmental Flow Standards

The general structure and metrics of the SB3 EFS are illustrated by Table 3.2 using the SB3 EFS at the USGS gage on the Trinity River near the city of Romayor as an example [8]. This gage site is located about twenty miles below Livingston Dam and fifty miles above the Trinity River outlet at Galveston Bay. The watershed area above the gage site is 17,200 square miles.

Table 3.2
Metrics for EFS at the USGS Gage on the Trinity River near Romayor

| Season | Subsistence Flow | Base Flow | High Pulse Flows (two per season) Trigger | Volume | Duration |
|---|---|---|---|---|---|
| | (cfs) | (cfs) | (cfs) | (acre-feet) | (days) |
| Winter | 495 | 875 | 8,000 | 80,000 | 7 |
| Spring | 700 | 1,150 | 10,000 | 150,000 | 9 |
| Summer | 200 | 575 | 4,000 | 60,000 | 5 |
| Fall | 230 | 625 | 4,000 | 60,000 | 5 |

For junior water right holders to which the EFS apply, any stream flow storage or diversions that diminish flows at the Romayor gage are not allowed unless the stream flow at the Romayor gage is above the subsistence flow limit shown in Table 3.2. If the flow at the gage location is above the subsistence flow limit but below the base flow limit, junior water right holders may divert or store water to the extent that the flow at the gage does not fall below the subsistence flow limit. If the flow is above the base flow limit, the water right holder may store or divert stream flow until the flow falls below the base flow standard.

The EFS at this site include preservation of two high flow pulses during each season if the specified pulse flow events occur. Quantities used to define high flow pulse events are tabulated in the last three columns of Table 3.2. A qualifying pulse event is initiated when the flow exceeds the prescribed trigger flow shown in Table 3.2 in cubic feet per second (cfs). A pulse flow event is terminated when either the volume limit in acre-feet in Table 3.2 or the duration limit in days is reached. Pulse flow events initiated in a particular season continue into the following season if and as necessary to meet the volume and/or duration termination criteria. Junior water rights are not allowed to store or divert stream flow in a manner that would adversely affect preservation of the high flow pulses.

Seasons are defined as follows for the EFS for the Trinity River system: Winter (December, January, February), Spring (March, April, May), Summer (June, July, August), Fall (September, October, November). The EFS for the different river systems in Table 3.1 differ a little in the selection of which months to define seasons. Unlike the EFS established for other river systems, hydrologic conditions are not specified for the Trinity River system EFS. For several of the other river systems in Table 3.1, the subsistence, base flow, and high pulse criteria vary with hydrologic condition as well as season of the year. Hydrologic conditions are defined in most of the EFS as a function of either storage content of one or more specified reservoirs or cumulative stream flow at a specified gage over a specified preceding period of time. The EFS for the Brazos River system uses the Palmer hydrologic drought index to define hydrologic conditions [7].

The EFS for the Trinity River system specify that two high flow pulses be preserved in each of the four seasons of the year. EFS for other river systems vary the number of high flow pulses to be protected in each of the seasons of the year.

## Statewide and Regional Water Planning

Motivated by severe drought conditions during 1995 and 1996, comprehensive water management legislation was enacted by the Texas Legislature in 1997 as Senate Bill 1 (SB1). The 1997 SB1 included creation of the present expanded regional and statewide water planning process. Local stakeholder-guided consensus-based planning was integrated with statewide TWDB planning that had been underway since the 1950's. TCEQ approval of water use permits requires consistency with SB1 regional and statewide water plans. The 1997 SB1 also authorized development of the water availability modeling system discussed in this report to support both the TWDB administered planning process and TCEQ administered water rights system. TWDB development of groundwater availability models (GAMs) was also authorized by the 1997 SB1.

### History of Water Planning in Texas

The U.S. Congress in 1925 directed the Corps of Engineers and Federal Power Commission to develop general plans for the improvement of rivers throughout the nation for navigation and the development of hydropower, flood control, and irrigation [19]. A list of streams was submitted to Congress in 1927 and printed as House Document 308. A series of general comprehensive planning studies for the rivers identified in House Document 308 conducted during the 1930's-1950's was known as 308 studies. Most of the USACE reservoirs now in operation in Texas were originally conceptualized in these basin-wide 308 studies. The USBR also conducted similar planning studies in the western states during the 1930's-1950's, including the western half of Texas, focused largely on irrigation but including multiple-purpose river basin development. Numerous reservoir and other projects were initially identified in the early federal river basin planning studies. The subsequent pathway to implementation of specific projects was lengthy [19].

The infamous devastating 1950-1957 drought ended by extreme flooding in April-May 1957 motivated creation of the TWDB by the Texas Legislature in 1957. A $200,000,000 water development fund administered by the TWDB to help local communities develop water supplies was created by a voter-approved constitutional amendment also in 1957. In 1977, the Legislature combined three state water agencies (TWDB, Water Rights Commission, and Water Quality Board) creating the Texas Department of Water Resources (TDWR). The TDWR was disbanded in 1985, and the TWDB again became a separate agency.

A 1984 version of the Texas Water Plan developed by the TDWR includes a section summarizing state water resources planning and development from 1900 through 1983 focusing on planning studies and legislation enacted by the Texas Legislature [46]. TWDB staff in 1966 completed and released for public review a preliminary version of the first state water plan, which contained proposed strategies for meeting the state's water needs through 2020. The preliminary plan proposed fifty-three new reservoirs and a 980-mile-long water transport project beginning in northeast Texas and ending in the Lower Rio Grande Valley. A 1968 revised plan with significant revisions recommended development of sixty-seven major new reservoirs with storage capacities greater than 5,000 acre-feet [47]. The 1968 Texas Water Plan was formally adopted by the TWDB governing board and Legislature in 1969. The TWDB statewide water planning during the 1950's-1960's focused on water supply but also recognized parallel federally funded planning by the USACE that focused largely on federal flood control projects.

Between adoption of the initial statewide water plan in 1969 and the 1984 update, construction of forty-three major reservoirs and three reservoir enlargements added almost ten million acre-feet of storage capacity. Twenty-four of the new reservoirs were for water supply, eighteen were off-channel cooling ponds for steam-electric power generation, and one was for natural salt pollution control [46]. TWDB released water plan update reports in 1990 and 1992 which were relatively brief additions to the much more voluminous 1984 report.

Water Planning Process Established Pursuant to 1997 SB1

The TWDB has a governing board of three members appointed by the governor and about 400 employees. The agency is responsible for statewide planning and administering grant and loan programs to assist public water agencies and communities in financing water management endeavors. The State Water Implementation Fund for Texas (SWIFT) established in 2014 and administered by the TWDB provides low-interest loans with favorable terms for implementation of projects included in the most recently adopted state water plan.

The SB1 planning process led by TWDB in collaboration with the water management community results in sixteen regional plans and a statewide plan at five-year planning cycles, with a 50-year future planning horizon. Updated plans were completed in 2002, 2007, 2012, 2017, and 2022. The current planning cycle is scheduled for completion in 2027. Updates of the sixteen regional plans and statewide plan are documented by voluminous reports available at the TWDB website along with rules governing the planning process and other information. The plans focus on water supply resources and future water needs and use. The 2022 Texas Water Plan [18] along with an array of information regarding the planning process and 16 regional and statewide water plans are available at the TWDB website (https://www.twdb.texas.gov/waterplanning/index.asp).

The sixteen planning regions were defined considering river basins, aquifers, and municipal and agricultural water use areas. The sixteen planning groups have a total of over 400 members representing diverse interests. TWDB provides administrative leadership and technical and funding support. Consulting firms provide services as needed. TWDB coordinates with the public in developing each regional plan and integrating the regional plans into a statewide plan.

Senate Bill 8 enacted by the Texas Legislature in 2019 authorized the creation of the first State Flood Plan under the leadership of the TWDB. The new flood control planning process is patterned after the regional and statewide water supply planning process established pursuant to the 1997 SB1. A regional planning group for each of fifteen flood control planning regions is responsible for developing a regional plan in accordance with requirements outlined in the Texas Water Code and TWDB administrative rules and technical guidelines. TWDB combined fifteen regional plans developed during 2021-2024 to create the first official statewide flood plan in 2024.

Population and Water Use Projections and Water Plans

The population of Texas increased from about three million people in 1900 to 9.6 million in 1960 to 20.9 million in 2000 and 29.7 million in 2020. State Water Plan projections of the future population of Texas are as follows: 33,900,000 in 2030, 38,100,000 in 2040, 42,300,000 in 2050, 46,800,000 in 2060, and 51,500,000 in 2070.

Water supplies are lowest and water demands are highest during droughts. TWDB staff in collaboration with the sixteen regional planning groups estimate annual water demands in specified years over a 50-year planning period and capabilities for supplying the demands based on the premise of a hypothetical repeat of the most hydrologically severe drought on record. Additional unmet water needs are estimated as the difference between water demands and available water supplies. Estimated annual water needs during severe drought conditions for the various types of water use are summarized in Table 3.3 [18].

Table 3.3
Projected Annual Water Demand (acre-feet) by Water Use Category [18]

| Category/Year | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 |
|---|---|---|---|---|---|---|
| Irrigation | 9,448,000 | 9,383,000 | 8,703,000 | 8,154,000 | 7,737,000 | 7,594,000 |
| Municipal | 5,223,000 | 5,826,000 | 6,440,000 | 7,089,000 | 7,783,000 | 8,507,000 |
| Steam-electric | 931,000 | 935,000 | 935,000 | 935,000 | 935,000 | 935,000 |
| Manufacturing | 1,339,000 | 1,531,000 | 1,531,000 | 1,531,000 | 1,531,000 | 1,531,000 |
| Mining | 407,000 | 409,000 | 365,000 | 323,000 | 287,000 | 281,000 |
| Livestock | 332,000 | 343,000 | 353,000 | 363,000 | 374,000 | 382,000 |
| Total | 17,680,000 | 18,427,000 | 18,327,000 | 18,395,000 | 18,647,000 | 19,230,000 |

TWDB also compiled estimates of water supply capabilities provided from currently available water supply sources. Estimated demands exceed supplies. The unmet water demands are summarized in Table 3.4. These needs for additional water are shortages in supplying demands assuming extreme drought conditions and no new water supply projects. The statewide quantities in Tables 3.3 and 3.4 are aggregations of quantities compiled for each of the 16 SB1 planning regions.

Table 3.4
Projected Unmet Annual Water Need (acre-feet) by Water Use Category [18]

| Category/Year | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 |
|---|---|---|---|---|---|---|
| Irrigation | 2,396,000 | 3,319,000 | 3,280,000 | 3,188,000 | 3,094,000 | 3,046,000 |
| Municipal | 215,000 | 802,000 | 1,371,000 | 1,912,000 | 2,502,000 | 3,144,000 |
| Steam-electric | 187,000 | 192,000 | 196,000 | 199,000 | 201,000 | 203,000 |
| Manufacturing | 159,000 | 264,000 | 275,000 | 286,000 | 295,000 | 301,000 |
| Mining | 119,000 | 123,000 | 111,000 | 102,000 | 96,000 | 101,000 |
| Livestock | 40,000 | 44,000 | 48,000 | 54,000 | 60,000 | 63,000 |
| Total | 3,116,000 | 4,744,000 | 5,281,000 | 5,741,000 | 6,248,000 | 6,858,000 |

Except for water for producing and condensing steam in thermal-electric power plants, the quantities in Tables 3.3 and 3.4 represent annual volumes of water to be withdrawn from groundwater aquifers or river and reservoir systems, reused return flows from municipal and industrial wastewater treatment plants, or otherwise supplied. The quantities represent water to be supplied as contrasted with consumptive use excluding return flow. In the case of steam-electric power plant water, most of the water withdrawn is returned to lakes and streams. Therefore, the steam-electric quantities in Tables 3.3 and 3.4 and TWDB planning reports are limited to consumptive evaporative losses excluding return flows. Quantities representing total diversions from water supply sources for steam-electric power plants would be far larger.

The quantities in Table 3.4 are the portions of the demands of Table 3.3 not supplied by currently existing facilities with a hypothetical repeat of the most severe drought of record. Without additional supplies being developed through the strategies and projects recommended in the regional and statewide planning reports, shortages are estimated to occur under drought conditions The future unmet water needs in Table 3.4 reflect decreases in water supply capabilities of existing reservoirs and groundwater well pumping facilities as well at the increases in water demands shown in Table 3.3. Decreases in water supply capabilities of surface water reservoirs result from loss of storage capacity over time due to sedimentation. Decreasing well pumping capabilities are due to the lowering of aquifer storage levels resulting from decades of pumping exceeding natural recharge.

The sixteen regional water plans and statewide plan recommend more than 5,800 water management strategies and projects for supplying increasing water needs over the next several decades. Construction of twenty-three new major reservoir projects is included in these proposed plans. Strategies for modifying the operations of existing reservoirs to address intensifying demands on limited resources are explored in the planning studies.

The water demands outlined in the preceding paragraphs and Table 3.3 are to be supplied by diversions from sources of supply. Hydroelectric power generation, recreation, and environmental flow needs involve instream use rather than withdrawals from supply sources. Hydroelectric power facilities are operated at twenty-six reservoirs in Texas. With the notable exception of Lake Texoma, hydropower generation is usually limited to releases for downstream water supply diversions. Recreation is popular at most of the major reservoirs. Appropriating stream flow pursuant to the 2007 SB3 to protect environmental instream flow requirements represents an important type of water need that has received increased attention during the past 25 years and will continue to increase in importance in water management.

## Dams and Reservoirs

Rivers throughout Texas exhibit great flow variability including severe multiple-year droughts and major floods along with year-to-year, seasonal, and continuous flow fluctuations. Dams and reservoirs are essential for managing hydrologic fluctuations encompassing the extremes of floods and droughts along with seasonal and continuous variability. Numerous reservoir projects are operated throughout the state to store and control river flows for beneficial purposes. Most reservoir projects in Texas were constructed during the 1940's-1980's era of large-scale water resources development nationwide. Most of the storage capacity in the numerous storage facilities located throughout Texas is contained in a relatively small number of the largest major reservoirs.

Conservation, Flood Control, and Surcharge Storage Capacity

Reservoir design and operation include dividing the total storage capacity of a reservoir into pools defined by designated water surface elevations [19]. A typical reservoir consists of one or more of the vertical zones, or pools, illustrated by Figure 3.1. Portions of the storage capacity may be viewed as being reserved for estimated volumes of future accumulated sediment deposits. Sediment accumulation represents a loss of storage capacity.

Conservation storage purposes, such as municipal and industrial water supply, agricultural irrigation, and hydroelectric power generation involve storing water during periods of high stream flow for later beneficial use as needed. Conservation storage also provides head for hydropower and opportunities for recreation. The reservoir water surface is maintained at or as near the designated top of conservation pool elevation as stream flows and water demands allow. Drawdowns are made as required to meet the various needs for water. "Normal operating level" is another expression commonly used for the top of conservation pool elevation. The term "normal operating level" is particularly common in the common case of reservoirs with no flood control pool.

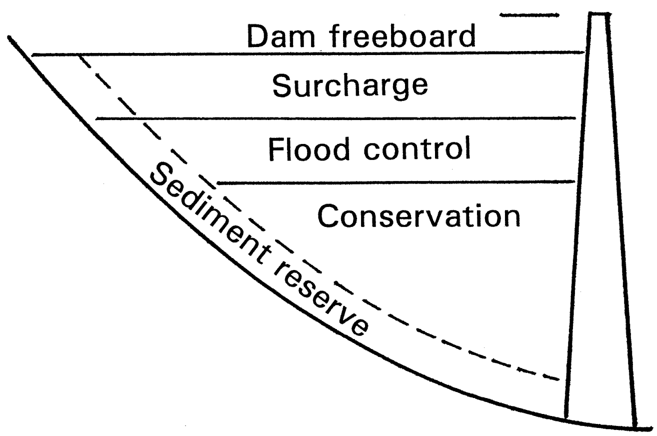


Figure 3.1 Reservoir Storage Pools or Zones

The conservation pool may include active and/or inactive storage capacity. Water is not withdrawn from the inactive portion of the conservation pool, except through evaporation and seepage. The top of inactive pool elevation may be fixed by the invert of the lowest water supply outlet or hydroelectric energy operating requirements. An inactive pool may be set to facilitate withdrawals from outlet structures that are significantly higher than the invert of the lowest outlet structure at the project. The inactive pool is sometimes called dead storage. It may provide head for hydroelectric power, a pool for recreation and fish habitat, and/or a portion of the sediment reserve.

The flood control pool remains empty except during and immediately following flood events. The bottom of the flood control pool is the top of the conservation pool. The top of flood control elevation is often set by the crest of an uncontrolled emergency spillway, with releases being made through other outlet structures. Gated spillways allow the top of flood control pool elevation to exceed the spillway crest elevation.

Multipurpose Corps of Engineers reservoirs are divided into a flood control pool and a conservation pool, allowing the two pools to be operated separately. Nonfederal water supply sponsors contract for storage in the conservation pool, with USACE flood control operations activated as the water level rises into the flood control pool. Most nonfederal reservoirs have no designated flood control pool. Without flood control, the term normal operating level is often used to refer to the top of conservation pool. The term top of conservation pool elevation is employed in this report regardless of whether the reservoir includes a flood control pool on top of the conservation pool. The water right term "authorized storage capacity" typically means total conservation pool capacity.

Flood control pool operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding, subject to the constraint of assuring that the maximum design water surface is never exceeded. Flood control pools are emptied as quickly as downstream flooding conditions allow to reduce the risk of future highly damaging releases being necessitated by filling of the available storage capacity. Minimizing the risks and consequences of storage backwater effects contributing to flooding upstream of the dam is also an important tradeoff consideration at some reservoir projects. When a flood occurs, the spillway and outlet structure gates are closed. The gates remain closed until a determination is made that the flood has crested and flows are below non-damaging target levels specified for each of any number of downstream gage sites. The gates are then operated to empty the flood control pool as quickly as practical without exceeding the allowable flows at the downstream locations.

The surcharge pool is storage capacity below the maximum design water surface and above the flood control pool or conservation pool if there is no designated flood control pool. Major flood events exceeding the capacity of the flood control pool encroach into surcharge storage. Without a flood control pool, surcharge storage occurs whenever inflow to a full reservoir exceeds outflow.

Reservoir storage capacities are defined as volumes below a specified elevation or between two specified elevations. Likewise, pool delineations are defined as specified elevations in feet above mean sea level. Although pool elevation designations imply a flat, horizontal water surface, the water surface along the length of a reservoir slopes in the downstream direction as inflows flow through the reservoir and outlet structures. At an instant in time, the water surface elevation in the upstream reaches of a reservoir can be expected to be higher that the water surface elevation near the dam. Conceptually, the reservoir surface is precisely horizontal and flat only when there is no inflow or outflow. Accepted practice is to define pool designations and operating rules as a function of water surface elevations in the main reservoir near the dam but outside of drawdowns near the outlet structures.

The maximum design water surface, or top of the surcharge storage in Figure 3.1, is set during project design from the perspective of dam safety. Reservoir design and operation are based on assuring that the reservoir water surface will never exceed the designated maximum design water surface elevation under any conditions. For most dams, particularly earth-fill embankments, the top of dam elevation includes a freeboard allowance above the maximum design water surface elevation to account for wave action and provide an additional safety factor against overtopping.

For a reservoir with a gated outlet structure, storage in the flood control pool may be regulated by gate operations controlled by operations personnel. For a reservoir with only ungated outlets, flood inflows are attenuated by surcharge storage resulting from limited spillway capacity, uncontrolled by human gate operating decisions. Flood flows are reduced by outlet structure discharge capacities, without human-operated gates, at over 2,000 ungated flood retarding structures in Texas constructed by the Natural Resource Conservation Service (NRCS) in smaller rural watersheds. Likewise, stormwater flow attenuation in thousands of urban detention facilities results from limited discharge capacities of ungated outlet structures. Most NRCS rural flood retarding structures and local community urban stormwater detention basins are much smaller than 5,000 acre-feet.

Reservoir Sedimentation

Storage capacity is lost over time due to sediment deposits. Soil transported by stream flow is deposited with decreases in flow velocity as inflows are stored in a reservoir. Sediment deposition begins in the upper reaches of a reservoir. Smaller particles will move further into the reservoir before depositing. Differences between sediment loads of reservoir inflows and outflows result in sediment accumulation. The rate of sediment deposition varies between reservoirs, depending on stream inflow rates, sediment loads from watershed and stream bank erosion, and reservoir sediment trap efficiencies. Because sediment transport increases greatly during high flows, the accumulation of sediments in reservoirs is highly dependent on the frequency and timing of major floods.

No attempt is made to estimate the volume and location of past or projected future sediment deposits for many smaller reservoirs. For most federal and other large reservoirs, sediment reserve storage volume is designated for sedimentation estimated to occur over a period of typically 50 to 100 years. Storage capacity reserved for future sediment accumulation may be reflected in water supply contracts and planning.

Some reservoirs have existed for decades without sediment surveys being performed. Reservoir sedimentation surveys are performed occasionally for many major reservoirs. Larger reservoir owners such as the USACE can perform their own sediment surveys. The TWDB has operated a non-profit cost reimbursable hydrographic survey program since 1991 which is described at the TWDB website. Reservoir owners contract with the TWDB to perform surveys to determine storage capacity, sedimentation rates, updated elevation-area tables, and bathymetric contour maps. The TWDB completed 197 hydrographic surveys on 114 reservoirs between 1991 and August 2021.

Inventories of Dams and Reservoirs in Texas

Of the approximately 3,400 storage facilities authorized by water rights in Texas, about 98 percent of the authorized storage capacity of about 42,500,000 acre-feet is contained in about 210 reservoirs that have authorized conservation storage capacities of at least 5,000 acre-feet. The remaining two percent of the storage volume is in the other over 3,000 facilities with capacities of from 200 to 5,000 acre-feet. Storage facilities of less than 200 acre-feet in size are generally not included in water right licensing. Water rights are not required for flood control storage. Reservoirs included in the water rights inventory include some projects that are licensed but not yet constructed.

The National Inventory of Dams (NID) is maintained by the USACE in support of dam safety programs. Inclusion in the NID is based on dam height and safety hazard criteria described at the NID website (https://nid.sec.usace.army.mil/#/). In June 2024, the NID included 91,856 dams in the United States, which includes 7,385 dams in Texas. Texas has more dams in the NID than any other state. The average age of the 7,385 dams located in Texas is 60 years compared to a national average of 63 years. Flood control dams are included in the NID along with all other types of dams but are not included in the water rights inventory cited in the preceding paragraph.

A major reservoir is conventionally defined as having at least 5,000 acre-feet of storage capacity. An acre-foot is a volume equivalent to covering an acre to a depth of one foot. As an aid in visualizing this common major reservoir criterion, a reservoir with a surface area of 500 acres and average depth of 10 feet contains a volume of 5,000 acre-feet. Since storage capacities decrease over time with sedimentation and may not necessarily be precisely measured, the application of this criterion for categorizing reservoirs is uncertain for reservoirs with storage capacities a little more or a less than 5,000 acre-feet.

TWDB maintains an inventory of information regarding existing major reservoirs that includes 188 water supply reservoirs and twenty other reservoirs serving recreation, hydropower, or other purposes without providing water supply. The 2022 state water plan includes proposals for construction of twenty-three additional reservoir projects in the future [18].

All major reservoirs in Texas, including Caddo Lake, are impounded by constructed dams. Caddo Lake on Cypress Bayou on the Texas and Louisiana border is the only natural lake in Texas with a storage capacity greater than 5,000 acre-feet. However, a dam was constructed by a private company in 1914 to raise the water level and reconstructed by the USACE in 1968-1971 to preserve the lake. Caddo Lake has a storage capacity of about 129,000 acre-feet.

A recent book [19] contains an inventory of 195 existing major dams and reservoirs located wholly or partially in Texas. The 195 reservoirs include 192 reservoirs with conservation storage capacities of 5,000 acre-feet or greater of which thirty-three also have large flood control pools. Three other reservoirs have gated flood control storage capacities of at least 5,000 acre-feet but no conservation storage capacity. The three major flood control only dams are Addicks and Barker Dams in Houston owned and operated by the USACE Galveston District and Olmos Dam in San Antonio owned and operated by the San Antonio River Authority.

The storage capacities in acre-feet of the 195 major reservoirs range in size as shown in Table 3.5. Ranges are specified in the table alternatively by the total storage capacity below the top of flood control pool, total capacity below the top of conservation pool, and total capacity of the flood control pool. The flood control capacity is the volume between the top of conservation and top of flood control. The conservation storage capacity is the volume below the top of conservation pool.

Table 3.5
Ranges of Storage Capacities of the 195 Major Reservoirs of Texas [19]

| Range (acre-feet) | Number of Reservoirs and Storage Capacity (acre-feet) | | | | | |
|---|---|---|---|---|---|---|
| | Total Storage | | Conservation Storage | | Flood Control | |
| ≥ 1,000,000 | 13 | 35,025,436 | 8 | 19,781,089 | 5 | 9,734,312 |
| 500,000 – 999,999 | 15 | 10,664,533 | 11 | 7,554,475 | 6 | 3,677,434 |
| 100,000 – 499,999 | 41 | 10,328,080 | 39 | 9,426,633 | 19 | 4,994,085 |
| 50,000 – 99,999 | 9 | 638,739 | 15 | 1,050,770 | 4 | 307,980 |
| 10,000 – 49,999 | 78 | 1,927,081 | 79 | 2,019,854 | 2 | 29,278 |
| 5,000 – 9,999 | 39 | 288,840 | 40 | 296,799 | 0 | 0 |
| Total | 195 | 58,872,709 | 192 | 40,129,620 | 36 | 18,743,089 |

The summation of the total storage capacity exclusive of surcharge storage of each the 195 major reservoirs is 58,872,709 acre-feet, comprised of 40,129,620 acre-feet of conservation storage in 192 reservoirs and 18,743,089 acre-feet of flood control storage in 36 of the 195 reservoirs. The 69 reservoirs with total capacities of at least 100,000 acre-feet account for 95.15 percent of the total capacity. Storage capacities decrease over time due to sedimentation. Best available (most recent) storage capacity data were compiled for the individual reservoirs. Some of the reservoirs have storage capacity estimates that have been updated at various times in the past. Storage capacity estimates for some of the reservoirs date back to their original construction.

Largest Reservoirs

The twenty-eight reservoirs located partially or completely in Texas with storage capacities of 500,000 acre-feet or larger are listed in Tables 3.6 and 3.7 in order of total storage capacity [19]. The locations of the dams are shown in Figure 3.2. Integer identifiers of dam sites on the map reference the first column of Tables 3.6 and 3.7. Watershed drainage areas in square miles above the dams are tabulated in the fourth column of Table 3.6. The reservoir name is followed by the name of the dam in parenthesis in the second column of Table 3.6 if the names are different. The third column of Table 3.6 is the year that outlet structure gates were initially closed to impound water. Water surface areas for full conservation pools are listed in the fourth column of Table 3.7.

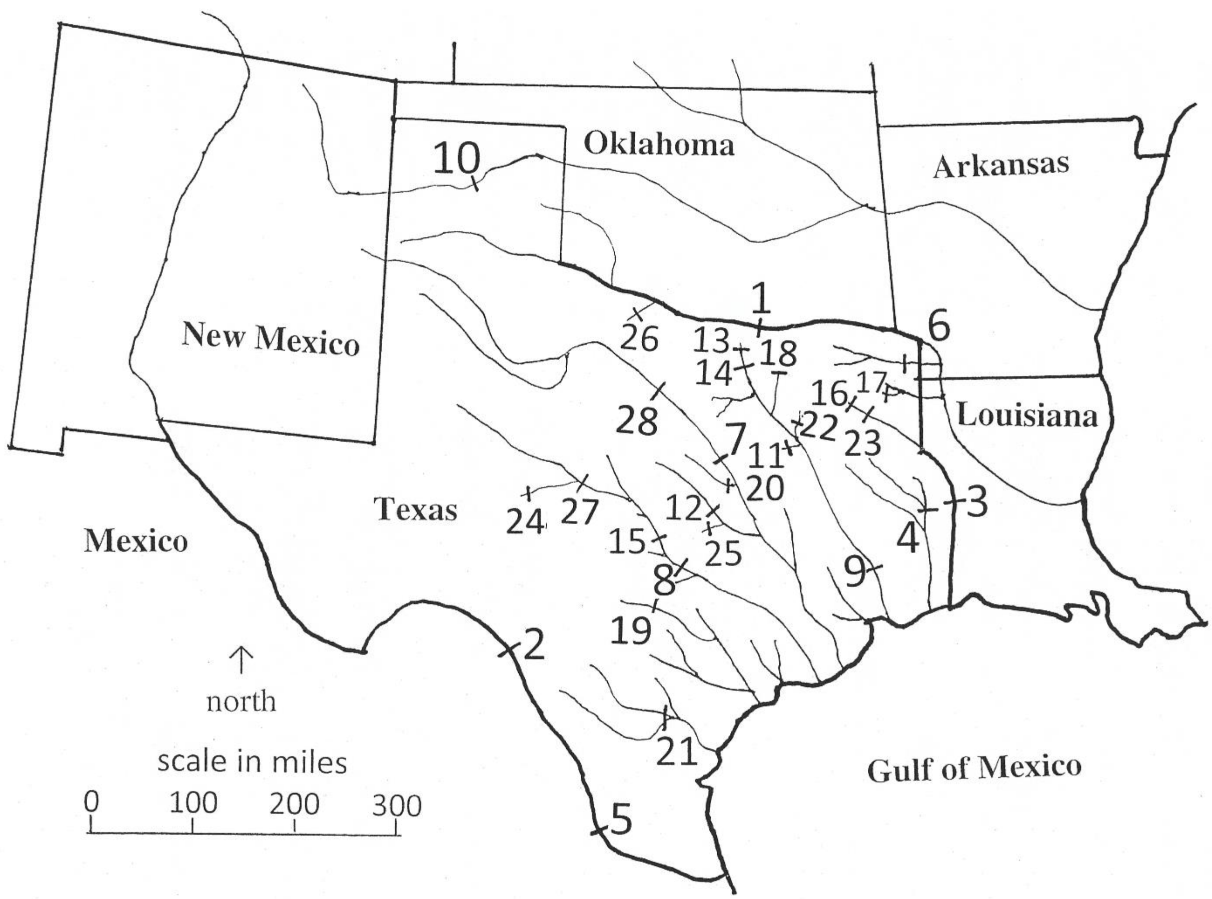


Figure 3.2 Locations of the Twenty-Eight Largest Reservoirs in Texas
(Numbers reference first column of Tables 3.6 and 3.7)

Table 3.6
Reservoirs with Total Storage Capacities of 500,000 acre-feet or Greater

| | Reservoir (Dam) | River of Dam | Watershed Area (mile$^2$) | Project Owner |
|---|---|---|---|---|
| 1 | Texoma (Denison Dam) | Red River | 33,783 | USACE Tulsa District |
| 2 | International Amistad | Rio Grande | 145,040 | IBWC |
| 3 | Toledo Bend | Sabine River | 7,178 | Sabine River Authority |
| 4 | Sam Rayburn | Angelina River | 3,449 | USACE Fort Worth |
| 5 | International Falcon | Rio Grande | 164,482 | IBWC |
| 6 | Wright Patman | Sulphur River | 3,443 | USACE Fort Worth |
| 7 | Whitney | Brazos River | 26,606 | USACE Fort Worth |
| 8 | Travis (Mansfield Dam) | Colorado River | 38,130 | Lower Colorado RA |
| 9 | Livingston | Trinity River | 16,616 | Trinity River Authority |
| 10 | Meredith (Sanford Dam) | Canadian River | 16,048 | Canadian River MWD |
| 11 | Richland-Chambers | Richland Creek | 1,957 | Tarrant Regional WA |
| 12 | Belton | Leon River | 3,570 | USACE Fort Worth |
| 13 | Ray Roberts | Elm Fork Trinity | 692 | USACE Fort Worth |
| 14 | Lewisville | Elm Fork Trinity | 1,660 | USACE Fort Worth |
| 15 | Buchanan | Colorado River | 11,900 | Lower Colorado RA |
| 16 | Tawakoni (Iron Bridge) | Sabine River | 756 | Sabine River Authority |
| 17 | Lake O' the Pines | Cypress Creek | 850 | USACE Fort Worth |
| 18 | Lavon | East Fork Trinity | 770 | USACE Fort Worth |
| 19 | Canyon | Guadalupe River | 1,425 | USACE Fort Worth |
| 20 | Waco | Bosque River | 1,670 | USACE Fort Worth |
| 21 | Choke Canyon | Frio River | 4,667 | City of Corpus Christi |
| 22 | Cedar Creek | Cedar Creek | 1,007 | Tarrant Regional WD |
| 23 | Lake Fork | Lake Fork Creek | 493 | Sabine River Authority |
| 24 | Twin Buttes | South Concho | 3,724 | City of San Angelo |
| 25 | Stillhouse Hollow | Lampasas River | 1,318 | USACE Fort Worth |
| 26 | Kemp | Wichita River | 2,086 | City of Wichita Falls |
| 27 | O. H. Ivie | Colorado River | 12,647 | Colorado River MWD |
| 28 | Possum Kingdom (Morris Sheppard Dam) | Brazos River | 13,310 | Brazos River Authority |

Conservation, operator-controlled flood control, and total storage capacities are tabulated in the last three columns of Table 3.7. These twenty-eight largest reservoirs have conservation, flood control, and total storage capacities totaling 29,747,900 acre-feet, 15,945,000 acre-feet, and 45,692,900 acre-feet, respectively, which represents 74.13%, 85.07%, and 77.61% of the totals for the 195 major reservoirs located partially or completely in Texas. The total water surface area at top of conservation pool for the twenty-eight reservoirs is 1,049,160 acres (1,640 square miles). Major portions of the storage capacity of International Amistad and Falcon Reservoirs on the Rio Grande, Lake Texoma on the Red River, and Toledo Bend Reservoir on the Sabine River are controlled by management entities and water users in Mexico, Oklahoma, and Louisiana.

Table 3.7
Water Surface Areas and Storage Capacities of the Twenty-Eight Largest Reservoirs

| Map No. | Reservoir | Began Storage | Area (acres) | Storage Capacity (acre-feet) Conservation | Flood Control | Total |
|---|---|---|---|---|---|---|
| 1 | Texoma | 1943 | 74,690 | 2,516,000 | 2,877,000 | 5,393,000 |
| 2 | International Amistad | 1968 | 66,460 | 3,276,000 | 1,734,000 | 5,010,000 |
| 3 | Toledo Bend | 1966 | 181,600 | 4,477,000 | – | 4,477,000 |
| 4 | Sam Rayburn | 1965 | 112,600 | 2,876,000 | 1,122,000 | 3,998,000 |
| 5 | International Falcon | 1953 | 85,200 | 2,647,000 | 501,000 | 3,148,000 |
| 6 | Wright Patman | 1956 | 18,250 | 97,900 | 2,556,000 | 2,654,900 |
| 7 | Whitney | 1951 | 23,220 | 554,000 | 1,445,000 | 2,000,000 |
| 8 | Travis | 1940 | 19,300 | 1,135,000 | 787,000 | 1,922,000 |
| 9 | Livingston | 1969 | 83,280 | 1,742,000 | – | 1,742,000 |
| 10 | Meredith | 1965 | 16,410 | 818,000 | 590,000 | 1,408,000 |
| 11 | Richland-Chambers | 1987 | 43,400 | 1,113,000 | – | 1,113,000 |
| 12 | Belton | 1954 | 12,140 | 435,000 | 663,000 | 1,098,000 |
| 13 | Ray Roberts | 1987 | 28,600 | 788,000 | 276,000 | 1,065,000 |
| 14 | Lewisville | 1954 | 27,200 | 599,000 | 383,000 | 982,000 |
| 15 | Buchanan | 1937 | 22,140 | 887,000 | – | 887,000 |
| 16 | Tawakoni | 1960 | 37,300 | 872,000 | – | 872,000 |
| 17 | Lake O' the Pines | 1957 | 16,900 | 241,000 | 601,000 | 842,000 |
| 18 | Lavon | 1953 | 20,600 | 409,000 | 339,000 | 748,000 |
| 19 | Canyon | 1964 | 8,310 | 379,000 | 362,000 | 741,000 |
| 20 | Waco | 1965 | 8,190 | 190,000 | 537,000 | 726,000 |
| 21 | Choke Canyon | 1982 | 26,440 | 663,000 | – | 663,000 |
| 22 | Cedar Creek | 1965 | 32,870 | 645,000 | – | 645,000 |
| 23 | Lake Fork | 1979 | 26,890 | 637,000 | – | 637,000 |
| 24 | Twin Buttes | 1962 | 9,080 | 186,000 | 446,000 | 632,000 |
| 25 | Stillhouse Hollow | 1968 | 6,480 | 228,000 | 403,000 | 630,000 |
| 26 | Kemp | 1922 | 15,360 | 245,000 | 323,000 | 568,000 |
| 27 | O. H. Ivie | 1990 | 19,150 | 554,000 | – | 554,000 |
| 28 | Possum Kingdom | 1941 | 7,100 | 538,000 | – | 538,000 |
| | Totals | | 1,049,160 | 29,747,900 | 15,945,000 | 45,692,900 |

Oldest and Newest Reservoirs

McDaniels [48], Dowell and Breeding [49], and Wurbs [50] discuss the early history of dam and reservoir projects in Texas. As previously noted, Caddo Lake is the only natural lake in Texas with a storage capacity of 5,000 acre-feet or greater, but a dam was constructed in 1914 and rehabilitated during 1968-1971 to preserve the lake. Although a few small dams were constructed in Texas before 1900, except for Caddo Lake, Eagle Lake is the oldest of the major reservoirs still in existence. Eagle Lake, with initial impoundment in 1900, is a 9,600 acre-feet irrigation reservoir in the Colorado River Basin. The thirty-five major reservoirs in operation in 1935 were small projects constructed for irrigation, municipal and industrial water supply, and/or hydroelectric power. Most of the present reservoir storage capacity in Texas was created between 1935 and 1985, with 1960-1970 being the period of greatest addition of storage capacity with completion of new projects.

Mansfield Dam and Lake Travis on the Colorado River was the first of the large multiple-purpose projects constructed in Texas by the federal government [48]. The project was constructed by the USBR during 1937-1942 and is now owned and operated by the Lower Colorado River Authority (LCRA). Denison Dam and Lake Texoma on the Red River was the first USACE project in the state. Construction was initiated and completed in 1939 and 1943. The USACE Tulsa District owns and operates the project. Denison Dam was the largest rolled earth fill dam in the United States at the time of construction. Lake Texoma is still the largest reservoir in Texas in terms of total flood control and conservation storage capacity as indicated by Table 3.7.

As of mid-2024, the Bois d’Arc project in northeast Texas is the newest major reservoir in Texas for which impoundment of water has begun. Bois d’Arc Reservoir on Bois d’Arc Creek in the Red River Basin is owned and operated by the North Texas Municipal Water District, which supplies water for thirteen member cities. The reservoir has a water supply storage capacity of 367,600 acre-feet and water surface area when full of 16,640 acres. The project also includes a water treatment plant and pipeline conveyance facilities for transporting water to the upper Trinity River Basin. Construction began in 2018 with some remaining work underway during 2024. Impoundment of water began in April 2021, with the reservoir first filling to full capacity in late April 2024.

Construction of the Lake Ralph Hall municipal water supply project owned by the Upper Trinity Regional Water District began in June 2021 with water delivery expected by 2026. This lake on the North Sulphur River in northeast Texas will have a conservation storage capacity of 180,000 acre-feet and surface area of 7,600 acres.

Reservoir Owners

The 195 major reservoirs are grouped by type of primary owner or controlling entity in Table 3.8 [19]. The number of reservoirs in each owner category is shown in Table 3.8 along with the conservation storage capacity, flood control storage capacity, and total storage capacity for reservoirs in each group expressed as a percentage of total storage capacity of all 195 reservoirs. The storage capacities for each owner group are expressed as a percentage of the volumes in acre-feet shown in the last line of Table 3.8. The total storage capacity in acre-feet shown as the last line of Table 3.8 is also found as the last line of Table 3.5.

The 195 major reservoir projects were constructed and/or are owned, maintained, and operated by the IBWC, USACE, USBR, US Fish and Wildlife Service, US Forest Service, eight river authorities, thirty-six water districts, forty-two cities, two county agencies, a state agency (TPWD), and twenty-three electric utility companies and other private companies. Other entities contract for the conservation storage capacity, water supplied, or electrical energy generated at the reservoir projects. In addition to twenty-five conventional USACE multipurpose reservoirs, the USACE Fort Worth District maintains Caddo Dam in the Cypress Creek Basin, and the USACE Tulsa District reconstructed and enlarged Lake Kemp and maintains a brine control dam in the Red River Basin. The USACE Galveston District owns and operates the Addicks and Barker flood control dams in Houston. Recreation lands adjacent to the 195 major reservoirs are managed by the reservoir owners, TPWD, and/or other organizations.

Table 3.8
Reservoir Storage Capacity by Type of Owner and Operator as Percentage of Total [19]

| Primary Reservoir Owner/Operator | Number Projects | Conser-vation | Flood Control | Total Capacity |
|---|---|---|---|---|
| IBWC, US and Mexico, Rio Grande | 2 | 14.76% | 11.93% | 13.86% |
| USACE FWD - Maintain Caddo Lake | 1 | 0.321% | 0.00% | 0.219% |
| USACE FWD - Multipurpose Reservoirs | 25 | 20.32% | 58.65% | 32.52% |
| USACE Galveston - Flood Control Dams | 2 | 0.000% | 2.183% | 0.695% |
| USACE Tulsa - Multipurpose Reservoirs | 3 | 7.352% | 17.45% | 10.57% |
| USACE Tulsa - Truscott Brine Control | 1 | 0.267% | 0.00% | 0.182% |
| US Fish & Wildlife - Buffalo Lake | 1 | 0.045% | 0.00% | 0.031% |
| US Forest Service - Coffee Mill Lake | 1 | 0.020% | 0.00% | 0.014% |
| TPWD – Shelton Reservoir | 1 | 0.014% | 0.00% | 0.009% |
| USBR Construction, Nonfederal Owners | 5 | 7.375% | 9.723% | 8.123% |
| River Authorities | 22 | 26.12% | 0.067% | 17.83% |
| Water Districts | 42 | 15.14% | 0.00% | 10.32% |
| Cities | 47 | 5.444% | 0.00% | 3.711% |
| Counties | 5 | 0.137% | 0.00% | 0.093% |
| Electric Utility Companies | 24 | 2.233% | 0.00% | 1.522% |
| Other Private Companies | 13 | 0.450% | 0.00% | 0.307% |
| Totals for 195 Major Reservoirs | 195 | 100.0% | 100.0% | 100.0% |
| Total Storage Capacity (acre-feet) | | 40,129,620 | 18,743,089 | 58,872,709 |

## Historical Reservoir Storage Contents

Reservoir storage contents provide a useful measure of water availability reflecting water resources development and use as well as weather and hydrology. Reservoir storage capacity is a metric of historical and present water resources development. The volume of water stored in one or multiple reservoirs reflects recent and past water use, water management practices, reservoir evaporation, interactions between surface and groundwater, and various aspects of weather and hydrology including rainfall and watershed evapotranspiration. The historical reservoir storage plots presented in this final section of Chapter 3 and Appendix A provide insights regarding water resources development throughout Texas over the past eighty years. The great differences in water availability and water supply capabilities found at different locations across Texas are illustrated. Observed reservoir storage plots are also explored in the investigation of river system hydrology in Chapter 4. Observed storage levels in Chapters 3 and 4 and Appendix A can be compared with WRAP/WAM simulated storage volumes presented in Chapters 7 through 12 and Appendix C.

### TWDB Reservoir Storage Database

Water conditions data compilations maintained by TWDB staff and accessible through a TWDB website include historical daily storage volumes as well as an array of other water-related information (https://www.twdb.texas.gov/surfacewater/conditions/index.asp). The daily historical storage database includes 122 reservoirs that contain 96 percent of the conservation storage capacity of the 188 major water supply reservoirs with storage capacities of at least 5,000 acre-feet located partially or completely in Texas. Elephant Butte Reservoir in New Mexico is also included due to its role in supplying water to Texas under the Rio Grande Compact. Addicks and Barker Dams in Houston and Natural Dam near the city of Big Spring, included in the database, serve only flood control with no conservation storage. The data include historical observations of the volume of water in each reservoir in each day from initial impoundment of water to the present. The reservoir storage database also includes storage capacities and other information.

TWDB obtains reservoir storage level observations from partner organizations that include the USGS, USACE, IBWC, USBR, and river authorities. Measurements of water surface elevations by these agencies are automatically transmitted to the TWDB in near real-time via the internet. Multiple observations during each day are combined to obtain averages for the day. The automated TWDB database system uses the latest updated storage volume versus water surface elevation relationships to convert observed water surface elevations to storage volumes. These relationships are occasionally updated by field surveys of sediment accumulation.

The following variables are included in the TWDB reservoir storage database: (1) average total storage contents during each day, (2) daily active conservation storage contents belonging to Texas, and (3) active conservation storage capacity belonging to Texas. All three variables are volumes in units of acre-feet. The daily total reservoir storage content is the actual observed total volume of water stored in a reservoir on a particular day, regardless of ownership. Associated volumes that include only water in active conservation storage committed to water users in Texas are computed and also recorded in the database. For reservoirs shared by Texas with Mexico or neighboring states, these active conservation storage values include only the Texas share of the conservation capacity and contents of that capacity. Inactive conservation storage for hydropower head or below the lowest outlet inverts is also omitted from the conservation storage amounts.

Plots of historical reservoir storage quantities from the TWDB database are included in Chapters 3 and 4 as insightful information for an enhanced understanding of hydrologic conditions, water availability, and water management capabilities throughout Texas. The database of historical observed storage volumes of 122 reservoirs is also useful in computations converting observed flows to naturalized flows in the WAM hydrology updates discussed in Chapter 5.

The daily storage plots in Chapters 3 and 4 and Appendix A were prepared by the author by downloading the data from the TWDB website in csv (comma-separated values) format, employing *HEC-DSSVue* to import the csv data into a DSS (data storage system) file, and preparing plots with *HEC-DSSVue*. All time series graphs throughout this report were plotted by the author with *HEC-DSSVue*.

<u>Summation of Historical Storage in 122 Large Reservoirs</u>

The storage volume plots in Figure 3.3 are summations for 122 reservoirs located totally or partially in Texas representing 96 percent of the Texas active conservation storage capacity of the major water supply reservoirs of the state. The following quantities are plotted in Figure 3.3.

1. Total observed daily storage contents (solid blue line in graphs of Figure 3.3 and Appendix A).

2. The portion of the observed daily storage contents that is contained in active conservation pools controlled by water managers for use by water users in Texas (red dashed line).
3. The active conservation storage capacity controlled by water managers for use by water users in Texas (black dotted line).

Several of the 122 reservoirs in the TWDB database are operated to supply water users in neighboring states and Mexico as well as Texas. The summations of conservation storage volumes for the 122 reservoirs are adjusted to reflect only active conservation capacity and contents belonging to Texas.

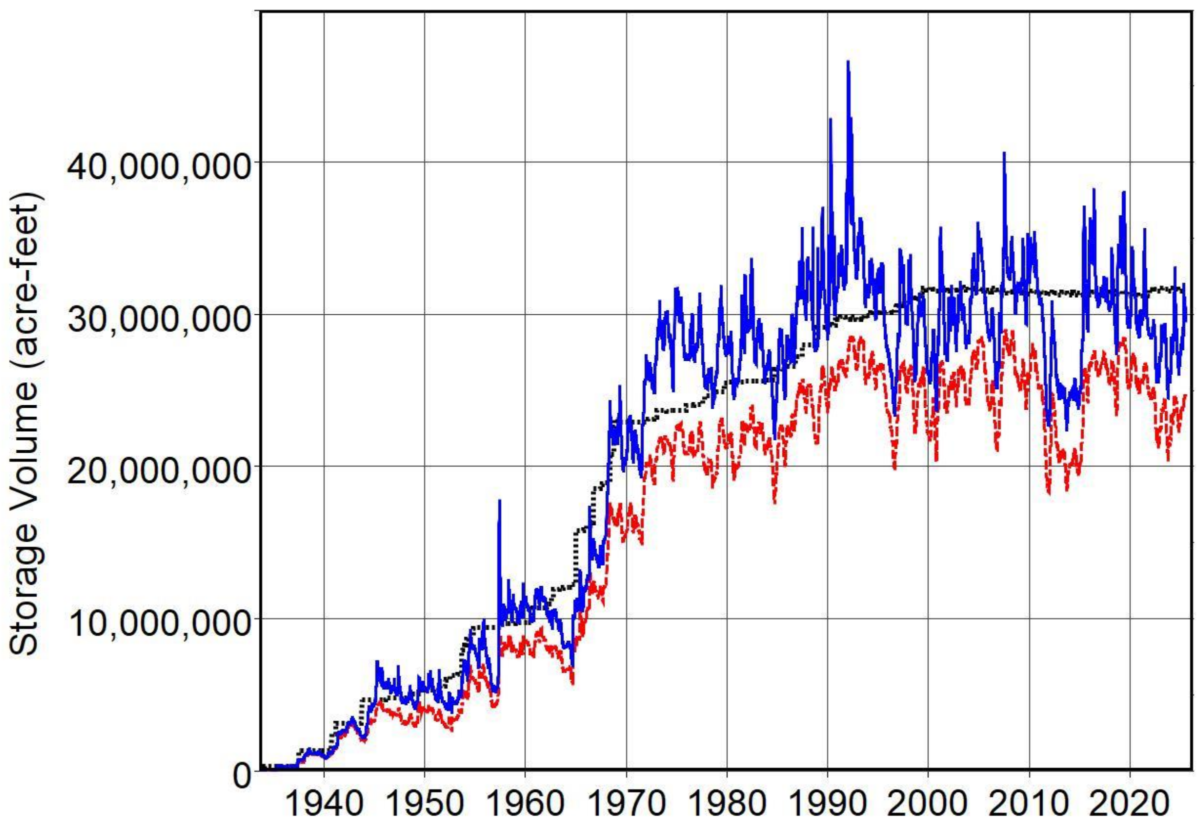


Figure 3.3 Total Contents (solid blue line), Active Conservation Contents (red dashes), and Active Conservation Storage Capacity (black dots) of 122 Reservoirs

The July 1, 1933 through July 1, 2025 time series plots in Figure 3.3 reflect storage in reservoirs that existed in July 2025, but the reservoir projects were constructed at different times and had different periods of initial filling. The majority were constructed during the 1960's-1980's. The 1940's-1980's nationwide construction era of water resources development is apparent in the reservoir storage capacity plot. The best sites for constructing reservoir projects were developed early. Economic feasibility (benefits exceeding costs), financial feasibility (funding availability), and environmental impacts of constructing additional new projects became more constraining over time. Population and economic growth resulted in continually increasing demands for the services provided by reservoir projects but also increased the economic and environmental costs of committing additional land and other resources to developing new projects [19].

Reservoir Storage Plots in Appendix A

The plots of historical daily total storage contents, active Texas conservation capacity, and active Texas conservation storage contents in Appendix A are the same variables plotted in the same format as Figure 3.3. Storage summations for the twenty-eight, twenty-four, eight, and nineteen reservoirs in the TWDB database located in the Brazos, Trinity, Neches, and Colorado River Basins are plotted in Figures A1 through A4. The TWDB data includes one reservoir (Lake Texana) and two reservoirs (Lakes Corpus Christi and Choke Canyon) in the Lavaca and Nueces Basins. Storage plots for Lake Texana and Lakes Corpus Christi and Choke Canyon are presented in Figures A5 and A6. WAMs for these six river basins are discussed in Chapters 6 through 12.

Storage contents of individual major reservoirs generally tend to fluctuate more than the summation of storage contents in all major reservoirs in a river basin or other aggregations of multiple reservoirs. Historical storage contents for each of twelve individual reservoirs are plotted in Figures A7 through A16, A18, and A20. Eleven of these twelve reservoirs are included in the 28 largest reservoirs in Texas described in Tables 3.6 and 3.7 and Figure 3.2.

The storage plots illustrate the great diversity in hydrology and water management spanning across Texas. Storage drawdown and fluctuation characteristics vary greatly between the extremes of West and East Texas. International Amistad and Falcon Reservoirs on the Rio Grande (Figures A7 and A8) have experienced two periods of dramatic storage drawdowns over the past thirty years with each drawdown spanning more than a decade. Storage levels are at or near record lows during 2023-2024. Storage levels in Lakes Texoma (A18) and Toledo Bend (A20) have been near or above top of conservation continuously since initial impoundment several decades ago.

Amistad, Falcon, Texoma, and Toledo Bend Reservoirs on the Rio Grande, Red River, and Sabine River are on state borders with conservation storage capacity allocated between Texas and Mexico, Oklahoma, and Louisiana. The active conservation storage capacity and contents in Figures A7, A8, A18, and A20 include only the storage volume allocated to Texas. The total storage plots for Amistad, Falcon, and Texoma include flood control pools and inactive hydropower pools as well as the storage contents of active conservation pools.

Changes in conservation storage capacity over time reflect updated sediment accumulation measurements and reallocations between flood control and conservation pools. Of all the plots in Appendix A, sediment losses are most noticeable for Possum Kingdom Reservoir (Figure A12).

The volume of water in reservoir storage is an index of drought and hydrologic conditions as well as a basic measure of water availability. However, the number of reservoirs and associated storage capacities and water demands have grown dramatically over time. Water use and reservoir storage capacity during the 1950-1957 drought were much less than during the 2011-2014 drought. Much of the water development and growth in water needs occurred since the 1950-1957 drought. Metrics generated with the WRAP/WAM computer modeling system for a defined stationary condition of water resources development and use, combined with historical natural hydrology, are adopted in water resources planning and management to assess water availability rather than metrics from actual past observations. The WRAP/WAM modeling strategy deals with the issue of water development and use growing historically over time. A defined constant scenario of water development and use is combined with computed reasonably statistically stationary hydrology.

# CHAPTER 4
# RIVER SYSTEM HYDROLOGY

Hydrologic conditions in Texas vary greatly both spatially and temporally. Spatial hydroclimatic differences ranging from arid and semiarid western regions of the state to water-abundant East Texas are dramatic. Flows in rivers throughout the state are highly variable over time with continuous, storm event, seasonal, and multiple-year fluctuations reflecting extremes of droughts and floods along with more frequent but less severe fluctuations. Stream flow variability is driven by variability in rainfall and evaporation. Hydrologic variability and associated water supply reliability, flood risk, and future uncertainty are fundamental to water management. Large volumes of reservoir storage are essential for developing water supplies with acceptable levels of reliability and partially controlling flood flows to reduce economic damages and protect public safety.

Characteristics of precipitation, reservoir evaporation rates, stream flow, and reservoir storage contents are explored in Chapter 4 with a focus on variability and stationarity. Stationarity refers to long-term homogeneity over time without permanent changes or trends. Stationarity or departures therefrom (non-stationarity) and variability of river system hydrology play governing roles in water management and WRAP/WAM modeling of water management. Interactions between surface water and groundwater briefly introduced in a latter section of this chapter are important statewide but much more prevalent in certain regions of the state than others. Water availability depends on water quality as well as quantity. Natural salinity contamination of surface water prevalent in certain regions of Texas is also discussed briefly later in Chapter 4.

## Precipitation and Reservoir Evaporation

Precipitation and evaporation are the climatic drivers governing water availability. Precipitation in Texas is mainly rainfall. Snow and sleet occur infrequently [53]. The majority of the precipitation falling on land is returned to the atmosphere through transpiration from vegetation and evaporation from water surfaces. Evaporation in this chapter refers to evaporation from reservoir surfaces. However, reservoir evaporation rates also approximate evapotranspiration rates from watersheds under very wet ground conditions. Evaporation from reservoir water surfaces is a major component of reservoir water budgets, representing a large volume comparable to volumes of water withdrawn from reservoirs for municipal, industrial, and agricultural water supply.

Statewide 1940-2024 mean annual precipitation and 1954-2024 mean annual reservoir evaporation rates are 28.09 inches and 59.76 inches, respectively, determined employing the Texas Water Development Board (TWDB) database discussed below. Bomar [53] cites a 1900-1999 statewide mean annual precipitation of 27.92 inches determined by the National Weather Service (NWS). The small difference between the NWS 1900-1999 mean of 27.92 inches and the 1940-2024 mean of 28.09 inches based on the data compilation and analysis methods adopted here can be attributed primarily to different periods-of-analysis and spatial averaging strategies.

### TWDB Precipitation and Reservoir Evaporation Database

TWDB maintains annually updated datasets of monthly precipitation rates and monthly reservoir surface evaporation rates for ninety-two one-degree latitude by one-degree longitude quadrangles comprising a grid that encompasses the state. The data are accessed through the following TWDB website: https://waterdatafortexas.org/lake-evaporation-rainfall. Precipitation data date back to January 1940. The reservoir evaporation database begins in January 1954. The monthly quantities for each quadrangle are depths in units of inches each month. Methods employed by TWDB staff in compiling the datasets are explained at the website. A 1975 TWDB report [52] describes the early history of compiling evaporation data. TWDB has continued and is currently still continuing to further expand reservoir evaporation data compilation capabilities.

The 92 quadrangles are delineated in Figure 4.1 with each grid cell representing a quadrangle with an identifying integer label assigned by TWDB. Land areas encompassed by each one-degree quadrangle range between 3,856 and 4,324 square miles. The 254 counties of Texas delineated without names in Figure 4.1 are labeled in Figure 3.1 of the *Hydrology Manual* [4].

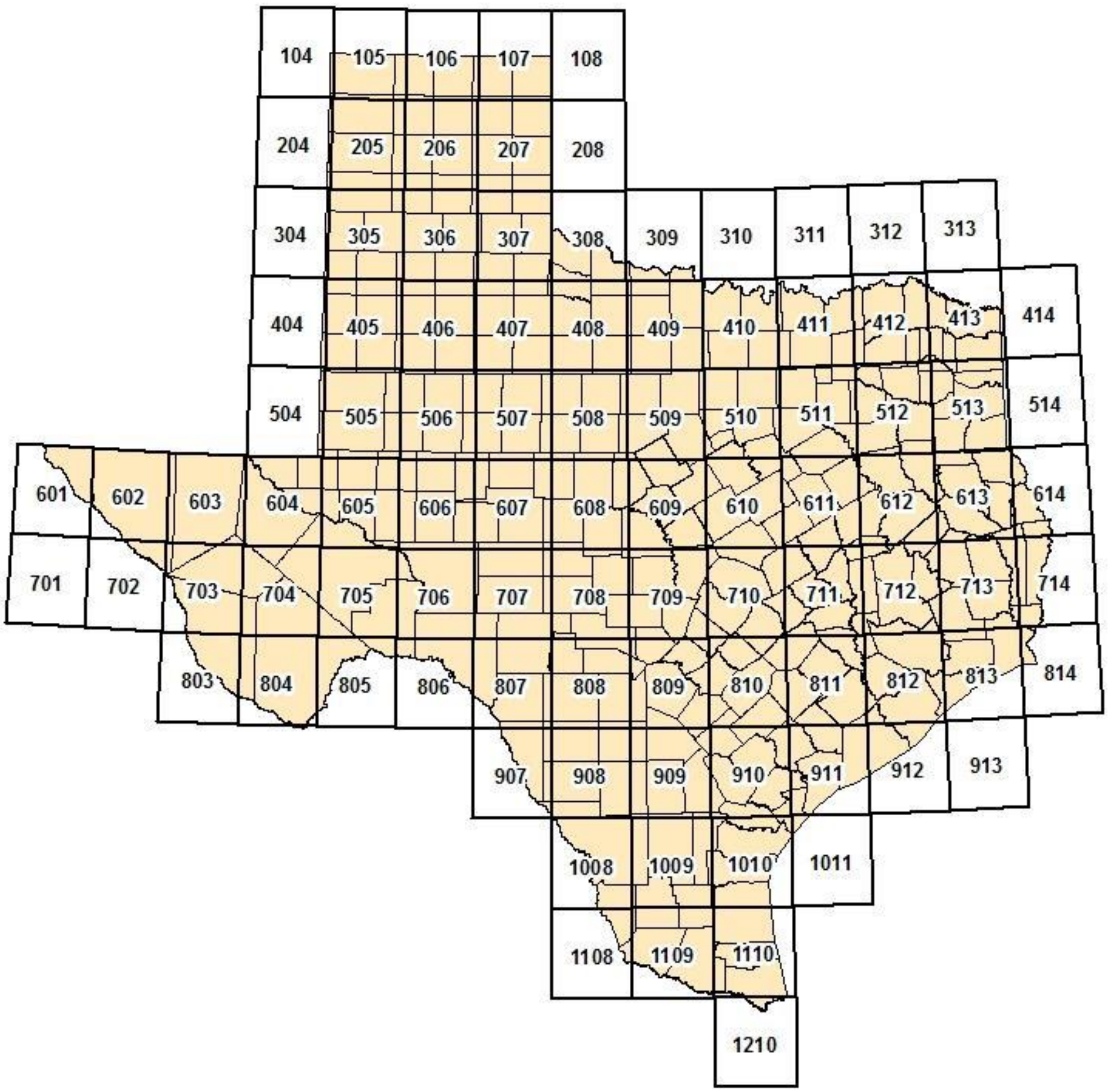


Figure 4.1
Quadrangles for TWDB Monthly Precipitation and Reservoir Evaporation Database

The WRAP modeling system includes features incorporated in the program *HYD* described in the *Hydrology Manual* [4] for organizing, managing, manipulating, analyzing, and displaying data from the TWDB monthly precipitation and reservoir evaporation database. The statewide averages presented in this chapter are computed within *HYD* as area-weighted means of the quadrangle quantities [4]. Statistical tabulations in this chapter are compiled with a combination of analysis options in the WRAP program *HYD* and Hydrologic Engineering Center *HEC-DSSVue*. All time series plots presented throughout this report were prepared with *HEC-DSSVue*, as described in the WRAP *Users* and *Hydrology Manuals* [2, 4] and *HEC-DSSVue* online manual.

The monthly 1940-2024 precipitation and 1954-2024 reservoir evaporation depths in inches for the 92 quadrangles were downloaded from the online TWDB database in csv format and reorganized as a DSS file using the *HydSeries* subprogram component of the WRAP program *HYD* [4]. *HydSeries* options explained in Chapters 2 and 3 of the *Hydrology Manual* [4] were used to convert monthly series to various annual time series, compute statewide average series, and perform linear regression and other analyses of the monthly and annual time series datasets.

Annual Precipitation and Evaporation

The statewide-average annual precipitation and reservoir evaporation depths are plotted in Figure 4.2 and tabulated in Table 4.1. Statewide-average 1940-2024 mean precipitation and 1954-2024 mean reservoir evaporation depths are 28.09 and 59.76 inches/year, respectively.

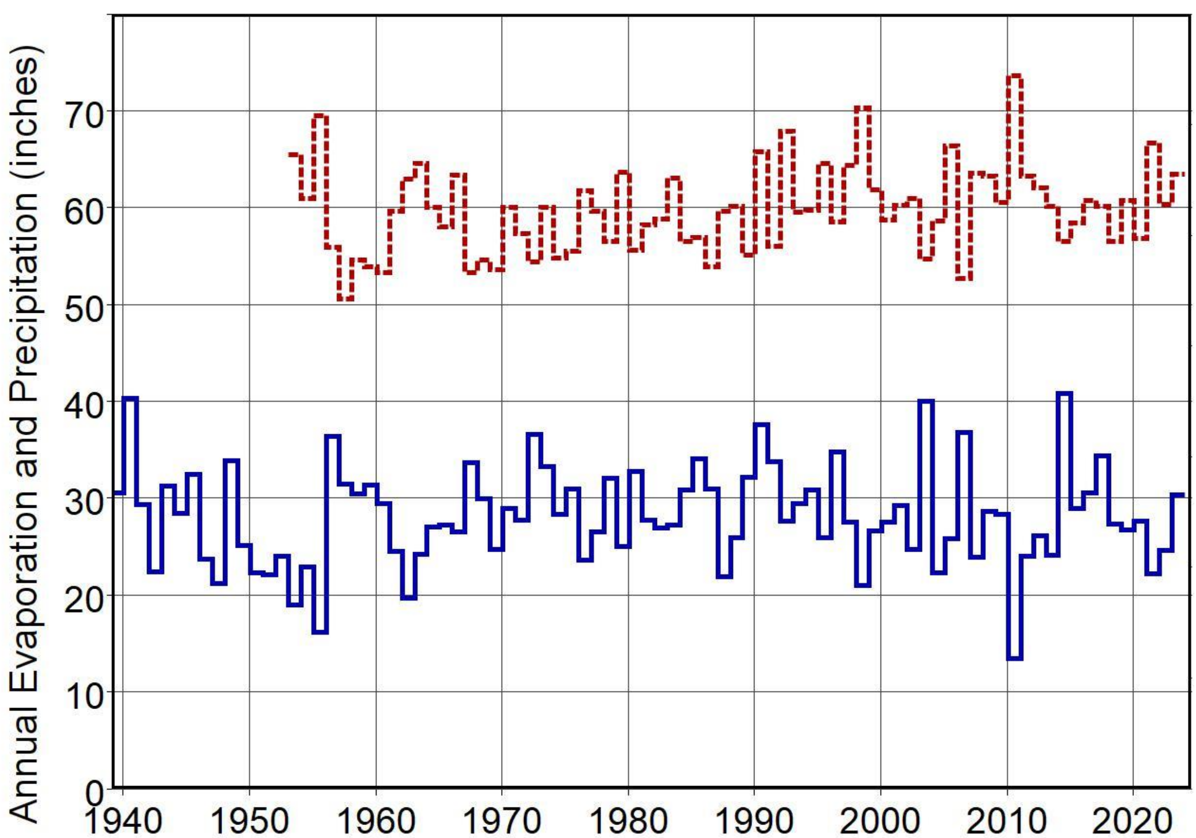


Figure 4.2 Statewide-Average 1940-2024 Mean Annual Precipitation (blue solid line) and 1954-2024 Mean Annual Reservoir Evaporation (red dashed line)

## Table 4.1
## Statewide Average Annual Precipitation and Reservoir Evaporation (inches/year)

| Year | Precip | Evap | Year | Precip | Evap | Year | Precip | Evap | Year | Precip | Evap |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1940 | 30.56 | | 1962 | 24.47 | 59.62 | 1983 | 26.88 | 58.86 | 2004 | 39.96 | 54.72 |
| 1941 | 40.25 | | 1963 | 19.70 | 62.96 | 1984 | 27.25 | 63.03 | 2005 | 22.33 | 58.57 |
| 1942 | 29.37 | | 1964 | 24.24 | 64.54 | 1985 | 30.86 | 56.45 | 2006 | 25.78 | 66.40 |
| 1943 | 22.38 | | 1965 | 27.02 | 60.04 | 1986 | 34.11 | 56.90 | 2007 | 36.77 | 52.65 |
| 1944 | 31.28 | | 1966 | 27.27 | 58.04 | 1987 | 30.91 | 53.84 | 2008 | 23.87 | 63.53 |
| 1945 | 28.38 | | 1967 | 26.47 | 63.37 | 1988 | 21.86 | 59.64 | 2009 | 28.61 | 63.26 |
| 1946 | 32.50 | | 1968 | 33.68 | 53.29 | 1989 | 25.96 | 60.10 | 2010 | 28.29 | 60.57 |
| 1947 | 23.70 | | 1969 | 29.91 | 54.58 | 1990 | 32.16 | 55.14 | 2011 | 13.41 | 73.65 |
| 1948 | 21.15 | | 1970 | 24.68 | 53.59 | 1991 | 37.57 | 65.71 | 2012 | 24.01 | 63.22 |
| 1949 | 33.82 | | 1971 | 28.97 | 60.00 | 1992 | 33.73 | 55.98 | 2013 | 26.08 | 62.03 |
| 1950 | 25.10 | | 1972 | 27.70 | 57.26 | 1993 | 27.62 | 67.89 | 2014 | 24.15 | 60.09 |
| 1951 | 22.25 | | 1973 | 36.58 | 54.34 | 1994 | 29.43 | 59.50 | 2015 | 40.76 | 56.53 |
| 1952 | 22.11 | | 1974 | 33.21 | 60.01 | 1995 | 30.80 | 59.69 | 2016 | 28.94 | 58.45 |
| 1953 | 24.00 | | 1975 | 28.36 | 54.80 | 1996 | 25.90 | 64.59 | 2017 | 30.58 | 60.72 |
| 1954 | 19.00 | 65.50 | 1976 | 30.95 | 55.50 | 1997 | 34.78 | 58.55 | 2018 | 34.37 | 60.14 |
| 1955 | 22.86 | 60.97 | 1977 | 23.65 | 61.78 | 1998 | 27.53 | 64.38 | 2019 | 27.31 | 56.46 |
| 1956 | 16.14 | 69.52 | 1978 | 26.47 | 59.64 | 1999 | 21.02 | 70.29 | 2020 | 26.67 | 60.75 |
| 1957 | 36.37 | 55.88 | 1979 | 32.01 | 56.51 | 2000 | 26.60 | 61.84 | 2021 | 27.58 | 56.84 |
| 1958 | 31.43 | 50.56 | 1980 | 24.97 | 63.66 | 2001 | 27.49 | 58.72 | 2022 | 22.19 | 66.69 |
| 1959 | 30.39 | 54.63 | 1981 | 32.74 | 55.56 | 2002 | 29.22 | 60.25 | 2023 | 24.60 | 60.35 |
| 1960 | 31.36 | 53.89 | 1982 | 27.70 | 58.17 | 2003 | 24.71 | 60.95 | 2024 | 30.32 | 63.41 |
| 1961 | 29.38 | 53.25 | | | | | | | Mean | 28.09 | 59.76 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | | | | 16.7<br>60.7 | 17.6<br>67.7 | 18.7<br>67.6 | 21.0<br>65.3 | 24.1<br>60.3 | | | | | | | 100 |
| 200 | | | | 16.5<br>63.7 | 18.2<br>66.6 | 20.2<br>66.9 | 23.8<br>64.8 | 27.5<br>59.4 | | | | | | | 200 |
| 300 | | | | 16.6<br>63.3 | 18.1<br>63.9 | 20.5<br>66.0 | 22.1<br>66.1 | 25.8<br>64.3 | 30.8<br>58.9 | | | | | | 300 |
| 400 | | | | 15.8<br>62.7 | 17.9<br>65.2 | 22.5<br>68.2 | 22.9<br>70.4 | 25.4<br>64.7 | 29.8<br>60.9 | 34.8<br>55.2 | 41.0<br>53.1 | 46.5<br>52.4 | 49.4<br>43.5 | 51.6<br>39.7 | 400 |
| 500 | | | | 15.2<br>68.2 | 16.8<br>71.9 | 20.4<br>71.2 | 22.6<br>66.4 | 26.4<br>63.4 | 30.2<br>59.4 | 33.9<br>56.9 | 39.0<br>56.6 | 43.9<br>54.8 | 47.9<br>49.0 | 51.0<br>45.5 | 500 |
| 600 | 10.7<br>69.7 | 14.0<br>70.3 | 14.3<br>64.9 | 11.4<br>67.4 | 13.2<br>71.4 | 17.9<br>69.6 | 21.3<br>66.4 | 24.7<br>66.6 | 28.9<br>56.5 | 33.1<br>56.1 | 38.6<br>59.4 | 44.5<br>52.8 | 49.6<br>47.2 | 53.8<br>48.6 | 600 |
| 700 | 9.15<br>69.9 | 15.2<br>62.0 | 13.6<br>55.6 | 14.7<br>57.8 | 13.6<br>63.4 | 18.6<br>64.4 | 22.3<br>62.8 | 25.2<br>57.4 | 30.1<br>53.7 | 33.1<br>51.7 | 39.9<br>54.0 | 46.7<br>50.2 | 54.8<br>45.3 | 57.2<br>46.5 | 700 |
| 800 | | | 19.4<br>55.9 | 14.3<br>55.7 | 11.6<br>66.6 | 16.7<br>70.3 | 24.2<br>68.5 | 26.4<br>56.7 | 31.0<br>53.5 | 34.3<br>52.5 | 41.6<br>49.9 | 47.6<br>47.1 | 49.4<br>45.8 | 57.4<br>45.7 | 800 |
| 900 | | | | | | | 20.5<br>68.7 | 21.8<br>60.0 | 25.3<br>57.6 | 34.7<br>52.6 | 39.7<br>50.2 | 44.6<br>48.5 | | | 900 |
| 1000 | | | | | | | | 20.3<br>64.4 | 23.8<br>62.9 | 29.4<br>58.9 | 34.7<br>54.4 | | | | 1000 |
| 1100 | | | | | | | | 17.9<br>63.7 | 21.8<br>60.4 | 26.0<br>61.2 | | | | | 1100 |
| 1200 | | | | | | | | | | 26.5<br>60.1 | | | | | 1200 |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | |

Figure 4.3 Quadrangle 1940-2024 Mean Annual Precipitation in inches (top number) and 1954-2024 Mean Annual Reservoir Evaporation in inches (bottom number)

The quantity in the top of each quadrangle (grid cell) in Figure 4.3 is the 1940-2024 mean annual precipitation depth in inches for that quadrangle. The bottom number is the 1954-2024 mean annual reservoir evaporation rate in inches. Quantities are provided for 92 quadrangles. TWDB quadrangle (grid cell) labels consisting of integers between 101 and 1214 are shown both in Figure 4.1 and along the vertical-plus-horizonal edges of Figure 4.3.

Annual, Monthly, and Seasonal Precipitation and Reservoir Evaporation Rates

Statewide average 1940-2024 annual and monthly precipitation depths are plotted in Figures 4.4 and 4.5. Quadrangles 604 and 713 in West and East Texas, respectively, are the driest and wettest quadrangles located entirely within Texas and have mean annual precipitation depths of 11.4 and 54.8 inches (Figure 4.3). Monthly precipitation depths for these quadrangles are plotted in Figures 4.6 and 4.7. Monthly precipitation in quad 604 varies from zero in many months to a maximum of 8.77 inches in September 1974, with a mean of 0.95 inch. Monthly precipitation in quad 713 varies from almost zero in multiple months to a maximum of 34.6 inches in August 2017 dominated by Hurricane Harvey. The 1940-2024 monthly mean for quad 713 is 4.56 inches/month.

The 1954–2024 annual reservoir evaporation depths and 1940-2024 annual precipitation depths are compared in Figures 4.2 and 4.3 and Table 4.1. Reservoir evaporation rates significantly exceed precipitation throughout most of Texas. The differences are dramatic in West Texas. Statewide averages of monthly evaporation depths are plotted in Figure 4.8. Evaporation rates are higher in western than eastern regions of Texas. However, the variations in evaporation rates from west to east are much less pronounced than the spatial variations in precipitation (Figure 4.3).

Seasonality characteristics are illustrated by the monthly time series plots of Figures 4.5-4.8 and by Tables 4.2 and 4.3. Rainfall is somewhat seasonal though it’s timing also reflects significant year-to-year fluctuations. Reservoir evaporation rates have a very distinct seasonal pattern within each year with smaller fluctuations in annual depths from year-to-year than precipitation. The distinct seasonal pattern of monthly reservoir evaporation depths is evident in Figure 4.8 and further defined in Tables 4.2 and 4.3.

Statewide average 1940-2024 mean monthly precipitation for each of the twelve months of the year are tabulated in Table 4.2 along with annual means. Statewide average 1954-2024 mean monthly and annual evaporation in inches and as a percentage of the precipitation for each of the twelve months of the year are also included in Table 4.2. The mean annual precipitation was 28.09 inches during 1940-2024. Adopting the same 1954-2024 analysis period for a consistent comparison, the 1954-2024 mean annual evaporation of 59.76 inches is 212 percent of the 1954-2024 mean annual precipitation of 28.18 inches.

Table 4.3 shows the number of years during 1940-2024 that the minimum and maximum monthly precipitation depth occurred in each of the twelve months of the year. The likelihood of high rainfall is highest in May, and the driest season of the year tends to be November through February. The maximum precipitation occurred in May during 25 of the 85 years. Table 4.3 also shows the number of years during 1954-2024 that the minimum and maximum monthly reservoir evaporation occurred in each of the twelve months. The maximum evaporation rates occurred during either June, July, or August during all 71 years of the 1954-2024 analysis period. The minimum evaporation was in January in 36 years and December in 28 of the years of 1954-2024.

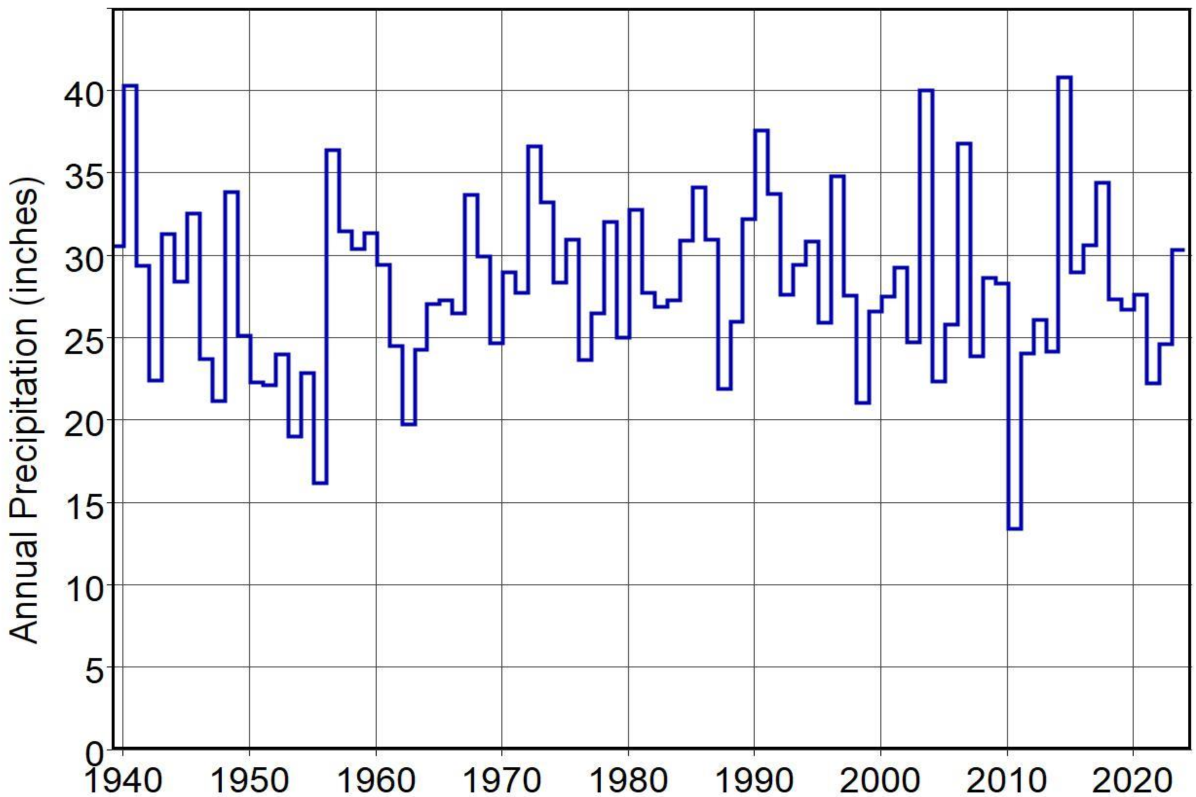


Figure 4.4 Statewide-Average Annual Precipitation Depths (inches/year) during 1940-2024

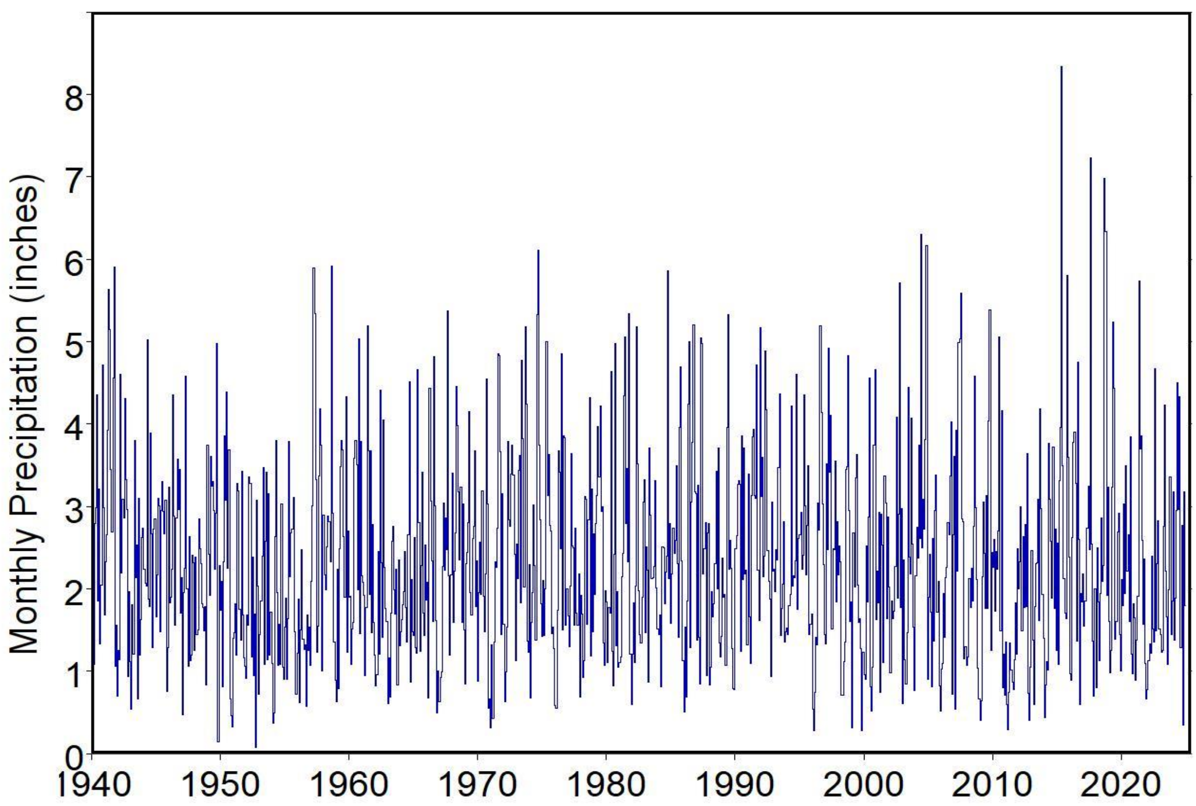


Figure 4.5 Statewide-Average Monthly Precipitation Depths (inches/month) during 1940-2024

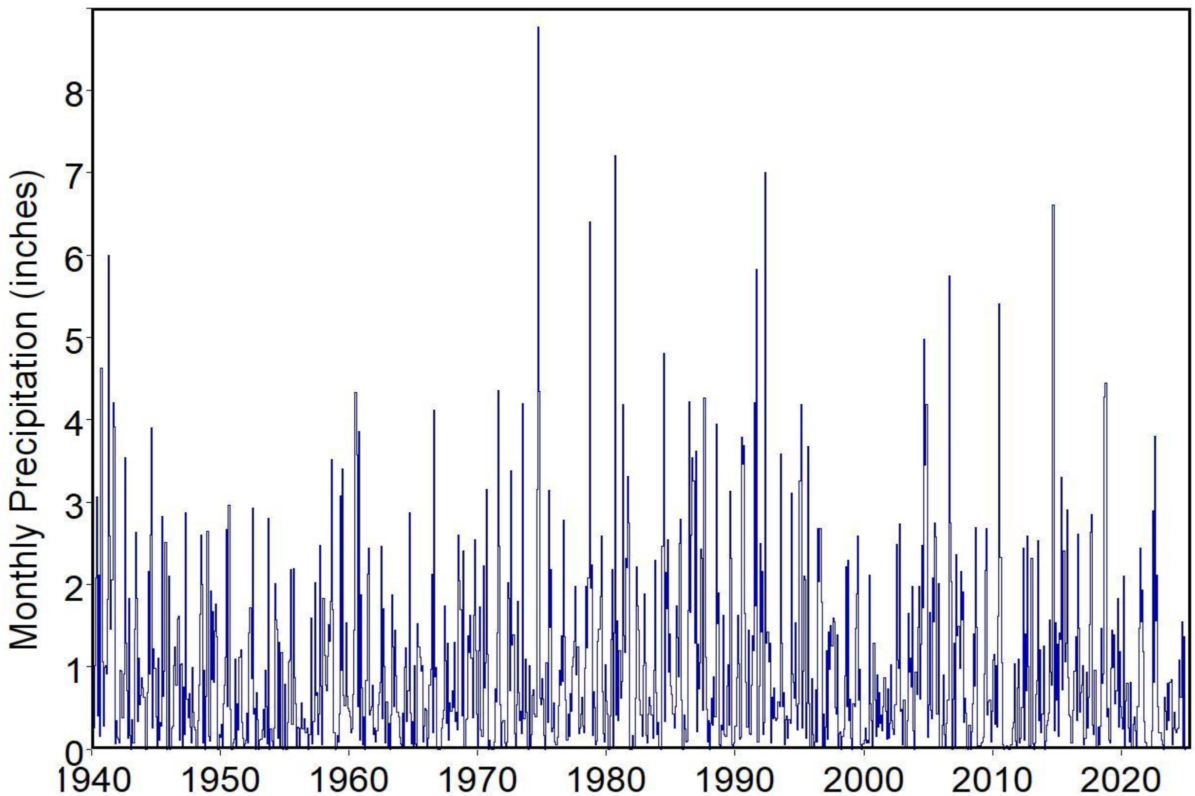

Figure 4.6 Monthly Precipitation for Quadrangle 604 with Annual Mean of 11.5 inches

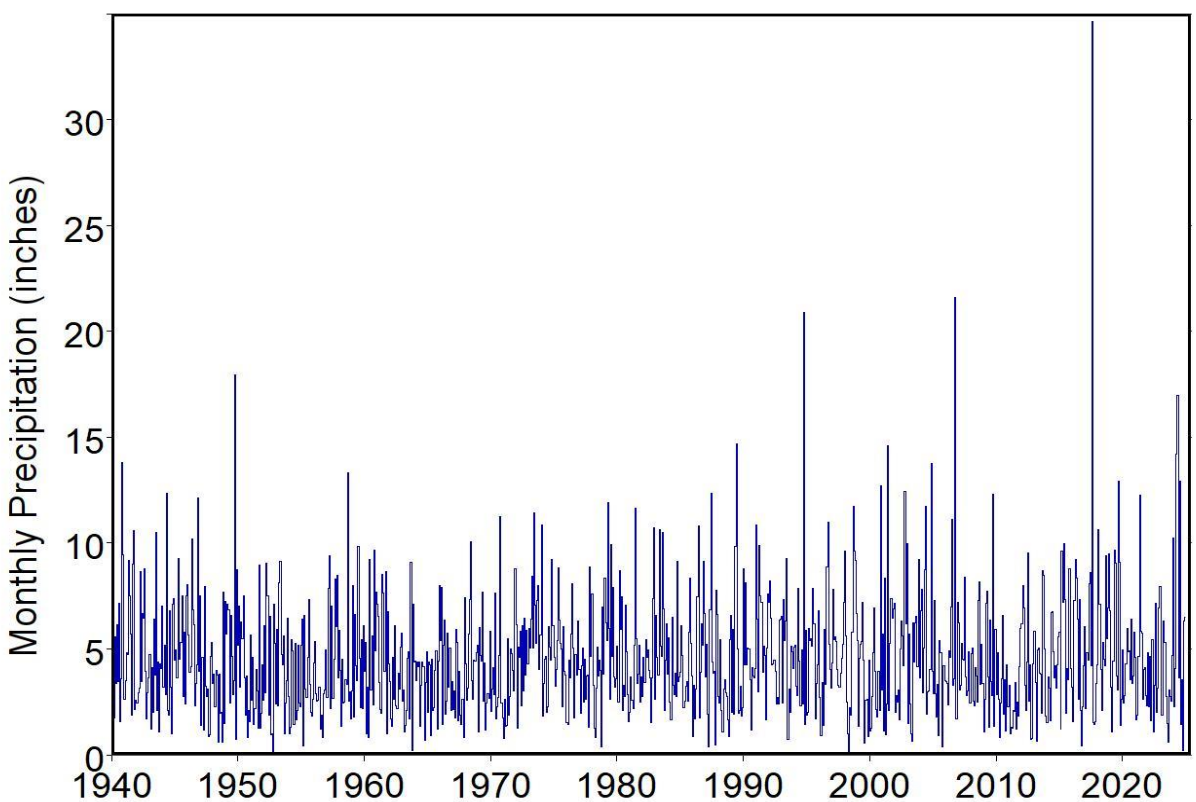

Figure 4.7 Monthly Precipitation for Quadrangle 713 with Annual Mean of 54.8 inches

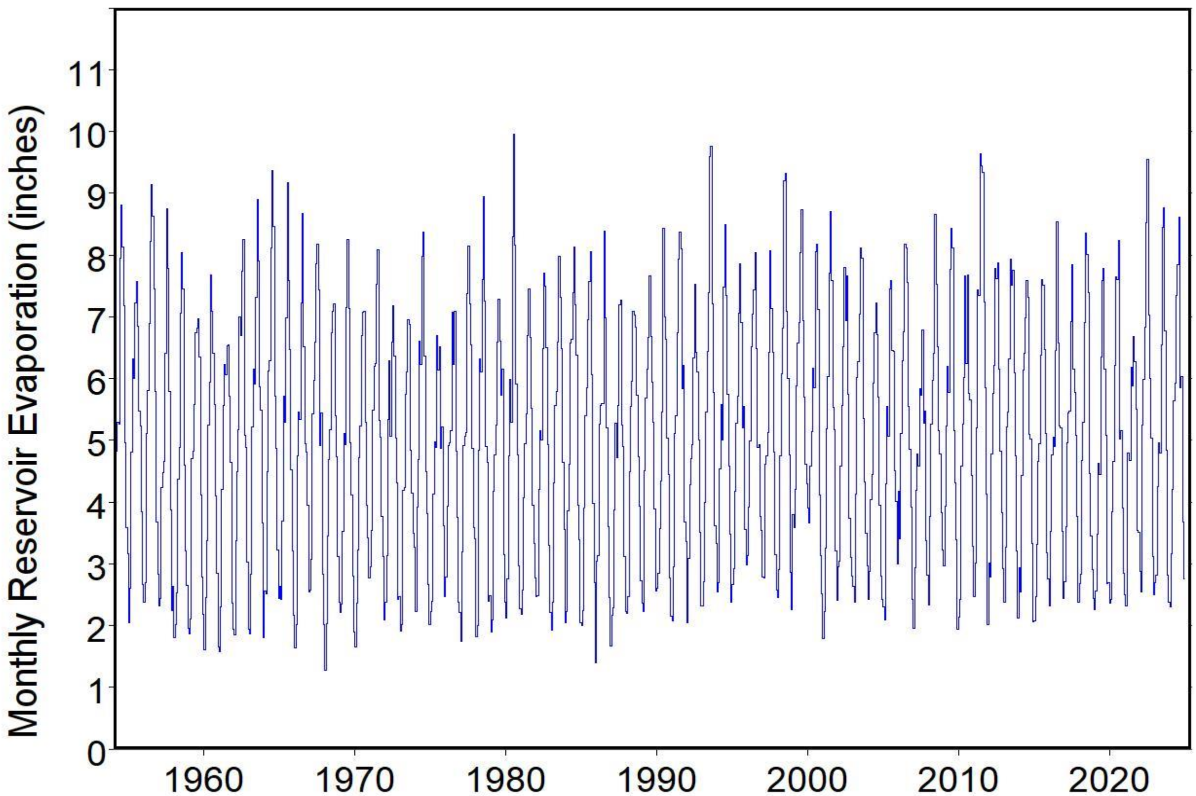


Figure 4.8 Statewide-Average Monthly Reservoir Evaporation Depths during 1954-2024

Table 4.2
Monthly (Seasonal) Variations in
Statewide Average Precipitation and Evaporation

| Month | Precipitation 1940-2024 (inches) | Precipitation 1954-2024 (inches) | Evaporation 1954-2024 (inches) | Evaporation 1954-2024 (% Precip) |
|---|---|---|---|---|
| Jan | 1.63 | 1.62 | 2.39 | 147% |
| Feb | 1.67 | 1.66 | 2.80 | 169% |
| Mar | 1.81 | 1.81 | 4.43 | 245% |
| Apr | 2.28 | 2.22 | 5.43 | 245% |
| May | 3.44 | 3.40 | 5.74 | 169% |
| June | 3.01 | 3.06 | 7.18 | 235% |
| Jul | 2.33 | 2.33 | 7.93 | 340% |
| Aug | 2.46 | 2.47 | 7.43 | 301% |
| Sep | 3.09 | 3.18 | 5.77 | 181% |
| Oct | 2.72 | 2.78 | 4.79 | 172% |
| Nov | 1.90 | 1.91 | 3.32 | 173% |
| Dec | 1.74 | 1.73 | 2.53 | 146% |
| Annual | 28.09 | 28.18 | 59.76 | 212% |

Table 4.3
Number of Years During Which Minimum and Maximum
Monthly Quantities for the Year Occurred in Each of the Twelve Months

| Month | Precipitation | | Evaporation | |
|---|---|---|---|---|
| | Minimum (years) | Maximum (years) | Minimum (years) | Maximum (years) |
| Jan | 17 | 0 | 36 | 0 |
| Feb | 12 | 0 | 6 | 0 |
| Mar | 6 | 0 | 0 | 0 |
| Apr | 6 | 5 | 0 | 0 |
| May | 1 | 25 | 0 | 0 |
| June | 1 | 8 | 0 | 9 |
| Jul | 2 | 7 | 0 | 43 |
| Aug | 2 | 9 | 0 | 19 |
| Sep | 1 | 14 | 0 | 0 |
| Oct | 7 | 13 | 0 | 0 |
| Nov | 13 | 2 | 1 | 0 |
| Dec | 17 | 2 | 28 | 0 |
| Total | 85 | 85 | 71 | 71 |

Linear Regression of Annual Precipitation and Evaporation Quantities

An array of optional variations of different types of statistics can be developed for variations of any monthly time series dataset are annual series derived therefrom using the subprogram *HydSeries* of the WRAP program *HYD*. The Hydrologic Engineering Center (HEC) program *HEC-DSSVue* provides a flexible array of computational analysis options as well as graphical capabilities for time series with any time interval and length. Means and least-squares linear regression metrics for annual precipitation depths and annual reservoir evaporation depths computed with *HYD* are tabulated in Chapter 3 of the *Hydrology Manual* [4] in the format produced by program *HYD*. These metrics were computed with standard statistical analysis methods using *HydSeries* options described in Chapter 2 of the *Hydrology Manual* [4]. Regression statistics for each of the 92 individual quadrangles along with the same statistics for statewide precipitation and evaporation reflecting area-weighted averages for all 92 quadrangles are tabulated in Chapter 3 of the *Hydrology Manual*. The tables also include simple averages of quantities for the 92 quadrangles as well as statewide averages computed as area-weighted means.

Conventional linear regression is described briefly in the *Hydrology Manual* [4] and in detail in many statistics and numerical methods textbooks. Regression computations are based on minimizing the summation of the squares of deviations from a linear trend line. A horizontal trend line with slope of zero and intercept equal to the mean indicates no trend or long-term change. A positive slope suggests an increase in precipitation, evaporation, stream flow, or any other time series variable being analyzed. A negative regression slope indicates a decreasing trend or change in the variable over time. Time series plots and regression analyses are descriptive of stationarity and departures from stationarity.

Regression metrics are shown in Table 4.4 for statewide-average annual precipitation (1940-2024) and reservoir evaporation (1954-2024 ) in inches/year. Program *HYD* also generates these same metrics for each of the 92 individual quadrangles along with statewide quantities in a single *HYD* execution. Counts of the number of the 92 quadrangles that have positive and negative linear regression slopes and ranges covered by the two sets of 92 slopes are tabulated in Table 4.5.

Table 4.4
Linear Regression Analysis Results for Statewide Annual Precipitation and Evaporation

| Variable | Mean (inches) | Intercept (inches) | Slope (inches/year) | Intercept (% of mean) | Slope (% of mean) |
|---|---|---|---|---|---|
| annual precipitation | 28.088 | 27.757 | 0.00769798 | 98.821 | 0.00274 |
| annual evaporation | 59.758 | 57.813 | 0.05403973 | 96.744 | 0.09043 |

Table 4.5
Number of Positive and Negative Regression Slopes for 92 Individual Quadrangles

| | Number of slopes that are | | Maximum Negative & Positive | |
|---|---|---|---|---|
| Time Series Variable | Positive | Negative | (inches/year) | (inches/year) |
| annual precipitation | 53 | 39 | -0.05877 | 0.1633 |
| annual evaporation | 61 | 31 | -0.17749 | 0.2660 |

The statewide-average annual precipitation has an increasing 1940-2024 trend slope of 0.007698 inch/year or 0.7698 inch per 100 years, which is essentially negligible considering the approximations reflected in linear regression analysis. Likewise, the intercept and mean in Table 4.4 are close to equal. The intercept of 27.76 inches is 98.82 percent of the mean of 28.09 inches. The intercept represents the linear trend line at the beginning of 1940. The intercept and mean would be equal for a perfectly horizontal linear trend line indicating no trend or permanent change. Table 4.5 indicates that trend slopes for the annual precipitation in the 92 individual quadrangles are positive for 53 quadrangles and negative for the other 39 quadrangles. The *Hydrology Manual* [4] includes a tabulation of all the regression parameters for each quadrangle for both annual precipitation and reservoir evaporation. Discussion of these metrics continues later in this chapter.

Statewide-average annual evaporation rates have an increasing 1954-2024 trend slope of 0.05404 inch/year or 5.404 inches per 100 years. The intercept of 57.81 inches is 96.74 percent of the mean of 59.76 inches (Table 4.4). The intercept represents the linear trend line at the beginning of 1954. Computed slopes for individual quadrangles are positive for 61 and negative for the other 31 quadrangles. As discussed later in this chapter, increases in evaporation rates would be consistent with the literature on global warming. Significant though generally non-definitive long-term changes or trends possibly reflected in the 1954-2024 reservoir evaporation dataset are difficult to detect and measure due to continuous monthly, seasonal, and annual variability. Also, the number and location of evaporation pans and pan coefficients used to convert measurements of pan evaporation to estimates of reservoir evaporation varied over time. These and other factors as well as climate change may affect the stationarity of the reservoir evaporation dataset.

Time series plots and statistical metrics provide meaningful insight regarding variability and stationarity characteristics of hydrologic variables. The preceding plots and tables along with those presented later support observations discussed throughout this chapter. Precipitation and evaporation are climatic variables. Thus, departures from stationarity may possibly reflect climate change resulting from global warming or other phenomena.

The length and timing of the analysis period are key considerations in interpreting either graphical time series plots or regression trend analysis metrics. The regression slope may vary greatly with different periods-of-record or analysis periods. For example, means and linear regression slopes for statewide average annual precipitation and reservoir evaporation rates are compared in Table 4.6 for alternative analysis periods. Widespread extreme drought conditions were experienced throughout Texas during 1950-1957, which followed a wetter than normal period in the 1940's and ended with massive widespread flooding in April-May 1957. The years 2022 and 2023 had below normal precipitation statewide followed by widespread higher than normal rainfall during April-May 2024 that resulted in significant flooding. Inclusion or exclusion of 1950-1956, April-May 1957, 2022-2023, or April-May 2024 can significantly affect linear regression trend slopes. All the alternative slopes in Table 4.6 are small. Information provided by regression analysis is insightful but not definitive.

Regression analyses have also been performed for individual quadrangle and statewide monthly depths in inches/month [4]. The mean, intercept, and slope for monthly precipitation are 2.341 and 2.311 inches/month and 0.00005827 inches/month per month. The mean, intercept, and slope for monthly reservoir evaporation are 4.980 and 4.815 inches/month and 0.0003863 inches/month per month. These are metrics are for monthly time series, not annual series.

Table 4.6
Annual Means and Regression Slopes for Different Analysis Periods

| Analysis | Statewide Annual Precipitation | | Statewide Annual Evaporation | |
|---|---|---|---|---|
| Period | Mean | Regression Slope | Mean | Regression Slope |
| | (inches/year) | (inch/year per year) | (inches/year) | (inch/year per year) |
| 1940-2024 | 28.09 | 0.007698 | - | - |
| 1954-2024 | 28.18 | 0.009951 | 59.76 | 0.05404 |
| 1957-2024 | 28.57 | -0.02452 | 59.51 | 0.08402 |
| 1940-2021 | 28.18 | 0.01502 | - | - |
| 1954-2021 | 28.29 | 0.02108 | 59.59 | 0.04649 |
| 1940-1993 | 28.21 | 0.05758 | - | - |
| 1954-1993 | 28.41 | 0.13325 | 58.63 | 0.01423 |
| 1994-2024 | 27.87 | -0.03128 | 61.22 | -0.02898 |

Annual Series of Maximum and Minimum Three-Month Average and One-Month Depths

Figures 4.9 and 4.10 are designed to explore stationarity and variability characteristics of within-year extremely dry or wet conditions. Determination of moving averages and maxima and minima were performed within *HEC-DSSVue* along with developing the statewide annual time series plots. The TWDB monthly precipitation and evaporation datasets for the 92 quadrangles are stored in a file with filename PrecipEvap.DSS. These types of plots for each individual quadrangle are easily prepared and viewed on the computer monitor (or printed) using *HEC-DSSVue*.

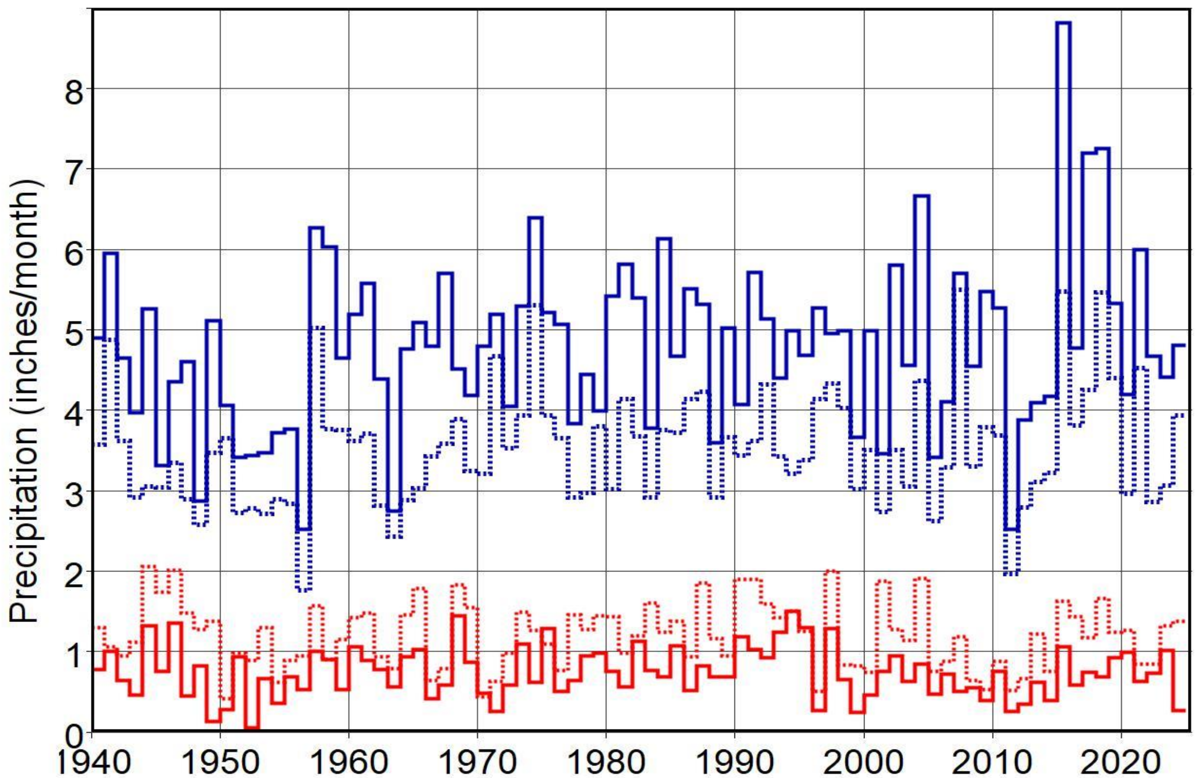


Figure 4.9 Annual Maximum and Minimum Monthly and 3-Month Average Precipitation

Legend for Figures 4.9 and 4.10

| | |
|---|---|
| blue solid line: | maximum monthly depth in each calendar year (inches/month) |
| blue dotted line: | maximum average depth for 3-month moving average (inches/month) |
| red solid line: | minimum monthly depth in each calendar year (inches/month) |
| red dotted line: | minimum average depth for 3-month moving average (inches/month) |

Maximum and minimum precipitation in any month and average precipitation over three consecutive months in each year of 1940-2024 are plotted in Figure 4.9. Likewise, the maximum and minimum evaporation depth in any one-month and average depth over three consecutive months in each year of 1954-2024 are plotted in Figure 4.10. The maxima and minima of one-month and three-month depths are in units of acre-feet per month. The one-month depth is the minimum or maximum for any of the 12 months in each calendar year. The three-month average depth in inches/month is the centered three-month moving average. The three-month centered moving average is assigned to the year of the center month.

The time series plots in Figures 4.9 and 4.10 further demonstrate the great within-year variability for both precipitation and reservoir evaporation rates. The one-month and three-month maxima are much higher than the corresponding one-month and three-month minima. Year-to-year variability of annual maxima and minima is greater for precipitation than evaporation but also significant for evaporation. Variability of the annual time series of monthly minima and maxima is less than the variability of precipitation and reservoir evaporation rates for all months.

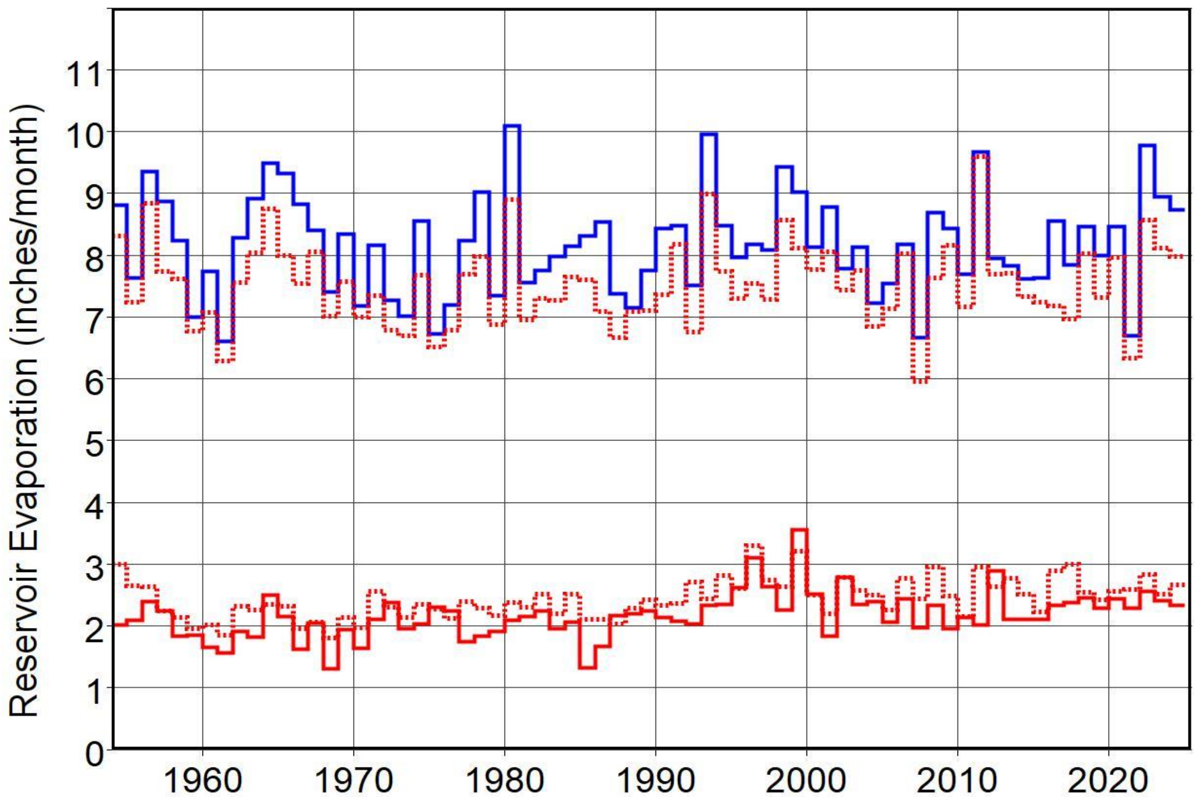


Figure 4.10 Annual Series of Maximum and Minimum Monthly Evaporation
and Three-Month Moving Average of Evaporation

Legend for Figures 4.9 and 4.10

| | |
|---|---|
| blue solid line: | maximum monthly depth in each calendar year (inches/month) |
| blue dotted line: | maximum average depth for 3-month moving average (inches/month) |
| red solid line: | minimum monthly depth in each calendar year (inches/month) |
| red dotted line: | minimum average depth for 3-month moving average (inches/month) |

The one-month and three-month precipitation minima appear essentially stationary in Figure 4.9. Three-month precipitation maxima also appear stationary. However, the four largest monthly precipitation depths since 1940 occur in 2015 (8.3 inches), 2017 (7.2 inches), 2018 (7.1 inches), and 2004 (6.3 inches), which may imply an increase in intense rainfall events associated with major floods. A shorter time period such as daily, hourly, or smaller would be required for detailed analysis of the characteristics of intense rainfall events associated with major floods.

The statewide-average annual evaporation depths plotted in the previous Figure 4.2 appear essentially stationary during about 1990-2024 and 1954-1989 but a little higher during 1990-2024 than during 1954-1989. The one-month and three-month evaporation minima in Figure 4.10 peak in 1999 after generally increasing from 1990 to 1999. The evaporation minima appear stationary since 2000 but higher than during the likewise stationary period of 1941-1989. The annual series of one-month and three-month maxima of statewide-average reservoir evaporation rates in Figure 4.10 appear essentially stationary without long-term trends.

## Hydrologic Variability and Stationarity

Variability and stationarity (or non-stationarity) of precipitation, reservoir evaporation, river flows, and reservoir storage contents are fundamental to river/reservoir system water management and water availability modeling. Several relevant general considerations regarding variability and stationarity are noted in the following paragraphs prior to further discussing variability and stationarity aspects of precipitation, evaporation, stream flow, and reservoir storage.

### General Observations

Temporal and spatial variability are decreased by averaging over larger time intervals or spatial areas. This chapter focuses on precipitation and evaporation depths in inches and stream flow rates in cubic feet per second (cfs). These variables may fluctuate from instant to instant. This continuous variability is dampened by averaging or summing quantities over a fixed time period. Monthly precipitation and evaporation depths fluctuate with time much more than annual totals. Likewise, average precipitation and evaporation depths over a 4,000 square mile quadrangle (Figure 4.1) fluctuate over time more than these same quantities averaged over the entire state of Texas. The daily stream flow rates discussed later in this chapter are quantities averaged across a stream cross-section area at a gage site and averaged over a day. Instantaneous flow rates vary more than daily averages at the same location which vary more than monthly or annual averages.

Stationarity refers to long-term homogeneity over time with no permanent changes or trends. Insights regarding stationarity as well as variability are provided by time series plots of precipitation, evaporation, observed river flows, naturalized river flows, and reservoir storage contents. Naturalized flows at WAM primary control points are comprised of observed flows adjusted to remove the effects of water development and other human activities. Reservoir storage contents may be either actual observed storage or WRAP/WAM simulated storage.

Least-squares linear regression provides a simple analysis tool to complement graphical visual analysis of time series datasets in assessing stationarity or lack thereof. Linearity of the trend line is a major simplifying approximation that reduces the validity of linear regression in detecting or measuring long-term changes. However, though reflecting computational simplifications, linear regression trend analysis provides useful general insight regarding stationarity or non-stationarity.

Subprogram *HydSeries* of the WRAP program *HYD* generates regression parameters and other statistics for any time series dataset [4]. Linear regression has been commonly applied in the past with various software to analyze naturalized stream flows incorporated in WAM datasets to evaluate stationarity or departures therefrom. Linear regression metrics computed with the WRAP program *HYD* for precipitation and evaporation are presented earlier in this chapter. Regression can be applied to monthly or annual quantities or any other time step. Annual series may consist of the minimum or maximum monthly or other sub-period quantity in each year.

As discussed earlier in this chapter, the length and timing of the period-of-analysis is a key consideration in interpreting either graphical time series plots or regression trend analysis metrics. Trend slopes may vary greatly with different periods-of-record or analysis periods. Characteristics of trends or long-term changes for a particular time series variable may also vary significantly with computational time interval, such as annual, monthly, daily, or hourly.

Long-Term Stationarity of Monthly and Annual Precipitation

Any changes in monthly or annual precipitation resulting from global warming or other phenomena are hidden by the great variability to the extent of being undetectable by the analyses discussed in this report. No permanent changes or multiple-decade long trends in precipitation are evident in the 1940-2024 time series plots of monthly and annual depths of Figures 4.4 and 4.5.

The statewide-average annual precipitation has a 1940-2024 linear trend slope of 0.77 inch per 100 years (Table 4.4), which is insignificant relative to the approximations inherent in linear regression. The intercept of 27.76 inches is 99.82 percent of the mean of 28.09 inches, which is also an essentially negligible difference considering the limitations of linear regression. The statewide monthly precipitation has a 1940-2024 trend slope of 0.0698 inch/month per 100 years.

Annual precipitation in 53 quadrangles have positive regression slopes, and annual precipitation in the other 39 quads have small negative slopes (Table 4.5). Most of the quadrangles with decreasing precipitation (negative slopes) are located in the western half of the state.

Referring to Figure 4.5, the four largest monthly precipitation depths since 1940 occur in 2015, 2017, 2018, and 2004. This reflects an increase during 2004-2018 in intense rainfall during major flood events that could perhaps indicate a longer-term trend. However, rainfall data with a time interval much shorter than monthly would be required to explore stationarity and other characteristics of extremely intense rainfall events. Reservoir storage is the main focus of flood control aspects of daily WRAP/WAM modeling applications. Total stream inflow volumes are more relevant than peak rainfall intensities in simulating reservoir operations. Daily or hourly rainfall extremes associated with infrequent flood events have not been investigated in this study.

Long-Term Stationarity of Monthly and Annual Reservoir Evaporation Rates

Increases in evaporation in Texas like elsewhere would be consistent with global warming. Based on the data analyses discussed in this chapter, reservoir evaporation rates appear to have possibly increased. However, any long-term increases in evaporation in Texas during 1954-2024 are obscured by the variability of the evaporation data and thus are difficult to accurately measure. Reservoir evaporation rates are based on pan measurements. Stationarity could be affected by changes in pan coefficient estimates and the number of pans employed in compilation of the TWDB database that have occurred over 1954-2024 as well as changes in climate variables.

Statewide annual evaporation rates plotted in Figure 4.2 appear to be stationary during 1954-1989, increasing in 1991-1999, and again stationary though higher during 1990-2024. Linear regression slopes for annual evaporation in Table 4.2 are small, positive (increasing) during 1954-2023 and 1954-1993, and negative (decreasing) during 1994-2024. The annual series of maximum monthly evaporation and three-month moving averages in Figure 4.10 appear stationary. The annual series of minimum monthly and three-month moving average quantities are higher during 2000-2013 than 1960-1999 and increase during 1990-1999, with a peak in 1999. Annual evaporation in 61 quadrangles have positive regression slopes (Table 4.5). Evaporation in the other 31 quads have negative slopes. Most of the quads with increasing evaporation (positive slopes) are located in either the northern panhandle region or southeast Texas. The quadrangles with decreasing evaporation are scattered from extreme West Texas to Northeast and South Texas.

Stream Flow Variability and Stationarity

River flows throughout Texas are extremely variable over time reflecting the extremes of floods and droughts along with great year-to-year fluctuations, seasonality, and continuous variability. Management of the water resources and constructed infrastructure of the river and reservoir systems of Texas is driven by hydrologic variability and associated uncertainty regarding both short-term and long-term future stream flow. Reservoir storage is essential for dealing with droughts and floods and less extreme continuous fluctuations in stream flow. Stationarity is also important in water management and water availability modeling. Non-stationarities may be difficult to detect and measure due to being hidden in extreme variability.

Stationarity of simulation input datasets of naturalized stream flows incorporated in the WAMs is important in water availability modeling [1, 4, 54]. The twenty WAMs listed in Table 5.1 of Chapter 5 include sequences of monthly naturalized stream flows at about 480 gage sites that are combined in the WRAP simulation model with watershed parameters to synthesize naturalized flows at over 14,000 ungaged locations. Naturalized flows incorporated in the WAMs represent flows that would have occurred if people had not developed and used the water resources of the river basins as reflected in the WAM water rights input dataset. These flows approximating natural undeveloped river basin conditions are created by computationally adjusting observed flows to remove the effects of reservoirs, water supply diversions, return flows, and other relevant factors as discussed in Chapter 5. Regression trend analysis and other analyses of naturalized flows in the WAMs have been routinely applied in the development of the datasets to test and assure stationarity. The naturalized flows are essentially stationary at most locations.

Actual observed historical stream flows are significantly different than natural flows under hypothetical undeveloped conditions for many river reaches in Texas. Conversely, the differences between natural and actual flows are negligible in many other river reaches. Storage and water use associated with major reservoirs account for most of the differences between natural condition and actual condition flows on major rivers of Texas. Major rivers with large watersheds are different in this regard than streams in smaller urban watersheds where urban land use changes dominate changes in stream flow characteristics.

Permanent changes (departures from stationarity) in river flow characteristics have resulted primarily from changes in water use accompanying population growth and construction of dams, reservoirs, conveyance facilities, and other infrastructure for storing, transporting, and using water. The impacts are significant, diverse, and vary with location. The impacts of water development and use on low flows are very different than on high flows. Regulation of rivers by dams reduces flood flows but may increase low flows at downstream locations. Changes in median flows are different than changes in average flows. The effects of a dam and associated water supply diversions on flows just below the dam or diversion site are much less evident further downstream.

## Observed Historical River Flows

Stream flow data recorded in the National Water Information System (NWIS) maintained by US Geological Survey (USGS, https://waterdata.usgs.gov/nwis) at the sixteen gage sites in Table 4.7 are adopted here to explore characteristics of flows of major rivers in Texas. The locations of these stream gage stations are shown on the map of Figure 4.11

Table 4.7
Selected Stream Flow Gage Stations

| Map ID | Location River and Nearest City | Beginning of Record | Watershed Area (square miles) Total | Watershed Area (square miles) Contrib. | Mean Flow (cfs) | Appendix B Figure | Appendix B Page |
|---|---|---|---|---|---|---|---|
| BW | Brazos River at Waco | 1/1900 | 29,559 | 19,993 | 2,356 | B1 | 320 |
| BR | Brazos River at Richmond | 10/1922 | 45,107 | 35,541 | 7,535 | B2 | 321 |
| NE | Navasota River at Easterly | 3/1924 | 968 | same | 428 | B3 | 322 |
| TD | Trinity River at Dallas | 10/1903 | 6,106 | same | 1,833 | B4 | 323 |
| TO | Trinity River near Oakwood | 10/1923 | 12,833 | same | 5,461 | B5 | 324 |
| TR | Trinity River at Romayor | 5/1924 | 17,186 | same | 8,076 | B6 | 325 |
| NR | Neches River near Rockland | 7/1904 | 3,636 | same | 2,398 | B7 | 326 |
| NE | Neches River near Evadale | 4/1921 | 7,951 | same | 6,266 | B8 | 327 |
| CS | Colorado River nr San Saba | 11/1915 | 31,217 | 19,819 | 939 | B9 | 328 |
| CB | Colorado River at Austin | 3/1898 | 39,009 | 27,606 | 2,038 | B10 | 329 |
| CC | Colorado River at Columbus | 5/1916 | 41,640 | 30,237 | 2,922 | B11 | 330 |
| LH | Lavaca River at Hallettsville | 8/1939 | 108 | same | 49.2 | B12 | 331 |
| LE | Lavaca River near Edna | 8/1939 | 817 | same | 362 | B13 | 332 |
| FD | Frio River, Derby | 8/1915 | 1,462 | same | 134 | B14 | 333 |
| NT | Nueces River, Three Rivers | 7/1915 | 15,427 | same | 708 | B15 | 334 |
| NM | Nueces River, Mathis | 8/1939 | 16,600 | same | 634 | B16 | 335 |

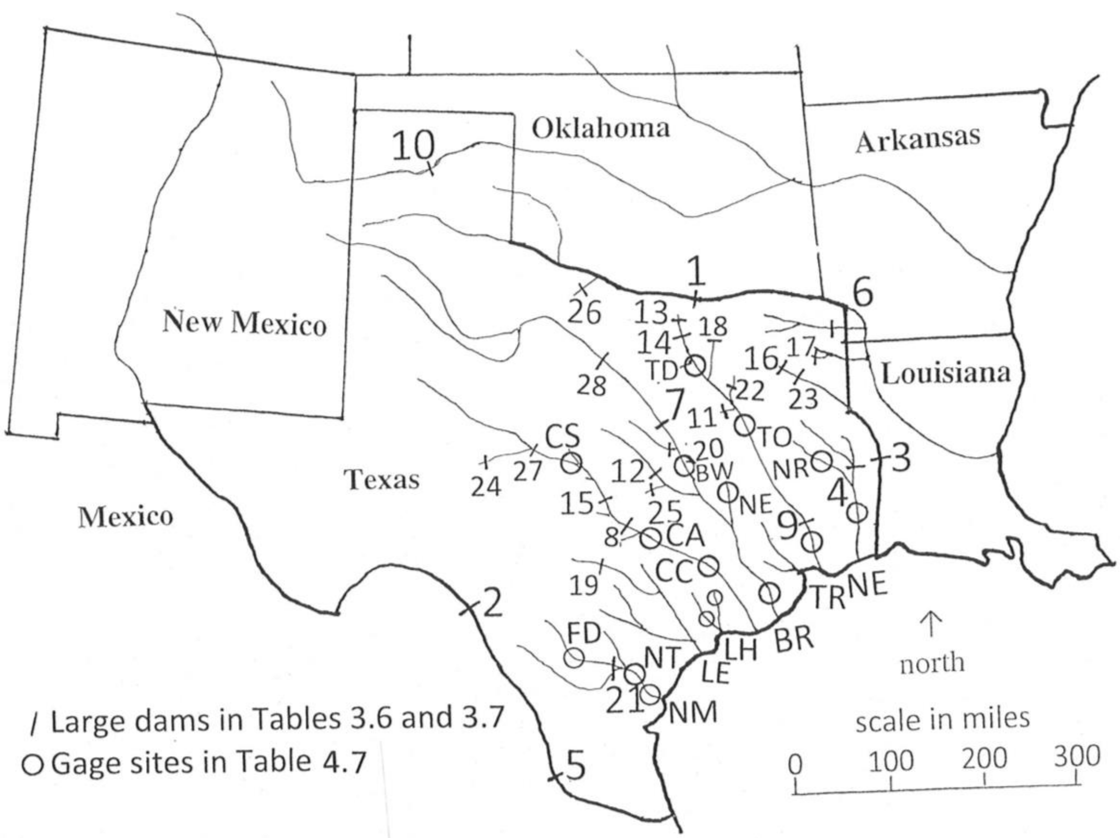


Figure 4.11 Sites of Stream Flow Gages and Large Dams

The map of Figure 4.11 is identical to Figure 3.2 except for the addition of the stream flow gage sites listed in Table 4.7. The gage site letter identifiers on the map of Figure 4.11 reference the first column of Table 4.7. The numbers labeling dam sites on the map reference the first column of Tables 3.6 and 3.7. Period-of-record daily and monthly means in cubic feet per second (cfs) of flows at each gage site are plotted in Appendix B. Figure labels and page numbers in Appendix B are listed in the last two columns of Table 4.7.

Daily flows were downloaded from the NWIS ( https://waterdata.usgs.gov/nwis) into a DSS file using *HEC-DSSVue*. As of August 2025, the NWIS includes 1,156 gages in Texas with historical daily data. The daily mean flows in cfs were aggregated to monthly and annual means in cfs and plotted with *HEC-DSSVue* to develop the figures in Appendix B. These selected USGS gages on major rivers have long periods-of-record. The beginning date of the period-of-record for each gage is tabulated in the third column of Table 4.7. The flow data extending through February 8, 2024 were downloaded on February 9, 2024. The mean flow for the period-of-record through February 8, 2024 is tabulated in the sixth column of Table 4.7. Additional information about the dataset is found in Appendix B. Additional analyses of period-of-record stream flows through June 2025 at selected USGS gage sites are found in Chapter 4 of the *Hydrology Manual* [4].

The total and contributing watershed areas are tabulated in the fourth and fifth columns of Table 4.7. The NWIS includes both the total watershed area above a gage site and the portion of this watershed area that actually contributes to stream flow. Portions of the river basins in dry flat West Texas and New Mexico contribute essentially no runoff to stream flow. The contributing area may be less than the total area of the river basin. Numerous small playa lakes found in the Texas High Plains are located within the non-contributing areas of the watersheds. Playa lakes are shallow hollows in the ground in the Southern High Plains of the United States that may contain water following rainfall events and may serve as wetlands. Water collected in the playa lakes during rainfall events evaporates and seeps into the ground without contributing runoff to streams.

With the exception of a dry riverbed with no flow, flow rates tend to fluctuate continually. Daily flow rates published by the USGS in the NWIS are averages over the day. Variability is dissipated with averaging over a larger time interval. Daily means are less variable than instantaneous rates. Computing monthly means in cfs as the average of daily means in cfs further averages-out variations. Daily, monthly, and annual flows throughout Texas exhibit extreme variability. Stationarity of flow rates or departures from stationarity vary with the time period over which the flow is averaged or summed as well as between locations.

All precipitation, reservoir evaporation, and stream flow data investigated in Chapter 4 is stored in DSS files managed using *HEC-DSSVue*. All the time series plots presented in this report were prepared by the author using *HEC-DSSVue*. The stream flow data discussed here were downloaded from the NWIS using *HEC-DSSVue*. Likewise, arithmetic operations were performed with *HEC-DSSVue*. Data files compiled in conjunction with this report, including the DSS files of datasets discussed in this chapter, are introduced in the last section of Chapter 1.

The 16 gage sites listed in Table 4.7 are in the six river basins with daily WAMs discussed in Chapters 7-12. Stream flows at these 16 gage sites in these six river systems are representative of flows of major rivers throughout most of Texas. However, river flow characteristics in several other river basins are noted as follows before discussing flows at these selected gage locations.

Diverse Flow Characteristics of the Rivers on the Texas Borders

River systems around the perimeter of Texas illustrate the extreme diversity of hydrologic conditions and water management spanning Texas. Lake Texoma impounded by Denison Dam on the Red River, International Amistad and Falcon Reservoirs on the Rio Grande, and Toledo Bend Reservoir on the Sabine River are the largest, second and fifth largest, and third largest reservoirs located partially or totally in Texas (Tables 3.6 and 3.7). Lake Meredith on the Canadian River, the tenth largest, is located totally within Texas but near state borders. Meredith is the most northern large reservoir in Texas. Appendix A consists of historical storage plots from the TWDB reservoir storage database discussed in Chapter 3 for these and other reservoirs. Texas is bounded on the southeast by the coastal basins and Gulf of Mexico.

The IBWC rather than the USGS maintains stream flow gages on the Rio Grande. However, the storage plots for International Amistad and Falcon Reservoirs in Appendix A are from the TWDB reservoir database. These plots show severe multiple-year reservoir draw-downs.

Dramatic decreases in flow of the Rio Grande following IBWC construction of Amistad and Falcon Reservoirs and continuing thereafter illustrate the impacts of irrigated agriculture and large reservoirs in a dry climate [19]. The flow of the Rio Grande into the Gulf of Mexico has been minimal over the last several decades compared to the early 1900's. The Lower Rio Grande Valley is the dominant region of Texas for irrigated agriculture supplied by surface water. The productive agricultural economy in this dry region relies upon water pumped from the Rio Grande.

The Canadian River is another extreme case of flows decreasing dramatically due largely to development of irrigated agriculture. However, whereas agricultural production from surface water irrigation is concentrated in the Lower Rio Grande Valley, agriculture in the High Plains of Texas and neighboring states relies almost completely on groundwater. Depleting groundwater reserves have driven a shift to surface water supplies statewide. However, surface water is not a viable alternative for supplying increases in water demands in the Canadian River Basin of Texas.

The upper watersheds of the Red, Brazos, and Colorado River Basins also extend into dry West Texas. Non-contributing areas of these river basins are in their upper watersheds in West Texas and New Mexico. The Red, Brazos, and Colorado River Basins have large watersheds extending across Texas. Significant volumes of flow enter the rivers in Central and East Texas.

The Red River below Denison Dam forming the border of Texas with Oklahoma and Arkansas and the Sabine River below Toledo Bend Dam on the border between Texas and Louisiana illustrate the other extreme of high flows with relatively high stationarity. Historical storage plots for these projects are included in Appendix A and discussed in Chapter 3. The flows of the Red River immediately below Denison Dam are comprised primarily of hydropower releases from Lake Texoma and spills when the conservation pool is full and overflowing. The USACE Tulsa District flood control operations of Lake Texoma are based on making no releases that would contribute to downstream flood damages. Toledo Bend Reservoir on the Sabine River is a nonfederal reservoir constructed by the Sabine River Authorities of Texas and Louisiana with no designated flood control pool. The reservoir is operated by the two river authorities primarily for water supply while mitigating downstream flooding to the extent possible. Hydropower and recreation are also major purposes served by Toledo Bend Reservoir as well as Lake Texoma [19].

Brazos River Basin

Observed daily mean and monthly mean flows at the gage site on the Brazos River at Waco in Figures 4.11 and 8.1 are plotted in Figure B1 of Appendix B. Flows at this gage are adopted for *HydSeries* examples in the *Hydrology Manual* [4]. This USGS gage is at Highway 340 just downstream of the City of Waco and about five miles downstream of the Bosque River confluence. The Corps of Engineers makes no releases from upstream flood control reservoirs that would contribute to flows of the Brazos River gage at Waco exceeding a non-damaging flow of 25,000 cfs. The USACE Fort Worth District uses this gage along with other gages in operating the flood control pools of the Lakes Waco, Aquilla, and Whitney located upstream of this site. The USACE system includes six other reservoirs on tributaries that enter the Brazos River downstream of the Waco gage. Many other water supply reservoirs are also located upstream of the Waco gage as well as throughout the river basin. The effects of the upstream reservoirs are evident in the daily gaged flows of Figure B1. However, the effects of reservoir flood control operations are dissipated in the process of averaging the daily mean flows to obtain monthly and annual mean flows.

Daily and monthly flows at the gage on the Brazos River at Richmond are plotted in Figure B2. This gage site is near Highway 90 about 60 miles above the Brazos River outlet near the City of Freeport. A maximum allowable non-damaging discharge of 60,000 cfs at the Brazos River gage at Richmond is designated by the USACE FWD for reservoir flood control operations. USACE uses this gage along with other gage sites shown in operating the flood control pools of the system of nine federal multipurpose reservoirs located on the Brazos River and its tributaries. Many nonfederal water supply reservoirs are also located upstream of this gage site.

With the exception of regulation by Limestone Reservoir, flows of the Navasota River at Easterly in Figure B3 reflect a relatively undeveloped watershed. Limestone Reservoir located eleven miles upstream of this gage site is owned and operated by the Brazos River Authority primarily to release water for downstream water supply diversions from the lower Brazos River.

Trinity River Basin

Figure 9.1 of Chapter 9 is a map of the Trinity River Basin. Daily flows of the Trinity River at the cities of Dallas, Oakwood, and Romayor are presented in Appendix B as Figures B4, B5, and B6. The Figure B4 gage is at West Commerce Street just west of downtown Dallas. A maximum allowable non-flooding discharge of 13,000 cfs at this gage site is designated by the Corps of Engineers for purposes of reservoir flood control operations. The USACE Fort Worth District uses this gage along with other gage sites in operating the flood control pools of the federal multipurpose Lakes Benbrook, Joe Pool, Ray Roberts, Lewisville, and Grapevine. A number of nonfederal water supply reservoirs are also located upstream of this site.

The gage on the Trinity River at Oakwood is at Highway 79 about forty miles below Richland Chambers Reservoir. The Romayor gage at FM 787 is twenty miles below Livingston Dam and fifty miles above the river outlet at Galveston Bay. Lake Livingston operated by the Trinity River Authority is the largest reservoir in the Trinity Basin and the ninth largest in Texas.

The Dallas and Fort Worth metropolitan area in the upper Trinity River Basin had a 2020 population of 6.8 million people and has been one of the fastest growing areas in the nation during the past several decades. Many reservoir projects were constructed on the Trinity River and its tributaries during the 1950's-1980's. Houston, another large continually growing city in the adjoining San Jacinto River Basin, transports water by pipeline from Lake Livingston on the lower Trinity River. Low flows in the Trinity River have increased with increases in wastewater treatment plant discharges. High flows have decreased with flood control operations of eight Corps of Engineers reservoirs. Long-term mean flows have deceased with increased water use.

Neches River Basin

Means of flows in each of the 44,053 days, 1,447 months, and 120 years of the July 1, 1903 through February 8, 2024 period-of-record of the USGS gage on the Neches River near Rockland are plotted in Figure B7. This gage is on the Highway 69 bridge twenty miles upstream of the confluence of the Angelina River with the Neches River. The only reservoir with a capacity exceeding 32,000 acre-feet upstream of the Rockland gage on the Neches River is Lake Palestine located in the far upper basin with a storage capacity of 411,300 acre-feet.

Flows of the Neches River at Evadale in Figure B8 were observed at a USGS gage at the Highway 96 bridge twenty-five miles upstream of Interstate Highway 10 in Beaumont. A maximum non-damaging discharge of 20,000 cfs at this gage site is designated by the USACE Fort Worth District for flood control operations of the federal multiple-purpose Sam Rayburn Reservoir located upstream on the Angelina River. The effects of the 3,998,000 acre-feet Sam Rayburn Reservoir with initial impoundment in 1965 are evident in the daily flows of Figure B8. Flood flows are reduced by flood control operations. Low flows are increased by hydroelectric power releases and releases for water supply diversions from the lower Neches River.

The 37,562 daily means of Figure B8 are averaged to 1,247 monthly means, and 103 annual means. The effects of the size of the averaging time interval on observations regarding variability and stationarity are illustrated by comparing these daily versus monthly time series.

Colorado River Basin

Daily flows of the Colorado River at San Saba, Austin, and Columbus are plotted in Figures B9, B10, and B11. The San Saba gage is at Highway 190 about sixty miles upstream of Buchanan Dam. The Columbus gage is at Highway 90 about a hundred miles below Austin and 190 miles above the river outlet at Matagorda Bay south of Bay City.

The 45,328 daily flows during January 1, 1900 through February 8, 2024 plotted in Figure B10 were observed at a USGS gage near downtown Austin a half mile below Highway 183. Flows at this site are regulated by Lakes Buchanan, Inks, LBJ, Marbles Falls, Travis, and Austin on the Colorado River operated by the Lower Colorado River Authority. Other reservoirs on tributaries entering the Colorado River upstream of Austin are operated by other entities. The maximum daily flow during 1900-2023 was 323,000 cfs on June 15, 1935. Impoundment of flows in Lakes Travis and Buchanan began in 1940 and 1937, respectively. The effects of these two large reservoirs on the daily flows of the Colorado River in Austin are shown by Figure B10 to be dramatic. The impacts of the reservoirs on the annual mean flows at this gage site are significant but not dramatic. The dams are storing high flows and maintaining a much more uniform river flow rate than provided by nature.

Lavaca River Basin

The 2,310 square mile Lavaca River Basin encompasses the smallest area of any of the fifteen major river basins of Texas. The Navidad River with a watershed area of 1,420 square miles is the largest tributary of the Lavaca River. Lake Texana on the Navidad River is the only major reservoir in the Lavaca River Basin. The watershed above Lake Texana Dam has an area of 1,410 square miles. The Navidad and Lavaca Rivers confluence downstream of Texana Dam before flowing into Lavaca Bay, which is a secondary bay of the Matagorda Bay system. Daily and monthly flows of the Lavaca River near Hallettsville and Edna are plotted in Figures B12 and B13. The USGS gage site near Edna is ten miles upstream of the Navidad River confluence.

Nueces River Basin

Flows of the Frio River near the City of Derby and the Nueces River near the Cities of Three Rivers and Mathis are plotted in Figures B14, B15, and B16. The USGS gage on the Nueces River near Three Rivers is just below the Frio River confluence downstream of the City of Three Rivers. Choke Canyon Reservoir located on the Frio River upstream of Three Rivers has a storage capacity of 663,000 acre-feet with impoundment beginning in 1982. The USGS gage on the Nueces River near Mathis is about a half mile below Mathis Dam and Lake Corpus Christi.

The hydrology of the basin is complicated by interactions between surface and ground water. The Nueces River and its tributaries cross major aquifer outcrop or recharge zones. The Edwards Aquifer recharge zone accounts for the largest volume of stream flow loss to groundwater. Stream flow recharge of the Carrizo-Wilcox, Bigford, Queen City, Sparta, Gulf Coast, and Goliad Sand groundwater formations is also significant.

Much of the flow of the Nueces River and its tributaries flows into the ground recharging the Edwards Aquifer. The Edwards recharge zone extends across middle reaches of the Nueces River and tributaries that include the Frio River, Sabinal River, and other smaller streams. Flows from these streams flow into the underlying fractured limestone contributing to aquifer recharge.

The Nueces WAM discussed in Chapters 6 and 12 includes 22 control points located at USGS gage sites with drainage areas ranging from 45.0 to 16,600 square miles. The means of observed flows at these 22 gages range from about 15.4 cfs to 707 cfs [12]. Mean annual flow can be expressed as a depth in inches covering the watershed drainage area. The mean annual flow at the 22 gages ranges from a minimum of 0.52 inches/year to maximum of 5.7 inches per. The mean annual precipitation varies a little across the basin but averages about 25 inches [12]. As discussed further in the next section, most of the rainfall runoff does not reach the stream flow gage sites.

Observed Stream Flow as a Percentage of Precipitation

The quantities in Table 4.8 comparing the Nueces River Basin with other locations throughout Texas are from a 2014 Texas Water Resources Institute technical report [51]. Means of observed stream flow at USGS gages with long gage records located near basin outlets are compared with long-term means of precipitation averaged over the river basins. For example, Table 4.8 indicates that the mean observed flow of the Nueces River at Mathis is an estimated 2.3% of the precipitation falling on the basin above this site. This long-term mean observed flow as a percentage of precipitation can be compared with quantities for other locations in Texas ranging from mean flows of 0.97% of precipitation on the Canadian River near the City of Canadian to mean flows of 24.7% of precipitation on the Sabine River near the City of Ruliff.

Table 4.8
Comparison of Precipitation and Observed Stream Flow at Sites Throughout Texas

| USGS Gage Location | Drainage Area | Mean Precip | Mean Flow | Mean Flow |
|---|---|---|---|---|
| | (sq miles) | (inches/yr) | (inches/yr) | (% Precip) |
| Nueces River at Three Rivers | 15,427 | 24.8 | 0.662 | 2.67% |
| Nueces River at Mathis | 16,503 | 24.8 | 0.574 | 2.31% |
| Canadian River near Amarillo | 19,445 | 19.5 | 0.218 | 1.12% |
| Canadian River near Canadian | 22,866 | 19.5 | 0.189 | 0.97% |
| Guadalupe River at Victoria | 5,198 | 32.7 | 5.079 | 15.53% |
| Colorado River near Bay City | 30,837 | 23.5 | 1.085 | 4.62% |
| Brazos River at Richmond | 35,541 | 28.9 | 2.807 | 9.71% |
| Trinity River at Romayor | 17,186 | 39.4 | 6.126 | 15.55% |
| Neches River at Evadale | 7,951 | 48.7 | 10.46 | 21.48% |
| Sabine River near Ruliff | 9,329 | 47.8 | 11.81 | 24.71% |

The metrics in Table 4.8 are necessarily approximate but provide relevant comparisons. Most precipitation falling in a river basin does not reach the basin outlet as runoff. Most precipitation is lost through the hydrologic abstractions of evaporation from water surfaces and land, transpiration from natural vegetation, crops, and urban landscapes, and seepage into the ground. As previously noted, rainfall is much is higher in East Texas than West Texas. Likewise, the portion of the rainfall that reaches watershed outlets is much higher in East than West Texas.

Stream flow as a percentage of precipitation is particularly small in the Nueces River Basin largely because groundwater recharge contributes significantly to reductions in stream flow. Interactions between surface and groundwater are further discussed later in this chapter.

The metrics in Table 4.8 are based on period-of-record observed daily flows at gages with long periods-of-record. However, the general observations of the preceding two paragraphs are generally the same for WAM naturalized or simulated regulated flows.

Naturalized Flows Relative to Observed Flows

WAM naturalized flow is a major topic covered in Chapter 5 and subsequent chapters of this report. The differences between actual observed flows and naturalized flows computed by adjusting observed flows vary significantly with location, computational time interval (monthly versus daily), and high versus low versus median flows.

Long-term means and medians of WAM naturalized flows tend to be about the same or higher than the corresponding metrics of observed flows as a result of flows decreasing historically with population growth and increases in water use. Conversely, flow of the San Antonio River below the City of San Antonio increased significantly over the past eighty years from wastewater effluent accompanying increased groundwater supply from the Edwards Aquifer and increased impervious land cover due to urbanization. Flows of tributaries of the San Jacinto River in the Houston area have similarly increased due to return flows from water use supplied by groundwater and inter-basin import from Lake Livingston on the Trinity River and increased runoff due to urban development. The eight coastal basins between the major river basins drain into the Gulf of Mexico through multiple small streams. In some areas of the coastal basins the actual observed flows measured at gage sites may be generally higher than computed WAM naturalized flows due to return flows from water use supplied by inter-basin transport from the major river basins.

## Droughts and Floods

Droughts and floods are fundamental aspects of Texas climate that govern water management and water availability. Floods may occur at a particular location in Texas concurrently with drought conditions in other regions of the state. Conversely, all or most of the state has experienced severe drought or flood conditions at the same time. Droughts have sometimes been ended by major floods.

The precipitation, evaporation, and stream flow databases explored in this chapter provide insight regarding the characteristics of floods and droughts. The time series plots of WRAP/WAM simulated reservoir storage contents in Chapters 7 through 13 and Appendix C provide meaningful drought indices as well as measures of water availability. The WAMs combine stationary water resources development/management/use information with stationary natural hydrology which allows simulation of drought characteristics over several-decade long hydrologic periods-of-analysis. Observed actual reservoir storage contents during 1994-2024 are employed later in this chapter to further contribute to exploration of droughts and floods in Texas.

### Droughts

A drought is an extended period during which water availability is significantly below normal. Drought is a normal, recurring feature of climate. The beginning and end of a drought and its geographical coverage are typically much more difficult to delineate than for a flood. Droughts may last from several months to several years. Development and operation of large reservoirs in Texas are driven primarily by preparation for severe multiple-year droughts rather the annual cyclic dry season of each year. A drought may be limited to a local region or be statewide, national, or international in extent.

Drought is defined from various perspectives. Meteorological drought refers to a period of below normal precipitation and above normal temperature and evaporation rates. Hydrologic drought refers to below normal stream flow and reservoir storage. Agricultural drought refers to conditions affecting agriculture, such as soil moisture and crop yield. The economic cost of drought is dependent upon economic development as well as meteorological and hydrological drought severity. More recent droughts in Texas were more economically costly than the 1950-1957 drought due to population and economic growth that has occurred since 1957.

The hydrologically most severe drought since before 1900 for much of Texas began gradually in 1950 and ended in April 1957 with one of the largest floods on record. The 2010–2014 drought is comparable in hydrologic severity to the 1950–1957 drought in some areas of the state [55]. For more than half of Texas, 2011 had the lowest annual precipitation since the beginning of official precipitation records in 1895 [56]. Major droughts in the 1910's and 1930's also affected large areas of Texas. The historic Dust Bowl drought of the 1930's centered on western Oklahoma and the northern Texas panhandle region and extended into New Mexico, Colorado, and Kansas.

Floods

Floods may be classified as quick flash floods over smaller areas versus sustained storms over larger areas [53]. Flash floods are caused by intense thunderstorms with massive amounts of rainfall during short periods of time over a concentrated area. Large volumes of rainfall runoff from relatively small watersheds quickly increase flows in streams with little warning or response time. Conversely, larger areal floods are caused by widespread, prolonged rain with slower rising stream stages that cause damages but allow warning time facilitating minimization of loss of life.

Texas's location relative to the Gulf of Mexico results in susceptibility to tropical storms, including hurricanes, and associated flooding [53]. A tropical cyclone is a rapidly rotating storm system characterized by a low-pressure center, fierce winds, and a spiral arrangement of thunderstorms that produce heavy rain. A hurricane is an extraordinarily strong tropical storm. Wind and flood damage caused by these storms is most intense near the Gulf Coast but extends significant distances inland. Hurricanes since 1900 include 1900 and 1915 unnamed hurricanes that damaged Galveston, 1961 Hurricane Carla, 1967 Hurricane Beulah, 1983 Hurricane Alicia, 2005 Hurricane Rita, 2008 Hurricane Ike, and 2017 Hurricane Harvey. With rainfall totals of up to more than forty inches in Southeast Texas, Tropical Storm Imelda in 2019 caused extreme flooding but did not reach the upgraded classification to a hurricane [53].

In terms of loss of human life, the greatest natural disaster in United States history was the hurricane that killed over 7,000 people in Galveston, Texas on September 8, 1900 [57]. The death toll is uncertain, and some estimates significantly exceed 7,000. Following the hurricane, construction of a seawall and placement of fill material made Galveston Island much less susceptible to tidal and rainfall flooding. However, decades of over-pumping of groundwater have caused land subsidence in the Houston and Galveston area. Highways used to evacuate Galveston Island during hurricanes are several feet lower than during the early and even late 1900's and thus more susceptible to inundation.

Hurricane Harvey in late August 2017 was the most economically costly natural disaster in Texas history and the second most costly in US history closely behind if not tied with Hurricane Katrina in late August 2005 [58]. Much of the damage from Katrina was in and near the City of New Orleans, Louisiana. Hurricane Katrina resulted in over 1,800 fatalities. Hurricane Harvey made landfall near Rockport, Texas on August 25, 2017 and caused damage in over forty Texas counties. Rainfall exceeding 60 inches occurred over several days in some areas. Much of the flood damage was in the City of Houston and throughout Harris County and surrounding areas.

## El Nino Southern Oscillation (ENSO) Multiple-Year Weather Cycles

The El Nino-Southern Oscillation (ENSO) is the best-known of the several cyclic weather phenomena resulting from connections between oceanic and weather systems. ENSO cycles of about two to seven years have occurred during at least the last several hundred years. El Nino and

La Nina are the warm and cool phases of the recurring ENSO climate pattern across the tropical Pacific Ocean. An irregular pattern occurs of shifts in ocean surface temperature and disruptions in wind and rainfall patterns across the tropics. The temporary changes in sea surface temperatures and accompanying changes in winds and atmospheric circulation cause temporary changes in weather patterns in various regions of the world. In response to ENSO conditions, particular regions of the planet may experience unusually warm or cold winters. Droughts or torrential rains may be more likely to occur within different phases of the ENSO cycle.

ENSO cycles may affect weather in the various regions of Texas or elsewhere in somewhat predictable ways. Winters and summers tend to be cooler or warmer, hurricanes more or less likely, and rainfall may increase or decrease during the occurrence of various ENSO conditions. However, measuring ENSO conditions or cyclic phases and predicting effects on temperature, precipitation, and weather patterns are not precise and involve significant uncertainties.

Observed metrics descriptive of ENSO or other climatic cycles can potentially enhance forecasts of hydrologic conditions useful in various water management applications. For example, Wei and Watkins [59] related naturalized stream flows from the TCEQ WAM dataset for the Colorado River Basin to various indices to improve probabilistic hydrologic forecasts that potentially could be useful to the Lower Colorado River Authority (LCRA) in operating the Highland Lakes System of Texas during drought. Probabilistic regression analyses were performed to relate WAM naturalized stream flows to autoregressive hydrologic persistence, Pacific Ocean water surface temperature patterns associated with ENSO and the Pacific Decadal Oscillation, and indices for other climatic cycles that could be incorporated into seasonal stream flow forecasts.

The conditional reliability modeling (CRM) features of the WRAP modeling system are designed for forecasting water availability over the next several months conditioned upon preceding reservoir storage contents. Bista [60] used the LCRA reservoir system as a case study to investigate various WRAP/WAM modeling capabilities for supporting drought management including CRM. Incorporation of ENSO indices in WRAP CRM was investigated but found to add little, if any, improvement to forecasting capabilities.

WAM naturalized stream flows are based on adjusted observed flows, which reflect governing weather phenomena including ENSO cycles. Thus, WAM hydrology datasets reflect ENSO cycles. WRAP CRM includes options for weighing likelihoods of multiple short-term hydrology sequences based on preceding reservoir storage. The research noted in the preceding paragraph addressed the possibility of including observed ENSO indexes in the weighing [60].

## Long-Term Climate Change Associated with Global Warming

In addition to daily, seasonal, annual, ENSO, and other cycles, global climate has slowly but continuously changed throughout earth’s history. Scientists have detected warming and cooling cycles spanning thousands of years. Effects of human activity on long-term climate change through increases in concentrations of carbon dioxide and other trace gages, known as the greenhouse effect, has been a major issue of scientific research and political debate over the past several decades [61, 62]. The year 2023 is the hottest year on record globally and the second hottest year in Texas, second only to 2011, since records began in the mid-1800's. Year 2023 was also significantly drier than normal in Texas. Precipitation was significantly more abundant during 2024-2025 than 2023.

Temperature is the variable most directly affected by global warming. Precipitation and evaporation are the climatic variables that most directly affect water availability and water management. Evaporation rates generally increase with increases in temperature. Various aspects of global warning may either increase or decrease precipitation in a particular region or have a negligible or no net effect on precipitation. Effects on precipitation may vary between intense high precipitation events, drought conditions, and periods of average or median precipitation.

Literature on Climate Change

The published literature exploring climate change due to global warming and the effects of humans on climate change is massive. Numerous investigations of global warming and its effects on hydrology, water management, and other aspects of human and environmental well-being have been reported [62]. Several references focused on Texas are cited in the following paragraphs.

Bomar [53] notes that the continuous great fluctuations in Texas weather renders any slow long-term changes in climate attributable to global warming very difficult to detect and measure. Cook et al. [63, 64] and others have predicted that weather will be more variable and droughts likely more severe in the American Southwest and Central Plains, including Texas, in the future due to climate change. Nielsen-Gammon et al. [65] assess future impacts and management strategies associated with droughts in Texas during the latter half of the 21st century that may be more severe than those experienced during the past hundred years or perhaps past multiple hundreds of years.

Computer Modeling of Effects of Climate Change on Hydrology and Water Management

Many researchers throughout the world over the past several decades have employed the general strategy of combining complex computer models simulating global circulation and climate with other complex computer models simulating watershed hydrology and water management to investigate the effects of scenarios of future climate change on hydrology and water management. Two such investigations of rivers and reservoirs in Texas are noted as follows.

The WRAP/WAM modeling system and the Soil and Water Assessment Tool (SWAT) watershed model (https://swat.tamu.edu/) were combined with precipitation and evaporation data from a global circulation model representing selected future climate scenarios to investigate possible impacts of climate change on water supply capabilities of river and reservoir systems in the Brazos and San Jacinto River Basins of Texas [66, 67]. This investigation during 2000-2005 was sponsored by the National Institute for Global Environmental Change of the US Department of Energy. Simulated effects of global warming on hydrology and water availability varied between regions within the two adjacent river basins. Results were inconclusive. All components of the modeling strategy were very approximate, but the global circulation model and associated scenarios of increases in greenhouse gases were considered to reflect much greater uncertainty than the river basin hydrology and water management components.

Shao et al. [68] recently developed an expanded modeling framework combining the WRAP/WAM modeling system and Distributed Soil Vegetation Model for simulating watershed hydrology under predicted future climate using downscaled versions of climatic data generated in the Coupled Model Intercomparison Project Phase 6 global circulation models. Effects on reservoir firm yields of six reservoirs in the upper Trinity River Basin of Texas of future climate change resulting from global warming were statistically assessed. The National Science Foundation, Pacific Northwest National Laboratory, TWRI, and TWDB sponsored this research.. Firm yields were found to generally decrease with global warming due primarily to increases in evaporation. A literature review performed in the research provides a lengthy list of references on modeling techniques for predicting future impacts of global warming on hydrology and water management [68].

Climate Change and Hydrologic Stationarity

Stationarity or lack thereof of river flows and water availability for beneficial use may be affected by population growth, economic development, land use change, water resources development and use, climate change, other factors, and combinations thereof. Permanent changes (non-stationarity) in river flow characteristics have resulted primarily from changes in water use accompanying population growth and construction of dams, reservoirs, conveyance facilities, and other infrastructure for storing, transporting, and using water. The impacts of water development and use are significant, diverse, and vary with location.

WAM hydrology time series datasets of naturalized monthly stream flows and net reservoir evaporation-precipitation rates are discussed in Chapters 5 through 12. Analyses have shown that the WAM naturalized monthly flows are generally stationary at most locations. Issues in regard to non-stationarities of naturalized flows in certain river reaches are due primarily to interactions between groundwater and surface water and other water resources development complexities rather than long-term climate change associated with global warming.

Monthly and annual precipitation and reservoir evaporation rates are climatic variables particularly relevant to managing river/reservoir systems and associated water availability modeling. Except for research studies [66, 67, 68] discussed in the preceding section, climate change due to global warming has not been incorporated in the compilation of WAM hydrology datasets. Analyses of the stationarity of precipitation and reservoir evaporation presented in this chapter provide further justification for not incorporating consideration of global warming in development of WAM hydrology. Past monthly and annual precipitation and reservoir evaporation rates throughout Texas appear to be essentially stationary for WRAP/WAM modeling purposes.

As discussed earlier in this chapter, observed 1940-2024 sequences of 1,020 monthly and 85 annual precipitation depths and 1954-2024 sequences of 852 monthly and 71 annual reservoir evaporation depths in 92 grid cells (quadrangles) covering Texas and associated statewide-average quantities appear generally to be stationary. Non-stationarities, if they exist, are hidden in the great rainfall variability. Stationarity or departures from stationarity conceivably may vary with location within the diverse regions of the state. Linear regression trend statistics vary somewhat between the 92 quadrangles, but spatial patterns are difficult to differentiate or measure.

The four largest monthly precipitation depths since 1940 occurred in May 2015 (8.3 inches), August 2017 (7.2 inches), September 2018 (7.1 inches), and June 2004 (6.3 inches) These precipitation depths reflect major floods occurring in these months. Variations in instantaneous rainfall intensities during severe storms are obscured in aggregation of hourly or daily quantities to the monthly quantities explored in this chapter. However, the monthly data imply an occurrence in intense rainfall events associated with major floods during 2004-2018 that may or may not represent a continuing trend or permanent change in the frequency of extreme rainfall events.

Global warming should logically be expected to result in increases in evaporation rates in Texas and worldwide. The analyses presented earlier in this chapter indicate that the estimates of reservoir evaporation rates during 1990-2024 are a little higher than during 1941-1989. However, detection and measurement of changes in evaporation rates from these analyses are approximate and inconclusive. Evaporation as well as precipitation appears, for practical WRAP/WAM purposes, to be essentially stationary with any departures from stationary being hidden by continual variability and uncertainties in measurement and analysis accuracy.

### Climate Change Uncertainties

Water management is driven by extreme hydrologic variability and uncertainties regarding the timing and characteristics of future floods and droughts, future economic and population growth, future changes in water needs and water management strategies, and various other future uncertainties. Analyses of hydrologic variables in this chapter are based on past observations. Differences between the future and past are uncertain and difficult to accurately predict. The scientific community generally expects global warming to increase evaporation and transpiration rates, agricultural and urban irrigation demands, and uses of water supplied by rivers and reservoirs and aquifers. Global warming may increase rainfall intensities of extreme storms, worsening flooding. Climate change resulting from global warming possibly increases hydrologic variability in various regions of the world and certainly adds to uncertainties regarding the future.

Dams, reservoirs, conveyance facilities, other constructed infrastructure, and institutional water resources planning, allocation, and management capabilities are essential for dealing with hydrologic variability and future uncertainty even without long-term changes in climate resulting from global warming. These water management capabilities are likewise essential in dealing with the added complexities and uncertainties of global warming and climate change issues.

## Connections Between Surface Water and Groundwater

Streams throughout Texas gain water from and lose water to the ground. The quantities of water involved in hydrologic interactions between surface water, groundwater, and unsaturated soil zones vary greatly between river basins. Groundwater refers to saturated zones. Aquifers are significant saturated formations that can be developed for water supply.

Groundwater occurs under water table and artesian conditions. Under water table conditions, the water is unconfined and does not rise in wells above the water table. Under artesian conditions, the water is confined within a water-bearing stratum by an overlying relatively impermeable stratum. Due to water being under pressure, it will rise in wells above the level at which it is encountered in drilling the wells. Rainfall infiltrating the ground surface replenishes soil moisture deficits before percolating by gravity to the water table. Much or most of the recharge of some groundwater aquifers is through rainfall and stream flow entering outcropping recharge zones as discussed later in this section.

### Ephemeral and Perennial Streams

Lower reaches of the larger rivers in Central and East Texas are perennial, meaning stream flow occurs throughout the year in most years. Streams that flow regularly during the wet seasons of the year but not year-round during dry seasons are called intermittent. Ephemeral streams flow only during and for a short duration after heavy rainstorms. Ephemeral flows occur in headwaters of perennial streams, in smaller streams, and in arid regions such as West Texas.

In perennial streams, the groundwater table is consistently above the bottom of the streambed, groundwater contributes to stream flow, and stream flow increases in a downstream direction. Perennial streams are commonly called effluent or gaining. Base flows are provided from the saturated ground through the bed and banks of the stream even during long periods without rainfall. In ephemeral streams, the underlying water table of groundwater is consistently lower than the bottom of the streambed. Stream flow seeps into the bed and banks, maintaining moisture in the underlying strata. Ephemeral streams are called influent or losing.

Water stored in a reservoir likewise interacts with water stored in the underlying and surrounding ground. Groundwater with a high water table may result in spring flow or seepage into a lake. Conversely, seepage from a lake may contribute to groundwater. Lake levels fluctuate. Lake seepage may contribute to raising water tables of underlying aquifers. As reservoir storage is drawn down by water use, water may flow from adjacent saturated ground into the reservoir. The adjacent ground is saturated again later when the reservoir refills.

Groundwater Aquifers in Texas

TWDB provides a comprehensive array of information regarding groundwater management (https://www.twdb.texas.gov/groundwater/index.asp). TWDB has delineated nine major aquifers (https://www.twdb.texas.gov/groundwater/aquifer/index.asp) and 22 minor aquifers (https://www.twdb.texas.gov/groundwater/aquifer/minor.asp) that underly Texas, which are described in a TWDB technical report [93].

Interconnections between surface water and groundwater are significant throughout Texas. Base flow from saturated banks of perennial streams maintains low flows during dry periods. Stream flow is loss through seepage in ephemeral streams. Spring flows contribute to stream flow. Losses of stream flow to aquifer recharge as streams flow over recharge zones can involve particularly large quantities of water. The effects of aquifer recharge zones and spring flows on stream flow are most significant in the Guadalupe, San Antonio, and Nueces River Basins and the western portions of the Colorado and Brazos River Basins. The Edwards Aquifer has particularly notable effects on stream flow in the Guadalupe, San Antonio, and Nueces River Basins from the perspectives of both aquifer recharge and spring flow to streams.

Unlike the Edwards Aquifer, most groundwater aquifers in Texas and elsewhere supplying large quantities of water consist largely of sand and gravel. The Edwards Aquifer is comprised of caverns through limestone that are essentially underground streams. The principal recharge zone of the Edwards aquifer is a 1,500 square mile area of fractured and cavernous limestone exposed on the surface allowing large quantities of water to flow into the aquifer. This recharge zone extends across the upper portions of the Nueces, San Antonio, and Guadalupe River Basins in the Texas Hill Country just north of the cities of Uvalde, Hondo, San Antonio, and New Braunfels.

Conjunctive surface and ground water management issues are relevant throughout Texas [40]. Management of the Edwards Aquifer has unique dimensions. Surface streams flow through the recharge zone into underground streams in the cavernous Edwards limestone. Protection of the water quality of the Edwards Aquifer is dependent upon protecting the water quality of the rivers that recharge the aquifer. Surface water development projects can affect the quantities of aquifer recharge. For example, flood flows of the Nueces, Frio, and other rivers crossing the recharge zone exceed the recharge capacity. Dams upstream of the recharge zone can be employed to store high flows for later release at optimal rates for aquifer recharge.

Investigations of Interactions between Surface and Groundwater

Creation of the statewide water availability modeling system was authorized by the Texas Legislature in its 1997 SB1 as discussed in Chapters 1, 2, and 3. Early development of the water availability modeling system included an assessment sponsored by the Texas Natural Resource Conservation Commission (TNRCC), later renamed TCEQ, of the interactions between surface and groundwater in each of the major river basins and coastal basins of Texas excluding the Rio Grande [69]. A later TCEQ-administered study by the Bureau of Economic Geology [70] provides a detailed review of available information on surface and groundwater interactions throughout the state. A 1998 study focused on recharge of the Edwards Aquifer [71]. A recent TWDB-sponsored study focuses on modeling interactions between surface and groundwater in Central and West Texas [72]. These and other technical reports exploring surface and groundwater interactions for specific aquifers, river basins, or regions are available from the TCEQ and TWDB.

During 2023-2025 the Bureau of Economic Geology at the University of Texas is investigating possibilities for increasing groundwater recharge. The WAMs are being employed to assess the availability of unappropriated stream flow that could be used to augment recharge of groundwater aquifers.

The WAM datasets include channel loss parameters used in a WRAP simulation to model losses of water in stream channel reaches due to seepage and evapotranspiration. Channel loss computations are not activated in several WAMs because the actual losses are considered negligible. In other WAMs, channel losses are computed for some but not all stream reaches.

The WAM for the Nueces River Basin illustrates a case of extremely high losses of stream flow to recharge of groundwater. Upper reaches of the Nueces River and its tributaries cross the Edwards Aquifer recharge zone where the entire flow of the stream may be loss to groundwater recharge. For middle and lower reaches of the Nueces River and its tributaries located downstream of the Edwards recharge zone, channel seepage losses per mile of stream length are estimated to generally range between 0.30 percent and 0.70 percent of the stream flow discharge per mile [91].

TWDB Groundwater Availability Models

TWDB maintains groundwater availability models (GAMs) for the aquifers of Texas pursuant to the 1997 SB3 [92] (https://www.twdb.texas.gov/groundwater/models/index.asp). The GAMs were developed and are maintained and updated by TWDB staff and consulting firm contractors. GAM software, datasets, and documentation can be downloaded through the TWDB groundwater webpage. The generalized MODFLOW groundwater model developed by the USGS and extensively applied throughout the United States is employed for the Texas GAMs. MODFLOW is widely used and tested, well documented, and in the public domain. The calibrated

GAMs simulate aquifer geology, hydraulics, recharge, and pumping. The models provide water availability information for SB1 regional and statewide planning studies, activities of the groundwater conservation districts, and various other TWDB programs.

## Salinity Constraints to Water Availability

Dissolved solids or salts are the inorganic solutes that occur in all natural waters because of weathering of rocks and soils. The terms total dissolved solids (TDS) and salinity are used interchangeably. Evapotranspiration produces essentially pure water vapor and increases salinity concentrations of the remaining liquid water. Human activities such as irrigated agriculture and construction of storage reservoirs increase evaporation and consequently increase salinity of water resources. Elevated salinity levels are detrimental to agricultural, municipal, and industrial water use. Seawater is a major source of salt in coastal areas. Saltwater encroachment from the Gulf of Mexico into the lower coastal reaches of rivers is a concern along the Texas coast. Several river systems of Texas and neighboring states share the common problem of extremely high salt concentrations in upper stream reaches resulting from geologic formations occurring in small isolated sub-watersheds

### Constraints to Water Supply

Seawater typically has a TDS concentration between 31,000 mg/l and 38,000 mg/l, averaging about 35,000 milligrams per liter (mg/l). Brackish water is generally defined as having TDS concentrations between 1,000 mg/l and 10,000 mg/l. Saline water has TDS concentrations greater than 10,000 mg/l. U.S. Environmental Protection Agency secondary drinking water standards recommend treatment of municipal water supply as necessary to prevent TDS, chloride, and sulfate concentrations from exceeding 500 mg/l, 250 mg/l, and 250 m/l, respectively. The most suitable TDS levels for drinking water are between about 50 and 100 mg/l.

According to an online TWDB desalination plant database, Texas has thirty-six municipal desalination facilities with a total capacity of 100,769 acre-feet/year that treat brackish groundwater and sixteen plants with a total capacity of 72,443 acre-feet/year that treat brackish surface water. Industrial operations mainly in the electric power and semi-conductor industries are estimated by the TWDB to provide an additional 67,000 to 112,000 acre-feet/year of desalination. A desalination plant in El Paso with a capacity of 30,800 acre-feet/year is the largest municipal desalination plant in Texas. Its supply source is brackish groundwater. The two largest desalination plants for treating brackish surface water are the plant in the City of Sherman that treats water from Lake Texoma and the plant in the City of Granbury that treats water from Lake Granbury.

There are no treatment plants in Texas for desalination of seawater. Untreated seawater is used for certain industrial uses. Seawater provides an essentially unlimited drought-proof supply of water for the many communities and industries located near the 367-mile-long Texas Gulf Coast. The principal constraint to using seawater for municipal, industrial, and agricultural water supply is the economic and environmental cost of removal and disposal of the salt. As noted in Chapter 12 of this report, the City of Corpus Christi and the Coastal Bend Region could possibly pioneer the use of seawater desalination to supplement conventional freshwater supplies as incremental additions to the use of limited freshwater resources become more expensive.

Natural Salt Pollution in the Permian Basin Geologic Region

Capabilities for supplying water for municipal, industrial, and agricultural use from the Arkansas, Brazos, Canadian, Pecos, and Red Rivers and their upper-basin tributaries in Texas, New Mexico, Oklahoma, and Kansas are significantly constrained by natural salt pollution in the geologic region of Permian salt shown in Figure 4.12 [33]. This region was covered by an inland sea during the Permian age 230 million years ago. Deposits of halite were formed as evaporating seawater precipitated salts. This semiarid region now consists of gypsum and salt-encrusted rolling plains containing numerous salt springs and seeps. Small tributary streams in primary salt areas have dissolved solids concentrations that sometimes exceed that of seawater.

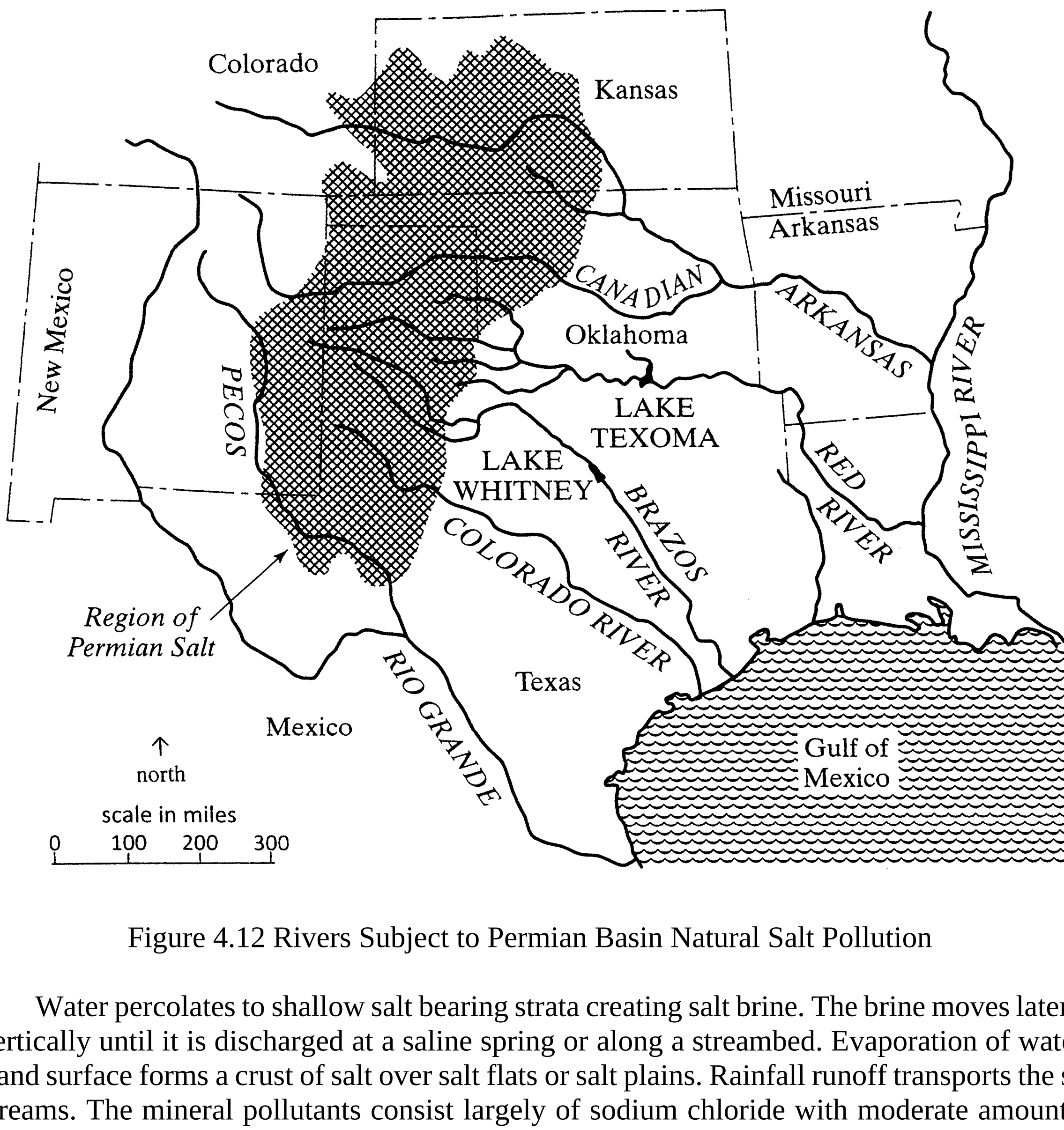


Figure 4.12 Rivers Subject to Permian Basin Natural Salt Pollution

Water percolates to shallow salt bearing strata creating salt brine. The brine moves laterally or vertically until it is discharged at a saline spring or along a streambed. Evaporation of water at the land surface forms a crust of salt over salt flats or salt plains. Rainfall runoff transports the salts to streams. The mineral pollutants consist largely of sodium chloride with moderate amounts of calcium sulfate and other dissolved minerals. Salt concentrations in the downstream reaches of the rivers decrease with dilution from low-salinity tributary inflows.

Studies of the effects of salinity on water supply capabilities in the Brazos River Basin performed using the WRAP modeling system with the WRAP salinity simulation program *SALT* are documented by Wurbs and Lee [34, 35]. Salinity was expressed in this study in terms of total dissolved solids (TDS) and chloride and sulfate which are two main constituents of TDS. USGS field measurements of salinity concentrations from 1964 through 1986 funded by the USACE Fort Worth District provided data required to support the WRAP/WAM study at TAMU as well as other natural salt pollution control studies performed by the USACE Fort Worth District.

Salt enters the upper Brazos River from geologic formations in the Permian Basin Region shown in Figure 4.12. Concentrations are diluted downstream by inflows from low salinity tributaries. Estimated long-term mean TDS concentrations decrease from 56,960 mg/l in Salt Croton Creek near Aspermont to 12,400 mg/l in the Salt Fork of the Brazos River near Aspermont to 1,530 mg/l in the Brazos River below Possum Kingdom Reservoir to 928 mg/l below Whitney Dam to 339 mg/l at the USGS gage on the Brazos River at Richmond [34, 35]. Concentrations are highly variable over time. Salinity may be a serious constraint to water supply if concentrations are too high some of the time even if mean and median concentrations are sufficiently low.

Salinity affects water supply operations of both the three reservoirs on the Brazos River and multiple-reservoir system operations that include the tributary reservoirs. Salt water encroachment in the lower Brazos River from seawater in the Gulf of Mexico is another issue that may overlap with the salinity from the Permian geologic region in the upper basin.

Water supply capabilities of multiple major reservoirs in each of the river systems in Figure 4.12 are significantly constrained by natural salt pollution. Lake Texoma on the Red River is another example of the very large reservoirs for which water supplies are severely constrained by salinity. The USACE Fort Worth District, USACE Tulsa District, USBR, USGS, state water agencies, river authorities, and university researchers have conducted extensive natural salt pollution control studies focused on salt containment strategies for these affected river basins over the past several decades. Many salinity control projects have been proposed, and some have been implemented [19, 33].

## Observed Reservoir Storage

This final section of Chapter 4 further explores river system hydrology employing a TWDB database of observed daily storage volumes for 122 reservoirs from initial impoundment to the present. The database is described in the last section of Chapter 3. The summation of storage volumes of 122 reservoirs from July 1, 1933 through July 1, 2025 is plotted in Figure 3.3. These 122 reservoirs contain 96 percent of the Texas share of active conservation storage capacity of major reservoirs located totally or partially within the state. Figures A1 through A20 of Appendix A are storage plots that extend from initial impoundment through February 5, 2024. Figures A21 through A35 are storage plots that extend from January 1, 1994 through May 22, 2024. Most of the total storage capacity in Texas reservoirs has been fully operational since about 1993.

### Reservoir Storage Content as a Metric of Hydrologic Conditions

Reservoir storage content is a practical measure of water availability that can also be used to explore characteristics of a river system hydrology. Reservoir drawdowns and refilling can be viewed as a drought index. High rates of refilling storage indicate flood conditions. Reservoir storage, depletions, and refilling reflect cumulative past and recent weather, hydrology, water use, and water management. The basic weakness of using historical observed reservoir storage contents as an index for comparing past, current, and possible future hydrologic conditions is the non-stationarity resulting from the changes in water development and use that have accompanied population and economic growth. For example, population, water needs, economic development, and water resources development during the 1950-1957 drought and April-May 1957 flood were very different than during the 2011-2014 drought and 2015, 2017, 2018, and 2024 floods.

The WRAP/WAM modeling system deals with this issue of non-stationarity of observed reservoir storage by simulating the occurrence of a defined stationary condition of water resources development and use during a repetition of stationary historical natural hydrology. Simulated reservoir storage generated with the WRAP simulation model with WAM datasets are discussed in Chapters 6 through 12 of this report. However, the following discussion focuses on observed actual daily reservoir storage volumes recorded in the TWDB reservoir database described in the last section of Chapter 3 (https://www.waterdatafortexas.org/reservoirs/statewide).

Observed reservoir volumes during the three-decade period since January 1, 1994 are adopted in the following discussion to further investigate drought and flood characteristics. Although population and water use have continued to grow, most of the currently existing reservoir storage capacity has been fully operational since before 1994. The most recently constructed of the 28 largest reservoirs (Table 3.7) are Richland-Chambers and O. H. Ivie Reservoirs with initial impoundment in 1987 and 1990, respectively. The 29th largest (Jim Chapman) is the most recently constructed USACE project with initial impoundment in 1991. Estimated storage capacities change with sediment accumulation updates and operational modifications to storage allocations as well as construction of new reservoir projects.

Most of the growth in the total conservation storage capacity of the 122 reservoirs in the TWDB database is shown in Figure 3.3 to have occurred during 1940-1992. The population of Texas increased from 9.6 million people in 1960 to 20.9 million in 2000 and 29.7 million in 2020. The associated increase in water use represents a significant driver of non-stationarity in reservoir storage contents. However, storage capacity has remained fairly constant since about 1994.

The following quantities are from the TWDB reservoir storage database employed in the last sections of the preceding Chapter 3 and present Chapter 4:

1. average total storage contents in acre-feet during each day,
2. average daily active conservation storage contents in acre-feet belonging to Texas,
3. and active conservation storage capacity in acre-feet belonging to Texas.

The daily total reservoir storage content is the observed total volume of water stored in a reservoir at a particular time, regardless of ownership. Volumes of only water in active conservation storage committed to water users in Texas are computed and also recorded in the database. For reservoirs shared by Texas with Mexico or neighboring states, these active conservation storage volumes include only the Texas share of the conservation capacity and contents of that capacity. Inactive conservation storage for hydropower head or below the lowest outlet inverts is also omitted from the active conservation storage amounts. The total storage contents include water stored in flood control pools as well as active and inactive conservation pools.

Individual water managers are interested in storage in their specific reservoir or multiple-reservoir system, which tends to fluctuate more than the summation of storage volumes in many reservoirs located throughout a river basin, region, or the entire state. The timing of stream inflows, water supply diversions and releases, and resulting reservoir storage drawdowns differ between reservoirs. Different reservoirs are drawn down and refilled at different times. Summations of storage in multiple reservoirs smooth out fluctuations of storage in the individual reservoirs. Fluctuations in statewide totals of reservoir storage contents are significant but not as dramatic as many of the individual reservoirs. However, broader basin-wide and state-wide perspectives also provide interesting and relevant insight into hydrology and water management.

Summation of Daily Storage in 122 Large Reservoirs Since 1994

The storage volume plots in Figure 4.13 are summations for 122 reservoirs located totally or partially in Texas representing 96 percent of the Texas active conservation storage capacity of the 188 major water supply reservoirs. The following quantities are plotted.

1. Total observed storage contents (solid blue line in graphs of Figure 4.13 and Appendix A)
2. The portion of the observed storage contents that is contained in active conservation pools controlled by water managers for use by water users in Texas (red dashed line)
3. The active conservation storage capacity controlled by water managers for use by water users in Texas (black dotted line in graphs of Figure 4.13 and Appendix A)

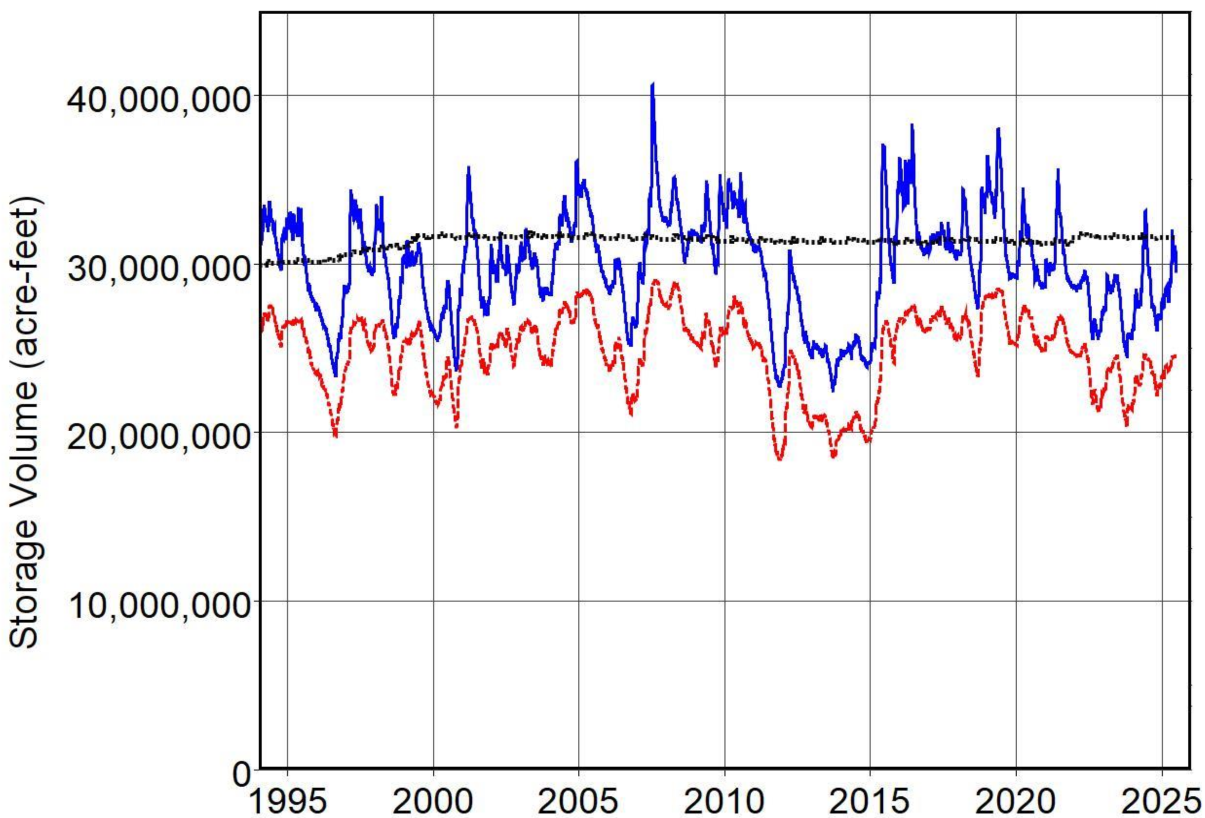


Figure 4.13 Total Contents (solid blue line), Active Conservation Contents (red dashes), and Active Conservation Storage Capacity (black dots) of 122 Reservoirs

Figures 3.3 and 4.13 are the same except for the period-of-analysis covered. Figure 3.3 extends from July 1, 1933 to July 1, 2025. Figure 4.13 covers from January 1, 1994 to July 1, 2025. Figure 3.3 provides insight on the history of water development in Texas. Figure 4.13 focuses on water availability and associated hydrologic conditions during the most recent three decades with almost constant total statewide reservoir storage capacity.

The summations of storage contents of the 122 reservoirs appear to be essentially stationary in Figure 4.13. No trends of permanent changes in storage characteristics are apparent. The total storage contents and Texas conservation storage contents have fluctuated up and down at various rates continuously. However, no permanent changes are trends are evident in the variability.

The plots of total and conservation storage contents in Figure 4.13 exhibit significant seasonal and multiple-year fluctuations. The summation of storage contents of 122 reservoirs exhibits less variability than many of the individual reservoirs included in the summation. Summations average-out variability of individual reservoirs. The most severe drawdowns statewide since 1994 occurred during 2010-2015. Statewide reservoir storage depletions during the hot and dry 2023 and partial refilling during 2024-2025 can also be seen in Figure 4.13.

Reservoir Storage Plots in Appendix A for Summations by River Basin

Historical daily total storage contents, active Texas conservation storage capacity, and active Texas conservation storage contents in Appendix A are the same variables plotted in the same format as Figures 3.3 and 4.13. Descriptive information for Figures A21 through A35 is provided in Table 4.9. The plots of daily average storage volumes cover the period from January 1, 1994 through May 21, 2024. The summation of storage for 121 reservoirs included in the TWDB database that are located in each of the major river basins are plotted in these figures. Natural Dam in the Colorado River Basin is omitted from the 122 reservoirs in the statewide summations. Natural Dam impounding salt reservoir is a relatively small flood control dam with no conservation storage capacity. The much larger Addicks and Barker flood control dams in Houston also have no conservation storage but are included in the storage summations for the San Jacinto River Basin.

Figure 1.1 of Chapter 1 is a map showing the major rivers and largest cities of Texas. The 15 major river basins and five coastal basins of Texas are delineated in both Figures 2.2 and 5.1. Descriptive metrics for each major river basin and coastal basin are tabulated in Table 1.1.

The 15 major river basins are listed in the first column of Table 4.9 with the number of reservoirs included in the storage summations from the TWDB database shown in parenthesis. The Appendix A figure label is listed in the last column of Table 4.9. The second and third columns are the conservation storage capacity as of January 1, 1994 and May 21, 2024 in acre-feet. The mean storage contents during January 1994 through May 21, 2024 is tabulated in the fourth column. The minimum and maximum storage contents in acre-feet and corresponding dates are tabulated in the other columns of Table 4.9.

The reservoir storage plots in Appendix A exhibit great spatial and temporal variability. Storage drawdowns in dry West Texas are dramatically greater than in wet East Texas. Differences in river system traversing the state from west to east are clearly demonstrated in the plots. The most severe drought during the three decades from January 1994 and May 2024 generally occurred sometime during 2010-2015. The lowest storage levels between January 1994 and May 21, 2024 occurred on May 21, 2024 for the Rio Grande, San Antonio, and Guadalupe Basins.

Table 4.9
Reservoir Storage Contents in Each Major River Basin

| River Basin | Conservation Capacity | | Mean | Storage Contents (acre-feet) and Date | | | | |
|---|---|---|---|---|---|---|---|---|
| (Reservoirs) | Jan 1994 | May 2024 | Storage | Minimum | Date Min | Maximum | Date Max | Figure |
| Rio Grande (3) | 3,542,966 | 3,526,885 | 2,800,793 | 973,379 | *5/21/2024* | 7,268,508 | *7/17/2010* | A21 |
| Canadian (2) | 500,000 | 561,066 | 199,229 | 18,277 | *8/6/2013* | 464,450 | *8/18/1999* | A22 |
| Nueces (2) | 936,503 | 918,882 | 552,101 | 239,140 | *8/21/1996* | 1,034,055 | *9/11/2002* | A23 |
| Lavaca (1) | 0 | 158,975 | 146,177 | 62,930 | *1/7/2012* | 168,058 | *9/5/2001* | A24 |
| San Antonio (1) | 0 | 254,823 | 155,434 | 6,627 | *5/21/2024* | 304,449 | *8/8/1997* | A25 |
| Guadalupe (2) | 409,821 | 409,821 | 386,961 | 249,098 | *5/21/2024* | 832,001 | *7/5/2002* | A26 |
| Colorado (19) | 3,954,543 | 3,975,089 | 2,350,691 | 1,066,907 | *10/18/2013* | 3,736,248 | *6/26/1997* | A27 |
| Brazos (28) | 3,208,761 | 3,574,637 | 3,111,646 | 2,169,368 | *10/6/2011* | 5,957,942 | *7/8/2007* | A28 |
| San Jacinto (4) | 516,700 | 549,895 | 555,555 | 384,392 | *11/6/2011* | 744,400 | *10/18/1994* | A29 |
| Trinity (24) | 6,491,878 | 6,776,855 | 6,496,727 | 4,904,932 | *10/8/2006* | 9,097,305 | *5/30/2015* | A30 |
| Neches (7) | 3,511,041 | 3,477,212 | 3,248,220 | 1,997,291 | *11/18/2011* | 4,840,139 | *6/1/2021* | A31 |
| Sabine (6) | 3,852,730 | 3,867,301 | 5,514,234 | 3,711,205 | *11/18/2011* | 6,644,897 | *3/9/2016* | A32 |
| Red (13) | 2,055,166 | 2,474,646 | 3,097,447 | 2,241,277 | *3/13/2014* | 5,507,133 | *7/13/2007* | A33 |
| Sulphur (3) | 395,343 | 586,852 | 621,095 | 264,530 | *2/23/2006* | 2,365,803 | *1/4/2016* | A34 |
| Cypress (5) | 454,713 | 592,377 | 604,286 | 363,895 | *12/22/2006* | 1,428,084 | *3/14/2016* | A35 |

The summations of storage in International Amistad and Falcon Reservoirs on the Rio Grande and the much smaller Red Bluff Reservoir on the Pecos River are plotted in Figure A21. Hydrology in the large dry Rio Grande Basin is characterized by filling reservoir storage during infrequent major flood events separated by long periods of severe drawdowns. The maximum total storage level in the three reservoirs since before 1994 was 7,268,508 acre-feet in July 2010 (Table 4.9). The minimum storage contents of 973,379 acre-feet occurred on May 21, 2024, the end of the period-of-analysis covered by Table 4.9 and Figure A21. Two long severe droughts are shown in Figure A21 with the second drought currently still continuing as of May 2024.

Figure A22 reflects the extreme of large reservoirs that have never filled to conservation storage capacity or even close to capacity. Lakes Meredith and Palo Duro in the Canadian River Basin, with initial impoundment in 1965 and 1991, have conservation storage capacities of 818,000 and 61,100, respectively. The Canadian River Compact limits Texas to storing no more than 500,000 acre-feet in Lake Meredith. Lake Meredith has a large flood control which has never stored water since the conservation pool has never filled.

The metrics in Table 4.9 and Figures A21 through A35 demonstrate dramatically different characteristics of hydrology and water development/management in each of the river basins. Storage fluctuation patterns and severity reflect floods, multiple-year droughts, seasonality, continuous daily variability, and stationarity or possible non-stationarities, along with various other factors differ greatly between the diverse river basins of Texas.

# CHAPTER 5
# WRAP/WAM MODELING OF RIVER SYSTEM HYDROLOGY

Both the monthly *SIM* and daily *SIMD* versions of the simulation model allocate naturalized stream flows to meet specified water right requirements subject to channel losses and losses or gains associated with evaporation from and precipitation falling onto reservoir water surfaces. Monthly naturalized flow volumes at primary control points are recorded on inflow *IN* records in the *SIM/SIMD* simulation input dataset. Monthly naturalized flow volumes at secondary control points are computed during execution of *SIM* or *SIMD* based on naturalized flow volumes at primary control points and watershed parameters in the WAM input datasets. For the daily *SIMD*, the hydrology input also includes daily flow pattern hydrographs used within the *SIMD* simulation computations to disaggregate monthly naturalized flow volumes to daily volumes.

The future is of concern in water planning and management, rather than the past. However, future hydrology is unknown. Past stream flows adjusted to remove the effects of water resources development and use along with net reservoir evaporation less precipitation rates are adopted as being representative of the relevant hydrologic characteristics of a stream system that can be expected to continue in the future. The hydrologic period-of-analysis adopted in the WAMs cover a long time span that reflects severe multiple-year drought and intense flood extremes along with seasonality and other hydrologic characteristics of the river system.

## Twenty TCEQ Full Authorization WAMs

Contractors employed by the Texas Natural Resources Commission (TNRCC) compiled the original versions of the water availability models (WAMs) and performed specified simulations during 1998-2004 [15, 16, 17]. TNRCC was renamed the TCEQ in 2002. The technical reports documenting development of the original WAMs are available from the online Texas Digital Library (TDL) repository directly through the TDL website and also through the TCEQ WAM website.

Sixteen final technical reports documenting creation of the original WAMs are listed in the WRAP *Reference Manual Appendix A Bibliography* [1]. These reports prepared for the TNRCC or TCEQ have dates ranging from June 1999 for the Sulphur WAM to March 2004 for the Rio Grande WAM. The Lavaca WAM and accompanying report were prepared by the U.S. Bureau of Reclamation for the TNRCC. The other WAM datasets and reports were prepared by engineering consulting firms. Both the water management (water rights) and hydrology components of the WAMs are occasionally updated by TCEQ staff and contractors.

The twenty full authorization WAMs are listed in Table 5.1. The major river basins and coastal basins are delineated in Figure 5.1. The Guadalupe and San Antonio River Basins are combined in a single Guadalupe-San Antonio (GSA) WAM. The Brazos WAM includes the San Jacinto-Brazos coastal basin as well as the Brazos River Basin. Likewise, the Colorado WAM includes the Colorado River Basin and the Brazos-Colorado Coastal Basin. The other six coastal basins are listed at the bottom of Table 5.1. The information in Table 5.1 is from versions of the WAMs last updated October 1, 2023 accessible at the TCEQ WAM website as of October 2023 through February 2025. The full authorization versions of all 20 WAMs are available at the TCEQ WAM website as of February 2025. The only current use scenario dataset available at the WAM website as of February 2025 is the WAM for the Red River Basin.

Water availability models (WAMs) are input datasets for the WRAP simulation models *SIM* and *SIMD*. The quantities in Table 5.1 were determined by executing the WRAP simulation model *SIM* with the twenty full authorization WAMs available from the TCEQ WAM website during 2024. These officially adopted TCEQ WAMs listed in Table 5.1 are not affected by the six daily and modified monthly WAM versions [7, 8, 9, 10, 11, 12] discussed later in this chapter and throughout subsequent chapters. The information in Table 5.1 is recorded in the message file (filename extension MSS) with each execution of the *SIM* simulation model.

Table 5.1
Full Authorization Scenario Water Availability Models

| Water Availability | Period of | Counts of *SIM* Input Records | | | | | | Reser- |
|---|---|---|---|---|---|---|---|---|
| Model (WAM) | Analysis | CP | IN | EV | FD | WR | IF | voirs |
| Brazos and SJ-B Coastal | 1940-2018 | 4,468 | 77 | 67 | 3,203 | 2,470 | 743 | 695 |
| Canadian | 1948-1998 | 85 | 12 | 9 | 73 | 56 | 0 | 47 |
| Colorado & B-C Coastal | 1940-2016 | 2,524 | 45 | 48 | 2,249 | 2,233 | 169 | 527 |
| Cypress | 1948-1998 | 150 | 11 | 12 | 126 | 149 | 3 | 92 |
| GSA | 1934-1989 | 1,612 | 46 | 11 | 1,225 | 1,079 | 421 | 238 |
| Lavaca | 1940-1996 | 220 | 8 | 7 | 179 | 86 | 61 | 22 |
| Neches | 1940-2018 | 380 | 20 | 12 | 276 | 420 | 75 | 206 |
| Nueces | 1934-1996 | 676 | 41 | 9 | 15 | 481 | 127 | 122 |
| Red | 1948-2018 | 479 | 29 | 40 | 404 | 538 | 122 | 249 |
| Rio Grande | 1940-2018 | 965 | 55 | 25 | 873 | 469 | 20 | 109 |
| Sabine | 1940-1998 | 469 | 27 | 20 | 3 | 394 | 79 | 216 |
| San Jacinto | 1940-1996 | 441 | 17 | 4 | 6 | 176 | 37 | 114 |
| Sulphur | 1940-2017 | 139 | 6 | 4 | 125 | 94 | 11 | 67 |
| Trinity | 1940-1996 | 1,407 | 40 | 50 | 1,251 | 1,073 | 76 | 699 |
| <u>*Coastal Basins*</u> | | | | | | | | |
| Colorado-Lavaca | 1940-1996 | 111 | 1 | 1 | 95 | 27 | 4 | 8 |
| Lavaca-Guadalupe | 1940-1996 | 109 | 2 | 2 | 72 | 45 | 25 | 0 |
| Neches-Trinity | 1940-1996 | 249 | 4 | 4 | 213 | 139 | 11 | 31 |
| Nueces-Rio Grande | 1948-1998 | 180 | 30 | 5 | 138 | 105 | 7 | 63 |
| San Antonio-Nueces | 1948-1998 | 53 | 9 | 3 | 40 | 12 | 2 | 9 |
| Trinity-San Jacinto | 1940-1996 | 94 | 2 | 3 | 78 | 24 | 0 | 13 |
| Totals | | 14,811 | 482 | 336 | 10,644 | 10,070 | 1,993 | 3,527 |

<u>Input Record Counts</u>

Control points are defined by *CP* records in the simulation input DAT file. The number of control points in each of the WAMs is tabulated in the third column of Table 5.1. Control points are categorized as either primary or secondary. Primary control points are locations for which monthly naturalized stream flow volumes in acre-feet are included in the WAM simulation input dataset as inflow *IN* records. Naturalized flows at secondary control points are computed from naturalized flows at primary control points within the simulation using parameters input on control point *CP*, flow distribution *FD*, and watershed parameter *WP* records. The total number of control points and number of primary control points in each WAM are tabulated in the third and fourth columns of Table 5.1. The number of secondary control points is the difference between the counts in the third and fourth columns. The twenty WAMs have a total of 14,811 control points consisting of 482 primary control points and 14,329 secondary control points. The number of flow distribution *FD* records providing specifications for synthesizing flows at secondary control points during each execution of *SIM* or *SIMD* is shown in the sixth column of Table 5.1.

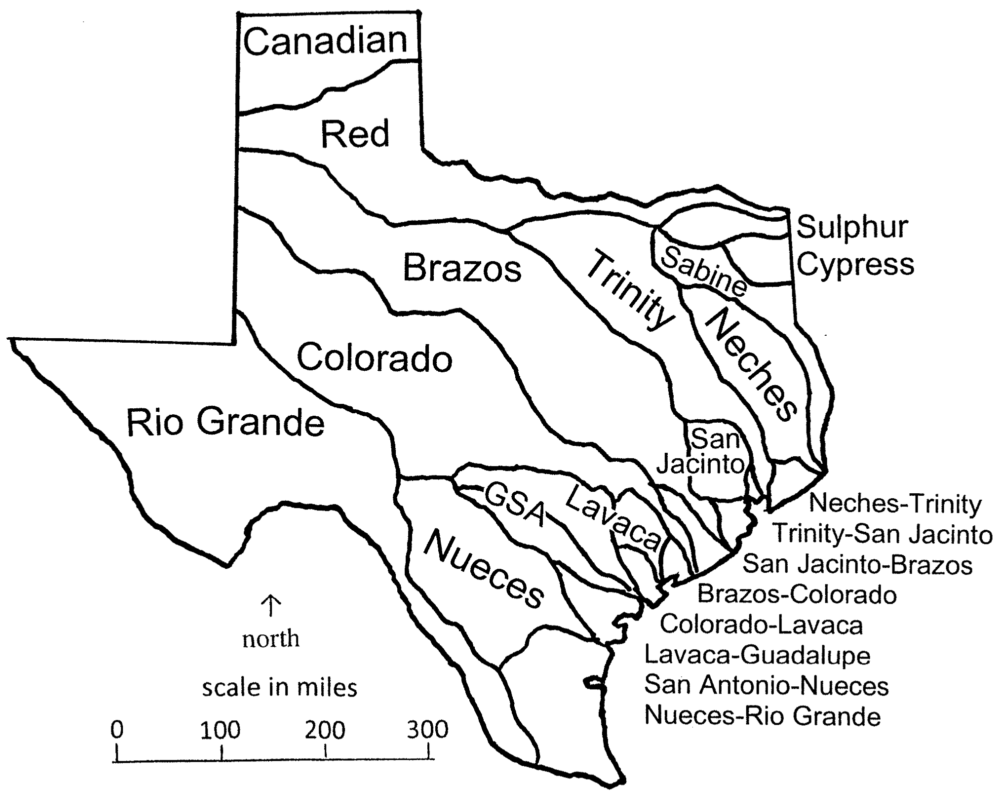


Figure 5.1 Fifteen Major River Basins and Eight Coastal Basins of Texas

Most but not all primary control points are sites of USGS stream flow gages, or for the Rio Grande, IBWC stream flow gages. Thus, observed flows at almost 482 gages are adjusted to develop monthly naturalized stream flows recorded on *IN* records in the twenty WAM simulation input datasets. Monthly naturalized flows at the numerous other control points are computed each time the *SIM* or *SIMD* simulation model is executed with one of the WAMs.

The number of sets of period-of-analysis monthly net evaporation-precipitation depths in feet recorded on evaporation *EV* records are shown in the fifth column of Table 5.1. The *SIM* simulation model allows the same set of *EV* records to be employed for any number of reservoirs.

A "*model*" water right is defined in WRAP as either a water right *WR* record or instream flow *IF* record followed in the DAT file by other optional supporting records. Counts of *WR* and *IF* records in each of the WAMs are listed in the seventh and eighth columns of Table 5.1.

All counts in Table 5.1 are found in the *SIM* message file (filename extension MSS). The third through eighth columns of Table 5.1 are comprised of counts of *CP*, *IN*, *EV*, *FD*, *WR*, and *IF* records in the *SIM* input dataset. As indicated in the next paragraph, the count of the number of reservoirs provided in the last column is a little more complicated than the model simply counting a single type of input record.

The numbers of "*model*" reservoirs tabulated in the last column of Table 5.1 are also from the information in the *SIM* message (MSS) file. These counts are performed within *SIM* based on information read from *WR* and *WS* records. The actual number of real reservoirs may be less than the number of model reservoirs. In some cases, a single reservoir may be divided into multiple storage volumes owned by different water right holders, with each component of the storage capacity treated as a separate reservoir. Some of the "*model*" reservoirs in several of the WAMs are artificial accounting reservoirs used to model complicated operating strategies, rather than actual real physical reservoirs. The full authorization WAMs include the several reservoirs that are permitted but not yet constructed as well as the many existing reservoirs. A total of 3,527 model reservoirs are counted by *SIM* in the twenty full authorization WAMs as of 2024.

Counts of components of the full authorization and current condition WAMs as of 2013 are tabulated in Table 1.2 of Chapter 1 of the July 2022 and earlier versions of the *Reference Manual*. The full authorization and current condition versions of each of the twenty WAMs had been last updated at dates ranging from October 2001 to January 2013 in the counts in the July 2022 *Reference Manual*. The twenty full authorization WAMs included totals of 13,401 control points, 500 primary control points, and 3,460 model reservoirs. The twenty current condition WAMs included totals of 13,436 control points, 500 primary control points, and 3,528 model reservoirs. The 80 reservoirs with authorized storage capacities exceeding 50,000 acre-feet contained about 92 percent of the total authorized storage capacity of the about 3,460 actual authorized reservoirs. The 210 reservoirs with authorized storage capacities exceeding 5,000 acre-feet contained about 98 percent of the total authorized storage capacity of about 3,460 reservoirs.

<u>WAM Data Files and Updates</u>

All the WAMs listed in Table 5.1 include the required main *SIM* simulation input file with filename extension DAT and optional FLO file with monthly naturalized flows (*IN* records), EVA file with net evaporation-precipitation depths (*EV* records), and flow distribution DIS file containing flow distribution (*FD*) and watershed parameter (*WP*) records. The WAMs noted in the next paragraph also have FAD and/or HIS files. All time series data are combined in a binary data storage system (DSS) file for each of the six daily WAMs discussed later in Chapters 6 through 12, replacing the FLO, EVA, FAD, and HIS text files.

The Colorado, Guadalupe-San Antonio (GSA), Red, and Rio Grande WAMs include a FAD file with flow adjustment *FA* records with adjustments to *IN* record naturalized flows. The Brazos, Colorado, GSA, Rio Grande, and Lavaca-Guadalupe Coastal WAMs include a hydrologic index series HIS file with hydrologic index *HI* records used in defining hydrologic conditions for instream flow *IF* record environmental flow requirements.

The original Rio Grande WAM was completed in 2004. The 19 other initial WAMs were completed between 1999 and 2002. TCEQ staff have updated the full authorization WAMs as new and amended water use permits are approved. The WAMs have also been updated by the TCEQ to employ new or modified features in the WRAP simulation model as applicable [15].

The current hydrologic period-of-analysis for each WAM is shown in the second column of Table 5.1. The hydrologic periods-of-analysis of the Brazos, Neches, Red, Rio Grande, Colorado, and Sulphur WAMs have been extended since the original compilation of the datasets [15]. The TCEQ was authorized by House Bill 723 of the 86th Texas Legislature enacted in 2019 to update and extend the hydrology for the Brazos, Neches, Red, and Rio Grande WAMs. Work completed in 2021 by contractors for the TCEQ included extending the hydrology of these four WAMs through 2018 [74, 75, 76, 77]. TCEQ has also participated in extending the hydrology in the Colorado WAM through 2016 and the Sulphur WAM through 2017 [73]. TCEQ is currently collaborating with stakeholders in the Cypress Creek Basin to update the hydrology for the Cypress WAM [15]. TCEQ has developed a priority list for updating the WAM hydrology for the seven major river basins and six coastal basins that have not yet been updated [15].

## Use of Programs *HYD* and *HEC-DSSVue in Compiling WAM Time Series*

WAM hydrology datasets have been compiled using Microsoft Excel and other spreadsheet software in the past, rather than *HEC-DSSVue* and *HYD*. *HEC-DSSVue*, data storage system (DSS) files, and the WRAP program *HYD* provide expanded capabilities for developing and updating datasets of monthly naturalized flows (*IN* records), net evaporation-precipitation depths (*EV* records), daily flow pattern hydrographs (*DF* records), and other time series datasets (*FA*, *HI*, *TS* records). Applications of *HEC-DSSVue* and *HYD* with the six daily and modified monthly WAMs covered in this report illustrate their efficient data management and computational capabilities.

*WRAP* program *HYD* documented by the *Hydrology Manual* [4] is designed to facilitate developing hydrology-related *SIM/SIMD* time series input datasets. Program *HYD* is a collection of multiple alternative routines for developing, updating, and analyzing monthly naturalized flows (*IN* records), monthly net evaporation-precipitation depths (*EV* records), and other time series variables including but not limited to precipitation depths, evaporation depths, and stream flow. Certain routines in *HYD* develop monthly naturalized flow sequences by adjusting observed flows. Evaporation and precipitation data can be combined and converted to datasets of net evaporation-precipitation depths recorded on *EV* records. A hydrologic model in *HYD* extends naturalized flow sequences by relating monthly naturalized flows to monthly precipitation and evaporation depths. Other program *HYD* methodologies facilitate various time series data manipulations and analyses.

The *WRAP* programs *SIM*, *SIMD*, *TABLES*, and *HYD* create and read Hydrologic Engineering Center (HEC) Data Storage System (DSS) files. The DSS interface program *HEC-DSSVue* is used for organizing, managing, manipulating, and displaying time series data, including the time series data in both the WAM simulation input datasets and the *SIM* and *SIMD* simulation results. WRAP/WAM applications of DSS files and *HEC-DSSVue* are explained in "*Chapter 6 HEC-DSS Data Storage System and HEC-DSSVue*" of the WRAP *Users Manual* [2] and discussed throughout the other WRAP manuals. DSS files always have the filename extension DSS.

The twenty monthly WAMs currently available at the TCEQ WAM website do not include DSS files. USACE Hydrologic Engineering Center (HEC) Data Storage System (DSS) files are incorporated in daily and modified monthly versions of the six daily and modified monthly WAMs discussed in this report. Binary DSS files and the *HEC-DSSVue* interface program are very useful when working with monthly WAMs and essential when working with daily WAMs. *HEC-DSSVue* is employed extensively in the analyses presented throughout this report.

## ***SIM* and *SIMD* Input Records for Simulating River System Hydrology**

The content and format of the *SIM/SIMD* input *IN*, *EV*, *CP*, *FD*, *WP*, *FA*, and *HI* records and *SIMD*-only *DF* record representing hydrology along with the other simulation input records representing water resources development/management/use (water rights) are explained in the *Users Manual* [2]. The use of the data from these input records within the simulation computations is explained in the *Reference* and *Daily Manuals* [1, 5].

River system hydrology is represented in the monthly simulation model *SIM* primarily by input sequences of naturalized stream flow volumes (*IN* records) and reservoir net evaporation less precipitation depths (*EV* records) for each month of the hydrologic period-of-analysis at each pertinent control point location. These same datasets of monthly naturalized stream flows and reservoir evaporation-precipitation rates (*IN* and *EV* records) are employed in a daily *SIMD* simulation. Conversion of a monthly WAM to daily includes addition of input datasets of daily flow pattern hydrographs (*DF* records) used within the *SIMD* simulation in disaggregating monthly naturalized flows to daily. Monthly evaporation-precipitation depths are uniformly subdivided to daily within the *SIMD* simulation without needing additional input data. *SIMD* knows the number of days in each of the twelve months and which years are leap years.

Additional data included in the WAM input datasets for both monthly *SIM* and daily *SIMD* simulations include watershed parameters (*CP*, *FD*, *WP* records) for distributing monthly naturalized flows from primary to secondary control points and channel loss factors entered on control point *CP* records. Forecasting and routing parameters are also required for a daily *SIMD* simulation if daily flow forecasting and routing options are activated. Forecasting and routing in *SIMD* are discussed in Chapter 2 of this report and Chapters 3 and 4 of the *Daily Manual* [5].

*SIM*, *SIMD*, and *HYD* include routines for incorporating channel losses in water accounting computations based on including loss factors for pertinent stream reaches in the control point *CP* record input data. Channel loss factors and the resulting simulated channel losses are also incorporated in the distribution of monthly naturalized flows from primary to secondary control points. Channel loss factors are included in the WAMs for selected relevant stream reaches while numerous other reaches are assigned no channel loss factors and thus do not employ channel loss computations. In compiling the WAM datasets, channel loss factors typically have been estimated based on water balance computations for stream reaches between gage sites.

Monthly naturalized flows at secondary control points are computed within a *SIM* or *SIMD* simulation from naturalized flows at primary control points input on *IN* records and watershed parameters input on *CP*, *FD*, and *WP* records. The parameter INMETHOD(cp) on the *CP* record allows selection between ten different options for synthesizing naturalized monthly flows at the particular control point. INMETHOD(cp) option 6 or 7 is activated for most of the secondary control points in the twenty WAMs. Naturalized flows are synthesized based on drainage area ratios and channel loss factors if channel loss factors are input (option 6) or just drainage area ratios (option 7). Sub-watersheds for the computations are selected with parameters on flow distribution *FD* records.

INMETHOD(cp) options 5 and 8 employ the Natural Resource Conservation Service (NRCS) curve number (CN) rainfall-runoff relationship [1, 2, 4, 54]. Option 8 also incorporates channel losses. Options 5 and 8 parameters are drainage area, CN, and mean annual precipitation input on watershed parameter *WP* records for pertinent watersheds or sub-watersheds. The WAMs include a flow distribution DIS file with sets of *WP* records with drainage area, CN, and mean precipitation. However, flow distribution options 6 and 7 have been adopted rather than options 5 and 8 due largely to concerns regarding the accuracy of the values for curve numbers (CNs).

The simulation modeling system is based on total stream flows, rather than incremental inflows. However, options are provided in *HYD*, *SIM*, and *SIMD* to address the issue of negative incremental monthly or daily naturalized flows [1, 2, 4, 5]. Negative incremental naturalized flows are a significant concern in monthly modeling and even much greater issue in daily modeling.

The term "*negative incremental stream flow*" refers to situations in which naturalized stream flow at upstream locations is greater than the naturalized stream flow further downstream in a particular month or day. The conceptual implications of negative incremental flows and computational options for dealing with negative incremental flow are explained in detail in the *Reference* and *Daily Manuals* [1, 5]. Adjustment options for dealing with negative incremental naturalized stream flows are activated by input parameter ADJINC on the *JD* record [2].

WRAP is a river/reservoir system water management modeling system with little capability for simulating interactions between surface water and groundwater or subsurface water. However, some interactions between stream flow and subsurface water may be modeled. Channel losses are modeled based on channel loss factors entered on *CP* records. Water supply return flows may originate from groundwater sources. Groundwater return flows have been modeled using constant inflow *CI* records in a DAT file. *WR* record type 4 right is another option. Changes in spring flows or stream base flows associated with aquifer pumping or management scenarios simulated with a groundwater model may be treated as *FA* record adjustments to naturalized stream flows.

## Compilation of Monthly Naturalized Stream Flows on *IN* Records

A *SIM* or *SIMD* simulation combines the following two sets of input data:

1. Data simulating a stationary fixed scenario of river/reservoir system development and water allocation, management, and use which are stored in a required simulation input file with filename extension DAT and perhaps in other optional input files.
2. Stationary hydrologic period-of-analysis sequences of monthly naturalized stream flow volumes and net reservoir evaporation less precipitation depths representing river system hydrology without the water development/management/use activities modeled by the data in the first dataset noted above.

The conceptual objective of stream flow naturalization is to develop flow sequences that reflect relevant characteristics of stream flows to be expected in the future without the effects of the water management endeavors and water use reflected in the first set of data listed above. This objective is achieved approximately by adjusting historical observed stream flows to remove the most significant effects of historical water resources development, management, and use. The resulting flows approximate natural undeveloped conditions and are called naturalized flows.

The twenty original WAMs were developed during 1998-2004, with hydrologic periods-of-analysis of 1940-1996, 1940-1997, 1940-1998, 1934-1989, 1934-1996, or 1948-1998. More than two decades of stream flow observations have accumulated since then. As indicated in Table 5.1, the hydrologic periods-of-analysis of six of the WAMs have been extended (updated) since the original versions by the TCEQ and consulting firm contractors [15, 73, 74, 75, 76, 77].

The term "conventional approach" is employed in this report to refer to the general computational strategy adopted by TCEQ in converting observed stream flows to naturalized flows in the original WAM compilations and later hydrology extensions. Other methods for extending (updating) the sequences of monthly naturalized flows have also been explored and applied as discussed later in this chapter and Chapter 6. These other alternative methods are employed in extending naturalized flows for the six daily WAMs forward past the hydrologic periods-of-analysis currently reflected in the official TCEQ monthly WAMs listed in Table 5.1.

TCEQ and its contractors compiled the monthly naturalized flows at primary control points representing stream flow gages for the WAMs listed in Table 5.1. The naturalized flows extend through the hydrologic periods-of-analysis shown in the second column of Table 5.1. This conventional approach to developing monthly naturalized stream flows consists of adjusting observed flows at gage sites to remove the effects of water resources development and use. The conversion of monthly observed flow volumes to naturalized flow volumes is viewed conceptually as follows.

Naturalized Flow = Historical Observed Flow + Upstream Diversions
– Upstream Return Flows from Surface Water Use
– Upstream Return Flows from Groundwater Use
+ Upstream Reservoir Evaporation – Upstream Reservoir Surface Precipitation
+ Increases in Upstream Reservoir Storage – Decreases in Upstream Reservoir Storage
+ or – other factors such as changes in spring flows or land use changes affecting rainfall runoff

The flow adjustments consist of quantities added to or subtracted from observed stream flows to compute naturalized stream flows. The effects of reservoirs, water supply diversions, and return flows at upstream locations are considered in the adjustments. Channel losses between upstream flow modifications and the site of the adjusted naturalized flows may be incorporated in the computations. The channel loss factors used in the flow naturalization process are also input on the control point *CP* records for use in the *SIM* or *SIMD* simulation. In many cases, channel loss factors of zero are assigned to stream reaches indicating that channel losses are treated as being negligible or insignificant in those reaches.

Most of the observed flows used in developing naturalized flows are from gages maintained by the U.S. Geological Survey (USGS). The International Boundary and Water Commission (IBWC) maintains gages on the Rio Grande. In some cases, measured releases from reservoirs have served as observed flows rather than USGS stream gage measurements.

Flow adjustments for effects of surface water development and use are relevant to all the WAMs. Stream flow adjustments for groundwater spring flows or effects of land use changes have also been incorporated in the development of naturalized flows for some locations in some WAMs.

Many thousands of storage facilities, water supply diversions at thousands of locations, return flows from water supplied by surface and groundwater sources, evapotranspiration and seepage losses in stream reaches, and many other factors affect stream flow. Past studies indicate that most of the effects of human activities on stream flow result from the largest reservoirs, largest water supply diversions, and largest return flows. Naturalized flows developed in the past are considered to be reasonably stationary and representative of undeveloped conditions.

## Methods for Intermediate Naturalized Flow Updates

TCEQ and engineering firm contractors have extended the hydrologic periods-of-analysis of the Brazos, Neches, Colorado, Red, Rio Grande, and Sulphur WAMs [15, 73, 74, 75, 76, 77]. Computational adjustments to observed monthly flows were performed to obtain the extensions of naturalized monthly flows in the same conventional manner employed in developing the original WAMs. These are the official hydrology extensions adopted by TCEQ for preparing and evaluating water use permit applications and otherwise administering water rights. Other more approximate hydrology extensions for the WAMs have been compiled as follows for intermediate use between the more expensive but less frequent official TCEQ hydrology updates.

### TWDB Hydrology Extensions

TWDB staff and regional planning groups use the TCEQ-maintained WAM datasets, including TCEQ hydrology extensions, in SB1 regional and statewide planning studies. TWDB staff perform additional updates as needed to support the SB1 planning studies performed in five-year planning cycles. TWDB intermediate extensions of *IN* record naturalized flow are based on linear regression with observed flows at the same site or other nearby sites [78]. TWDB staff employ the TWDB quadrangle evaporation and precipitation database discussed in Chapter 3 to extend *EV* records. The *IN* and *EV* record extensions are available online.
https://www.twdb.texas.gov/surfacewater/data/index.asp

TWDB hydrology (*IN* and *EV* record) extensions are available at the TWDB website for the following WAMs: Canadian, Cypress, GSA, Lavaca. Nueces, Red, Sabine, San Jacinto, Sulphur, and Trinity. The sets of *IN* and *EV* records extensions begin in the year immediately following the WAM hydrology periods-of-analysis shown in Table 5.1. As of late 2024, the *IN* and *EV* records had been extended through 2023.

### TCEQ-Sponsored Research and Development at TAMU

Chapters 7 through 12 of this report focus on daily and corresponding modified monthly WAMs for the Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces previously developed in TCEQ sponsored research at Texas A&M University [7, 8, 9, 10, 11, 12]. The following other alternative methods for updating naturalized flows have also been investigated with the developmental daily and modified monthly WAMs as discussed in Chapters 6 and 7-12.

- The WRAP program *HYD* includes a feature for developing hydrologic regression models for extending monthly naturalized flows based on complex calibrated relationships to monthly precipitation and reservoir evaporation depths [4]. The original monthly naturalized flows and observed monthly precipitation and reservoir evaporation depths are used for model calibration. Routines in program *HYD* have been used for complete or partial hydrology extensions for several of the WAMs.

- An earlier Trinity WAM naturalized flow extension combined (1) naturalized flows synthesized with the program *HYD* model noted above at sites with flows significantly affected by upstream water management and (2) unadjusted observed flows at locations that have experienced no significant effects of upstream water management [8].
- Daily observed flows were adjusted to remove effects of reservoirs for the daily Neches WAM. The adjusted daily observed flows were adopted as *DF* record daily flow pattern hydrographs and also summed to obtain *IN* record naturalized monthly flows [9].

Chapter 6 includes comparative investigations of the alternative hydrology extension strategies developed at TWDB and TAMU. A selected extended hydrology dataset adopted for each of the six individual WAMs is employed in the simulation studies of Chapters 7 through 12.

<u>*HYD* Flow Extension Model Based on Relating Flow to Precipitation and Evaporation</u>

The WRAP program *HYD* includes a hydrologic regression model with many empirical parameters requiring calibration that relates monthly naturalized stream flow to TWDB quadrangle monthly precipitation and reservoir evaporation depths. The TWDB quadrangle precipitation and reservoir evaporation database is described in the preceding Chapter 4. The program *HYD* hydrologic model is described in Chapters 6 and 8 of the *Hydrology Manual* [4]. The hydrologic model is calibrated for each individual primary control point using the original WAM period-of-analysis monthly naturalized flows and monthly precipitation and evaporation depths for selected relevant quadrangles. The calibrated model is then applied to synthesize naturalized flows for the extension period based on known precipitation and evaporation depths for the extension period.

Calibration of hydrologic regression models for each control point is complex requiring significant time and expertise. However, application of the calibrated models to extend naturalized flows is relatively simple. WAM naturalized flows can be conveniently extended following completion of the annual TWDB update of the precipitation and evaporation database each year.

The *HYD* hydrologic model is less accurate in most cases than the conventional approach for developing naturalized stream flows. The model replicates statistical characteristics of naturalized flows reasonably well but is too high or low in individual months. The *HYD* hydrologic model provides a convenient means for multiple intermediate flow extensions between infrequent but more accurate extensions employing the more expensive conventional approach.

The hydrologic regression model was added to the WRAP program *HYD* in conjunction with past WRAP research and development at TAMU sponsored by TCEQ. This past research included development of calibrated models for the Brazos [79], Trinity [80], Colorado [81], Neches [82], Sabine [83], and GSA [84] WAMs. The previously calibrated *HYD* hydrology models for the Brazos, Trinity, Colorado, and Neches WAMs were employed in the current work reported in Chapters 6-10 to update *IN* record naturalized monthly flows to extend through 2023.

## Reservoir Net Evaporation-Precipitation Depths on *EV* Records

Net evaporation minus precipitation depths in feet are recorded on *EV* records in the WAM datasets for each month of the hydrologic period-of-record. Each hydrologic period-of-record *EV* record sequence of evaporation-precipitation depths may be assigned to one or multiple reservoirs. The *EV* record "control point" identifiers simply label the set of *EV* records rather than refer to a specific site. This is unlike control points for stream flows that refer to specific sites on streams.

Evaporation from a reservoir and precipitation falling directly on the reservoir water surface are combined as a net evaporation minus precipitation. Net evaporation less precipitation volumes are computed in the *SIM* simulation by multiplying the reservoir water surface area in acres by net evaporation-precipitation depth in feet provided on *EV* records [1].

<u>Compilation of Net Evaporation-Precipitation Datasets</u>

Monthly precipitation and reservoir evaporation depths incorporated in the WAMs are from the following two sources: (1) the TWDB quadrangle database covering all of Texas discussed in the preceding Chapter 4 or (2) observations at weather stations located at individual reservoirs. Data from the TWDB database are employed for most of the reservoirs in the WAMs. Data from local precipitation gages and evaporation pans maintained by reservoir operators are adopted for some of the larger reservoirs.

Reservoir surface evaporation depths are computed by multiplying depths measured in standard evaporation pans by pan coefficients. The TWDB evaporation and precipitation online database website includes information regarding evaporation pan locations, pan coefficients, and computation of quadrangle averages. Precipitation depths reflect observations at precipitation gages. The TWDB website also describes the number and location of precipitation gages and methods for computing quadrangle averages. The number of gage sites vary over time.

The annually updated TWDB database of monthly precipitation depths and monthly reservoir evaporation depths for ninety-two quadrangles encompassing Texas is discussed in Chapter 4. For reservoirs crossing TWDB quadrangle boundaries, the data may represent averages for two, three, or four adjacent quadrangles. For large reservoirs with measurements at precipitation gages and evaporation pans maintained near to the reservoir, the observed data from multiple weather stations may be combined.

The TWDB online database includes 1940-present monthly precipitation depths in inches and 1954-present monthly gross lake evaporation rates in inches for ninety-two one-degree latitude by one-degree longitude quadrangles that encompass Texas. The data from this database are explored in Chapter 4 and employed in the WAMs discussed in  Chapters 5 through12.

<u>Computer Software</u>

The original WAM datasets, including the hydrology data, were developed during 1998-2004 by consulting firms hired by the TNRCC/TCEQ. Microsoft Excel and other spreadsheet software were used to compile the hydrology datasets of *IN* and *EV* records for the original WAMs and later updates and extensions discussed earlier in this chapter.

The WRAP program *HYD* was developed at TAMU with various capabilities added at different times during 1999-2012. All applications of *HYD* to date have been in research at TAMU.

The various routines in WRAP program *HYD* are designed for compiling and updating WAM hydrology and otherwise manipulating and analyzing hydrologic time series datasets. *HYD* includes features for reading, manipulating, and analyzing quadrangle monthly precipitation and evaporation depths from the TWDB database as well as other capabilities discussed elsewhere in this report. Program *HYD* routines for compiling and extending *EV* record monthly net evaporation-precipitation depths were used to update the *EV* records for the Brazos, Trinity, Colorado, and Neches daily WAMs as discussed in Chapter 6. *EV* record evaporation-precipitation extensions by the TWDB discussed in the preceding section were adopted for the Lavaca and Nueces daily WAMs along with the TWDB-synthesized *IN* record naturalized flow extensions.

The program *HEC-DSSVue* and features of *HYD* and the other WRAP programs for creating and accessing DSS files expand capabilities for developing and analyzing WAM hydrology datasets. *HEC-DSSVue* and DSS files are employed extensively in the daily WAM studies discussed later in this report.

## Precipitation Adjustments to Prevent Double-Counting

*SIM*, *SIMD*, and *HYD* include capabilities explained in Chapter 3 of the *Reference Manual* [1] 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. Without a reservoir, rainfall runoff from the land area covered by water stored in the reservoir would contribute to stream flow. However, without the reservoir, only a portion of the precipitation falling on the land 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/SIMD* includes options for computing precipitation adjustments to evaporation-precipitation depths within the simulation that are employed in the Brazos, Colorado-Lavaca Coastal, GSA, Lavaca-Guadalupe Coastal, and Nueces WAMs. Precipitation adjustments are reflected in the net evaporation-precipitation depths input on the *EV* records in the other WAMs. These adjustments were performed externally to *SIM* during the original compilation of the *EV* records. In this case, the automated adjustment algorithm incorporated within *SIM* is not employed.

### Net Evaporation-Precipitation Adjustments External to *SIM*

For some of the WAMs, an adjustment to prevent double-counting the precipitation falling on the reservoir water surface has been included in the input dataset of *EV* record net evaporation-precipitation depths. Although different variations of the adjustment methodology were adopted for different WAMs, the basic concept is to multiple the monthly precipitation depth by a factor representing a watershed runoff coefficient. Equation 5.1 expresses the conceptual strategy used to adjust net evaporation-precipitation depths from *EV* records to prevent double counting rainfall runoff included in both naturalized stream flow and precipitation on the reservoir water surface.

$$\text{Adjusted Net Evaporation-Precipitation Depth} = \text{Evaporation Depth} - \text{Precipitation Depth} + (\text{Precipitation Depth} \times \text{Runoff Coefficient}) \quad (5.1)$$

The runoff coefficient in Equation 5.1 represents the fraction of the rainfall falling on the land that runs off to the stream and becomes observed and naturalized stream flow. The runoff coefficient is a number between 0.0 and 1.0. The multiplier factor in Equation 5.2 is equivalent to one minus the runoff coefficient term of Equation 5.1.

$$\text{Adjusted Net Evaporation-Precipitation Depth} = \text{Evaporation Depth} - (\text{Precipitation Depth} \times \text{Multiplier Factor}) \qquad (5.2)$$

The WRAP program *HYD* includes a feature for adjusting the precipitation component of the net evaporation-precipitation depths in the compilation of the *EV* record dataset using Equation 5.2. Although similar to the precipitation adjustment procedures that were adopted in compilation of *EV* record datasets for several of the WAMs, the *HYD* feature has not actually been used in the past in developing WAMs. Microsoft Excel spreadsheets have been employed rather than *HYD*.

Optional *SIM* Feature for Adjusting Precipitation

An evaporation-precipitation adjustment computation within *SIM* and *SIMD* is activated as the default for all the reservoirs in a WAM by parameter EPADJ on the *JD* record [2]. EWA(cp) on the *CP* record allows different adjustment options to be applied to individual reservoirs [2]. An algorithm that is conceptually analogous to the drainage area ratio method for transferring stream flow is employed to compute the portion of the naturalized stream flow derived from precipitation falling on dry land that is now covered by the reservoir included in the simulation model. A precipitation adjustment depth is computed within *SIM* or *SIMD* for inclusion in Equation 5.3 where (Evaporation Depth – Precipitation Depth) is the depth in feet read from *EV* records.

$$\text{Adjusted Net Evaporation-Precipitation Depth} = (\text{Evaporation Depth} - \text{Precipitation Depth}) + (\text{Precipitation Depth Adjustment}) \qquad (5.3)$$

*SIM* or *SIMD* divides the monthly naturalized stream flow volume in acre-feet in each month of the hydrologic period-of-analysis at the specified control point by a specified watershed area in acres to obtain a depth in feet representing rainfall runoff volume. This approximation of rainfall runoff volume expressed as a depth per unit watershed area is added within the simulation computations to the net evaporation-precipitation depth for the month read from *EV* records. The watershed area of the reservoir is determined from *CP* and *FD*/*WP* record parameters. The area of the reservoir water surface is determined in the volume balance computations.

The feature for adjusting evaporation-precipitation depths for precipitation runoff from reservoir-covered land reflected in the naturalized flows was initially incorporated in the August 1999 version of *SIM* and restructured in the July 2001 *SIM* [13]. The feature was expanded and refined in the August 2025 version of *SIM*, providing greater flexibility and clarity particularly in regard to dealing with computed negative values of the precipitation adjustment term in Equation 5.3. The options that can be assigned as a default by EPADJ on the *JD* record or selected for individual reservoirs by EWA(cp) on the *CP* record are defined in Table 5.2 [1, 2].

The options labeled 1, 2, and 4 were added with the August 2025 versions of *SIM* and *SIMD*. The other options with "all" in the second column of Table 5.2 are included in preceding as well as the August 2025 *SIM* and *SIMD*. Negative precipitation depth adjustments (Equation 5.3) may occur in the computations as a result of negative incremental monthly naturalized flows. Options 1 and 2 change computed negative precipitation adjustments to zero.

Table 5.2
Precipitation Adjustment Options

| Option | Version | Description of EPADJ and EWA(cp) options |
|---|---|---|
| | | |
| 1 | 2024 | Incremental flow and watershed area for control point in *FD* record field 2. Computed negative precipitation adjustments are changed to zero. |
| −1 | all | Incremental flow and watershed area for control point in *FD* record field 2. Precipitation adjustments are applied even if negative. |
| 2 | 2024 | Incremental flow and watershed area for control point in *FD* record field 3. Computed negative precipitation adjustments are changed to zero. |
| −2 | all | Incremental flow and watershed area for control point in *FD* record field 3. Precipitation adjustments are applied even if negative. |
| 3 | all | No adjustment even if a default is specified by EPADJ on the *JD* record. |
| 4 | 2024 | Watershed area in square miles is read from *WP* record in DIS file. |
| 5 | all | Watershed area in square miles is entered for EWA(cp) on the *CP* record. |
| | | |

The August 2025 *SIM*/*SIM* includes a new feature activated by an added *JD* record parameter EPYEAR. More than half of the existing WAMs have *EV* records with evaporation-precipitation depths adjusted externally to *SIM* during compilation of the dataset. The optional EPYEAR feature allows the internal *SIM/SIMD* options listed in Table 5.2 to be applied to hydrology extensions without modifying the *EV* records covering the original period-of-analysis.

## Daily Flow Pattern Hydrographs

The WRAP simulation model *SIMD* can be employed without monthly naturalized flows by directly employing daily naturalized flows on *IN* or *DF* records in the input dataset. In this case, either *IN* or *DF* record flows serve directly as daily naturalized flows and naturalized flow disaggregation computations are not activated. However, the daily simulations discussed in this report are developed by converting monthly WAMs to daily with naturalized monthly flows disaggregated to daily using *DF* record daily flows to define within-month patterns. The monthly naturalized flow volumes are preserved.

The daily and monthly versions of the WAMs employ the same hydrology data with the following additional data added to the daily version. Daily flow pattern hydrographs are added on *DF* records for use within the *SIMD* simulation in disaggregating monthly naturalized flows to daily. Optionally, flow forecasting and routing can be activated as discussed in Chapter 2.

Monthly reservoir net evaporation-precipitation depths read from the *EV* records are distributed by *SIMD* uniformly over the multiple days of each month. No additional input data is needed for disaggregation of evaporation-precipitation depth from monthly to daily.

### *SIMD* Disaggregation of Monthly Naturalized Flows to Daily

The WRAP daily simulation model *SIMD* disaggregates monthly naturalized flow volumes to daily volumes in proportion to the flows in the daily pattern hydrographs while preserving the monthly volumes [5]. Although monthly and daily flow volumes in a *SIMD* simulation are in units of acre-feet, flow rates in cubic feet per second (cfs) or other units can be used for the *DF* record flow sequences defining patterns since only relative within each month, not absolute, quantities are relevant. However, the final daily flows adopted for the pattern hydrographs for the six daily WAMs are daily naturalized flow volumes in acre-feet/day as explained in the next paragraph.

Daily flows on *DF* records are compiled in units of cfs. A *SIMD* simulation is performed with these *DF* records in the *SIMD* hydrology input DSS file. *SIMD* simulation results including daily naturalized flows in acre-feet are recorded by *SIMD* in its simulation results DSS output file. The daily naturalized flows in acre-feet in the *SIMD* simulation results DSS file are converted to *DF* records which are copied within *HEC-DSSVue* to the *SIMD* hydrology input DSS file.

Input parameter DFMETH on the daily simulation options *JU* record controls the multiple alternative options for disaggregating monthly naturalized flows to daily. The default DFMETH option 4 is the standard alternative for almost all cases. DFMETH option 4 consists of employing *DF* record flow pattern hydrographs with automatic repetition as discussed below. DFMETH option 1 consisting of uniformly distributing the monthly naturalized flows to the days of each month requires no *DF* record daily flows. DFMETH option 1 is relevant in cases where daily variability is not relevant. The six daily WAMs employ primarily the standard DFMETH option 4, with option 1 used in special cases discussed in later chapters. None of the other alternative disaggregation options are used with the six daily WAMs.

Monthly naturalized stream flows are input for all primary control points and synthesized for all other control points (called secondary) in exactly the same manner in both *SIM* monthly and *SIMD* daily simulations. Monthly naturalized flows at many control points are disaggregated to daily naturalized stream flows using *DF* record daily flow pattern hydrographs input for a much smaller number of control points. The total number of control points in each of the six daily WAMs and the number of control points with *DF* records are shown in Table 6.1 of Chapter 6.

The *DF* records for one control point could conceptually be repeated for all control points. Adding different *DF* records for as many control points as practical increases the accuracy of capturing the differences in variability at different locations in the stream system. DFMETH option 4 employs *DF* record flow pattern hydrographs with automatic repetition. The automatic repetition algorithm employed within *SIMD* to repeat the same *DF* record pattern flows at any number of control points is explained on page 28 in Chapter 2 of the *Daily Manual* [5].

<u>*DF* Record Daily Flows in the Six Daily WAMs</u>

The periods-of-analysis for the original and latest daily WAMs are listed in in Table 6.1 of Chapter 6. Compilation of *DF* record daily flows for each daily WAM is described in the reports cited in row 2 of Table 6.1. The *DF* record daily flows compiled for the original daily WAMs continue to be used in the latest daily WAMs. Observed daily flows are used to extend the hydrologic periods-of-analysis for the *DF* records to cover the period shown in row 6.

Observed daily flows at USGS gage sites are the primary source of the *DF* record flows in the six daily WAMs. Preference was given to USGS gages with periods-of-record covering the entire WAM hydrologic periods-of-analysis. However, in some cases, the adopted gages have gaps of missing observed flows. In these cases, daily flows at other gages are used to fill in the gaps.

The majority of the daily flows recorded on *DF* records in the six daily WAMs are daily observed flows from USGS gages with no naturalization adjustments. However, the following other alternative forms of adjusted daily flows are included in the compilations.

- Unregulated daily flows from a USACE Fort Worth District modeling system for sites in the Brazos and Trinity River Basins for 1940-1997 and 1940-2009, respectively, are adopted for some of the *DF* record control points in the Brazos and Trinity WAMs.
- The observed daily flows at several control points representing USGS gage sites in the Neches WAM were adjusted to remove the effects of upstream reservoirs to develop 1940-2019 *DF* record flows. The 2020-2022 *DF* record flows in the Neches WAM are observed flows without adjustments.

*HEC-DSSVue* is used to download daily flows in cubic feet per second (cfs) from the National Water Information System (NWIS) website maintained by the USGS. Due to USGS modifications to the NWIS website, the latest version of *HEC-DSSVue* (Version 7) is required for downloads rather than previous versions. DSS version 7 was released by the USACE Hydrologic Engineering Center (HEC) in 2021, replacing DSS version 6. *HEC-DSSVue* can be downloaded free-of-charge from the Hydrologic Engineering Center website. The flow data are imported from the USGS website by selecting relevant stations from the Texas component.

Specification of "daily" results in all daily data being imported into the DSS file for the selected gages. Daily data other than flows, such as stage and water quality parameters, are easily deleted from the DSS file within *HEC-DSSVue*. Data manipulations such as conversion to *DF* record format are performed within *HEC-DSSVue*.

*DF* record daily flows in cfs defining within-month flow patterns for each month of the period-of-analysis are converted into daily naturalized flows in acre-feet by executing *SIMD*. The daily flows in the *SIMD* simulation results DSS file are transported to the DSS input file.

Hydrologic period-of-analysis sequences of daily flows recorded on *DF* records in the Colorado, Lavaca, and Nueces daily WAMs are based solely on unaltered daily observed flows from the USGS NWIS. The only daily flow data manipulations are filling in gaps of missing data by combining observed flows from multiple gage sites using *HEC-DSSVue*. Complete sequences of *DF* record flows at the number of control points tabulated in row 10 of Table 5.2 are provided covering the hydrologic period-of-analysis shown in row 6.

The majority of the *DF* record flows in the Brazos and Trinity daily WAMs are also simply observed daily flows at USGS gages downloaded from the NWIS into DSS files. Exceptions are the USACE unregulated flows discussed in the next paragraph.

The Fort Worth District of the U.S. Army Corps of Engineers (USACE) maintains a daily computational time step reservoir system simulation modeling system designed to support operations of nine and eight USACE multipurpose reservoirs in the Brazos and Trinity Basins, respectively, particularly flood control operations. Daily unregulated flows in the USACE modeling system are analogous to WAM naturalized flows. USACE unregulated flows are similarly developed by adjusting gaged flows to remove the effects of major reservoirs and water users, but the selection of sites and flow adjustments are focused on flood flows at and below the seventeen USACE reservoirs. Unregulated daily flows for 1940-1997 and 1940-2009 at sites in the Brazos and Trinity River Basins were obtained from the USACE Fort Worth District Office early in the TCEQ sponsored studies at TAMU investigating development of daily WAMs [7, 8].

The Neches daily WAM includes *DF* records for 17 of the 20 primary control points. The 2020-2022 daily flows are unadjusted daily observed flows. The 1940-2019 daily flows at some control points include adjustments to remove the effects of reservoirs located upstream as explained in the daily Neches WAM report [9]. The adjustments include storage changes and evaporation from and rainfall on water surfaces for selected large reservoirs.

A research study at TAMU reported as a Ph.D. dissertation [85] investigated the application of the SWAT Soil and Water Assessment Tool (https://swat.tamu.edu/) watershed rainfall-runoff model to synthesize WAM daily naturalized stream flows for use primarily as *DF* record daily flow pattern hydrographs. The Neches, Sabine, and Guadalupe and San Antonio (GSA) River basins served as case studies for the SWAT modeling research. Daily naturalized flows generated with SWAT were also summed to monthly naturalized flows. Issues that prevented actual adoption of this approach in compiling data for the WAMs include inaccuracies in generating reasonable low flows and the effort required to conduct the watershed modeling studies.

## Time Series Input Data for the *SIM* and *SIMD* Simulation Models

The different types of *SIM* and *SIMD* time series input data are listed in the following table replicated from Chapter 3 of the *Users Manual* [2]. Daily flows on *DF* records are used only in daily simulations as discussed in the preceding section and the *Daily Manual*. The other simulation input variables in Table 5.3 are sequences of quantities for each month of the hydrologic period-of-analysis that may be employed in either a monthly *SIM* or daily *SIMD* simulation.

Table 5.3
Simulation Time Series Input Datasets

| Time Series Data | *JO* or JU Record Switch | Alternative Input Files | Record Identifier |
|---|---|---|---|
| monthly naturalized flow volumes | INEV | DSS, DAT, FLO | IN |
| monthly evaporation-precipitation depths | INEV | DSS, DAT, EVA | EV |
| monthly naturalized flow adjustments | DSSFA, FAD | DSS, FAD | FA |
| regulated-unappropriated flow adjustments | DSSRU, RUF | DSS, RUF | RU |
| monthly hydrologic index | DSSHI | DSS, HIS | HI |
| water right targets or flow depletion limits | DSSTS | DSS, DAT, TSF | TS |
| *SIMD* daily flow pattern hydrographs | DFFILE | DSS, DCF | DF |

### IN, EV, FA, RU, HI, TS, and DF Records

Datasets of monthly naturalized flows and net evaporation-precipitation rates in acre-feet stored on *IN* and *EV* records are included in all the WAMs listed in Table 5.1 as discussed earlier in this chapter. Daily flows on *DF* records are included in all of the developmental daily WAMs discussed in this report. The Colorado, Guadalupe-San Antonio (GSA), Red, and Rio Grande WAMs (Table 5.1) include flow adjustment *FA* records with adjustments to *IN* record naturalized flows. The Brazos, Colorado, GSA, Rio Grande, and Lavaca-Guadalupe Coastal WAMs include hydrologic index *HI* records used in defining hydrologic conditions for instream flow *IF* record environmental flow requirements. Target series *TS* records are employed with the six case studies discussed in Chapters 7-12 to input monthly aggregations of daily instream flow targets computed in a daily *SIMD* simulation for inclusion in monthly *SIM* input datasets.

The time series input data are all assigned to control points with the exception of the *TS* record time series which are assigned to *IF* or *WR* record water rights. *HI* record hydrologic indices are identified by control point and referenced by *TO*, *LO*, *CV*, and/or *FS* records for water rights. *TS* record time series are required as specified by inclusion of *TS* records in sets of records accompanying *WR* or *IF* records that define water rights. *HI* record hydrologic indices are required if referenced by one or more *HC*, *TO*, *LO*, *CV*, and/or *FS* records associated with water rights.

Condensed Simulation Input Datasets

Applications of regulated-unappropriated flow adjustments on *RU* records are described in "*Chapter 4 SIM Input Datasets Based on Simulation Results"* of the *Hydrology Manual* [4]. *HYD* capabilities covered in Chapter 4 of the *Hydrology Manual* for incorporating *SIM* simulation results into *SIM* input datasets are generic for addressing various types of modeling issues. However, addition of the *RU* record to *SIM* was motivated by the concept of a condensed *SIM* input dataset described here in the next paragraph and in Chapter 4 of the *Hydrology Manual*. This methodology was developed and applied to the Brazos WAM in research at TAMU [94, 95].

The larger WAMs contain numerous control points, water rights, and reservoirs. The size of these datasets contributes to complexity in applying the WRAP/WAM modeling system. This complexity is necessary to support water right permitting and planning activities. However, certain operational planning applications may be enhanced by simplifying the simulation input datasets to focus on particular water management systems. A methodology referenced in the preceding paragraph develops a condensed dataset for a selected reservoir system that reflects the impacts of all water rights and accompanying reservoirs that are removed from the original WAM dataset. The *RU* record is employed to model a set of stream flows available to the selected reservoir system considering the effects of all other water rights contained in the original WAM that are not included in the condensed dataset.

Time Series Input Files

All WAM time series input data can be stored in a single DSS file shared by *SIM* and *SIMD* as illustrated by the six case studies presented in Chapters 7-12. A hydrology time series DSS file has a filename in the format rootHYD.DSS. Alternatively, the different types of data records can be stored in text files listed in the third column of Table 5.3. The record identifiers are placed in the first two columns of the text file records or as pathname part C in DSS records. The WAMs listed in Table 5.1 are comprised totally of text files with no DSS files. The alternative file types listed in the third column of Table 5.3 are employed. DSS files have not been adopted to date for the official monthly WAMs. All time series input datasets (Table 5.3) for six the developmental case study WAMs in Chapters 7-12 are stored in a single DSS file for each WAM.

# CHAPTER 6
# EXAMPLE WAM AND CASE STUDY WAMS

The first half of Chapter 6 is comprised of a hypothetical example simulation study that illustrates the basics of the WRAP simulation and analysis modes outlined in Chapter 2. The second half of the Chapter 6 introduces the six case studies reported in Chapters 7 through 12.

WRAP manuals and training resources are referenced on pages 14-15 of Chapter 1. The *Fundamentals Manual* provides a hypothetical but realistic example WAM with eleven control points and six reservoirs. Examples in the *Reference* and *Daily Manual*s build upon and extend the example in the *Fundamentals Manual*. Other simple examples illustrating specific modeling features are found throughout the manuals. Input data files for the examples in the manuals are available at the WRAP website along with the manuals. The additional introductory set of example simulations and analyses in this chapter are designed to further enhance basic instructional information regarding WRAP/WAM modeling prior to exploring the six complex case studies.

Earlier versions of daily Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces WAMs served as case studies in investigating daily WRAP modeling capabilities [7, 8, 9, 10, 11, 12]. Updated and refined versions of the six daily WAMs are presented in Chapters 7 through 12 of this 2025 report. Conversions of monthly WAMs to daily and other modifications to monthly WAMs are covered in each of the six case study chapters. Instream flow targets for SB3 EFS computed with daily WAMs are incorporated in monthly WAMs. Updated hydrology extensions through 2023 for each of the six WAMs are included in Chapters 7 through 12. Approximate hydrology extension strategies introduced in Chapters 5 and 6 and employed in Chapters 7 through 12 are designed for intermediate hydrology updates between more detailed updates providing greater accuracy but requiring more time and effort.

## Hypothetical Example of WAM Analyses

This hypothetical example consists of a series of illustrative simulations and analyses of water supply capabilities of Lake Palestine and environmental flow requirements downstream on the Neches River. The simple example WAM was created by excerpting information for control points NEPA and NENE from the Neches WAM discussed in Chapter 9. The locations of these two sites on the upper Neches River are shown on the basin map of Figure 9.2. Control point NEPA represents Backburn Crossing Dam impounding Lake Palestine with an authorized storage capacity of 411,840 acre-feet. Control point NENE is the site of the USGS gage on the Neches River near the city of Neches. Environmental flow standards (EFS) established through the process created by the 2007 Senate Bill 3 (SB3) at this gage site are included in the example WAM. Control points NEPA and NENE have watershed drainage areas of 839 and 1,145 square miles.

The example WAM is simplified by ignoring water development and use at all locations other than the two upper basin locations represented by control points NEPA and NENE. Management of water resources at these two locations is also significantly simplified in the example WAM. Comprehensive simulations with the complete WAM reflecting interconnected water management activities throughout the Neches River Basin as well as interbasin transfers are presented in Chapter 9. The simple hypothetical upper Neches WAM employed in the following simulations facilitates an instructional focus on the general logistics of WRAP/WAM modeling.

The following example WRAP/WAM simulation study includes the following simulations and analyses of water availability at this location in the upper Neches River Basin.

1. The municipal water supply firm yield of Lake Palestine is determined using *SIM*.
2. Allocation of water supply capabilities of Lake Palestine between firm municipal and additional interruptible supplies is simulated and a reliability analysis is performed.
3. A daily version of the WAM is developed.
4. Addition of SB3 EFS to the daily and monthly WAMs is explored.
5. A short-term conditional reliability modeling (CRM) analysis is performed.

*SIM* and *SIMD* Input Files

The example WAM employs variations of two *SIM* or *SIMD* input files with filenames Example.DAT and ExampleHYD.DSS. Input records in the DAT file are modified, added, or removed for the alternative simulations illustrating alternative analysis modes. The initial DAT file is replicated as Table 6.1. Pathnames for the time series records stored in the DSS input file are listed in Table 6.2. *IN*, *EV*, and *TS* records such as those contained in the hydrology time series DSS file have typically in the past been stored in separate FLO, EVA, and TSF files. These (*IN*, *EV*, *TS*) and other (*HI*, *DF*) time series input data records are combined in a single DSS file in the case studies of Chapters 7-12. The time series records in this WAM cover a hydrologic period-of-analysis extending from January 1940 through December 2023.

Table 6.1
Initial DAT File Used to Determine Firm Yield

```
**      1         2         3         4         5         6         7
**3456789012345678901234567890123456789012345678901234567890123456789012
**     !       !       !       !       !       !       !       !       !
JD    84    1940         1         1                     4
JO     6
FY        250000.  10000.   1000.    100.        Municipal
UC  UMUN    0.065   0.059   0.068   0.070   0.080   0.095
UC          0.122   0.121   0.100   0.086   0.069   0.065
CP  NEPA     NENE
CP  NENE      OUT
WR  NEPA       0.    UMUN19560430                               Municipal
WSPALEST 411840.
**  Reservoir storage volume (acre-feet) versus surface area (acres).
SVPALEST      0    2450    9750   26750   57550   80875  110050  159000  238109  317343  362620  411840
SAPALEST      0     600    1600    3500    6800    8750   10700   13750   17978   21678   23625   25562
ED
```

The twenty actual WAMs listed in Table 5.1 of Chapter 5 also include a flow distribution file with filename extension DIS containing parameters recorded on flow distribution *FD* and watershed parameter *WP* records used by *SIM* to synthesize monthly naturalized stream flows at secondary (ungaged) control points based on naturalized flows at primary (*IN* record) control points. However, monthly naturalized flows on *IN* records are included in the example DSS file for both control points NEPA and NENE and thus a DIS file is not needed for the example WAM.

Table 6.2
Pathnames for Records in *SIM* and *SIMD* Shared Hydrology Input DSS File

| Part A | Part B | Part C | Part D | Part E |
|---|---|---|---|---|
| Example | NEPA | IN | 01Jan1940-31Dec2023 | 1MON |
| Example | NENE | IN | 01Jan1940-31Dec2023 | 1MON |
| Example | NEPA | EV | 01Jan1940-31Dec2023 | 1MON |
| Example | NENE | DF | 01Jan1940-31Dec2023 | 1DAY |
| Example | NENE | TS | 01Jan1940-31Dec2023 | 1MON |

The first endeavor in the series of simulation analyses consists of computing the water supply firm yield of Lake Palestine. The DAT file in Table 6.1 is employed for this initial task. The DAT file is then modified as needed for other simulations required for the other analyses to be performed. The DAT file in Table 6.1 begins with comment records that number the columns or characters on the other records. Courier new font adopted for the DAT file results in evenly spaced characters. The first two characters of each record serve as labels defining record type. Comment records beginning with two asterisks ** are not read by the computer but provide information for people who read the DAT file. The two asterisks can also be used to deactivate records without removal. The 61 types of records that can be included in both *SIM* and *SIMD* input files and 16 other *SIMD*-only records are each explained in detail in the *Users Manual* [2]. The parameters on all the input record types (**, *JD*, *JO*, *FY*, *UC*, *CP*, *WR*, *WS*, *SA*, *SV*, *ED*) in the DAT file of Table 6.1 are explained in the *Fundamentals Manual* [4] as well as *Users Manual*.

The Hydrologic Engineering Center (HEC) Data Storage System (DSS) is discussed in *″Chapter 6 HEC-DSS Data Storage System and HEC-DSSVue″* of the WRAP *Users Manual* and throughout the WRAP manuals as well as throughout this report. Only software with DSS capabilities such as WRAP programs *SIM*, *SIMD*, *TABLES*, and *HYD* read and create binary DSS files. *HEC-DSSVue* provides flexible capabilities for managing, organizing, plotting, analyzing, and manipulating time series datasets stored in DSS files. The pathnames for the *IN*, *EV*, *DF*, and *DF* records stored in the file ExampleHYD.DSS are listed in Table 6.2. The *IN*, *EV*, and *TS* records are each comprised of 1,008 quantities for the 1,008 months of 1940-2023. The *DF* record contains 30,681 daily flows. Only the *IN* and *EV* records are employed in the first simulations discussed on the next page. The *DF* and *TS* records are employed in simulations discussed later.

*SIM* and *SIMD* read only relevant data from a DSS file, skipping any records not needed. With DAT and other text files, *SIM* and *SIMD* read all records except comment (**) records or records stored after the end-of-data *ED* record. A simulation may be limited to a subset of the years covered by the time series input records by *JD* record parameters NYRS and YRST. For example, as discussed in Chapter 9, the 2019-2023 *IN* and *EV* record extension may be more approximate than 1940-2018 data. Simulations can be limited to 1940-2018 by changing NYRS from 84 to 79.

<u>Firm and Interruptible Water Supply</u>

The *SIM* input DAT file replicated as Table 6.1 is used to compute the firm yield for a municipal water supply diversion from Lake Palestine. Monthly naturalized stream flows in acre-feet and reservoir evaporation-precipitation depths in feet are read by *SIM* from *IN* and *EV* records stored in the hydrology input DSS file (Table 6.2). The iterative firm yield computations are controlled by the firm yield *FY* record in the DAT file. The resulting yield/reliability output file with filename extension YRO is replicated as Table 6.3.

Table 6.3
Yield/Reliability Output YRO File

```
          One right (100%): Municipal

  If more than one right, the target amount is distributed using the percentages
  shown above. The total number of periods is 1008. The period reliability is the
  percentage of the periods for which at least 100.0 percent (FY record field 2;
  default=100%) of the target is supplied.

  The table ends with the maximum target that results in a mean annual shortage
  of less than 0.05 units if such a firm yield is possible.
```

| Iteration | Level | Annual Target | Mean Shortage | Mean Actual | Volume Reliability (%) | Periods Without Shortage | Period Reliability (%) |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 250000.0 | 3823.5 | 246176.5 | 98.47 | 980 | 97.22 |
| 2 | 1 | 240000.0 | 2460.3 | 237539.7 | 98.97 | 988 | 98.02 |
| 3 | 1 | 230000.0 | 1421.6 | 228578.4 | 99.38 | 998 | 99.01 |
| 4 | 1 | 220000.0 | 747.7 | 219252.3 | 99.66 | 1002 | 99.40 |
| 5 | 1 | 210000.0 | 270.8 | 209729.2 | 99.87 | 1005 | 99.70 |
| 6 | 1 | 200000.0 | 0.00 | 200000.0 | 100.00 | 1008 | 100.00 |
| | --- | | | | | | |
| 7 | 2 | 209000.0 | 221.5 | 208778.5 | 99.89 | 1005 | 99.70 |
| 8 | 2 | 208000.0 | 172.1 | 207827.9 | 99.92 | 1005 | 99.70 |
| 9 | 2 | 207000.0 | 122.7 | 206877.3 | 99.94 | 1006 | 99.80 |
| 10 | 2 | 206000.0 | 72.9 | 205927.1 | 99.96 | 1006 | 99.80 |
| 11 | 2 | 205000.0 | 23.1 | 204976.9 | 99.99 | 1006 | 99.80 |
| 12 | 2 | 204000.0 | 0.00 | 204000.0 | 100.00 | 1008 | 100.00 |
| | --- | | | | | | |
| 13 | 3 | 204900.0 | 18.1 | 204881.9 | 99.99 | 1006 | 99.80 |
| 14 | 3 | 204800.0 | 13.2 | 204786.8 | 99.99 | 1006 | 99.80 |
| 15 | 3 | 204700.0 | 8.18 | 204691.8 | 100.00 | 1006 | 99.80 |
| 16 | 3 | 204600.0 | 3.21 | 204596.8 | 100.00 | 1006 | 99.80 |
| 17 | 3 | 204500.0 | 0.00 | 204500.0 | 100.00 | 1008 | 100.00 |
| | --- | | | | | | |
| 18 | 4 | 204590.0 | 2.71 | 204587.3 | 100.00 | 1006 | 99.80 |
| 19 | 4 | 204580.0 | 2.21 | 204577.8 | 100.00 | 1006 | 99.80 |
| 20 | 4 | 204570.0 | 1.71 | 204568.3 | 100.00 | 1006 | 99.80 |
| 21 | 4 | 204560.0 | 1.21 | 204558.8 | 100.00 | 1007 | 99.90 |
| 22 | 4 | 204550.0 | 0.70 | 204549.3 | 100.00 | 1007 | 99.90 |
| 23 | 4 | 204540.0 | 0.18 | 204539.8 | 100.00 | 1007 | 99.90 |
| 24 | 4 | 204530.0 | 0.00 | 204530.0 | 100.00 | 1008 | 100.00 |

The firm yield *FY* record described in the *Users* and *Fundamentals Manuals* [2, 4] activates the iterative yield-reliability analysis algorithm further explained in Chapter 6 of the *Reference Manual* [1]. The *FY* record in Table 6.1 controls an automated iterative search for the maximum annual diversion volume for the specified water right that has volume and period reliabilities of 100.0%. Optional extensions of the yield-reliability analysis feature not employed in this example along with the basic procedure illustrated by the example are described in the manuals [1, 2, 4].

Following *FY* record specifications in the DAT file of Table 6.1, *SIM* repeated the 1940-2023 simulation 24 times, changing the annual diversion amount AMT of *WR* record field 3 after each simulation. In the yield-reliability mode activated by the *FY* record, AMT for the specified water right is not read from the *WR* record and thus the *WR* record AMT entry can be blank or any number. The estimated firm yield of Lake Palestine is 204,530 acre-feet/year (Table 6.3).

In reservoirs throughout Texas, the volume of water committed for beneficial use can be significantly increased by accepting computed reliabilities of less than 100.0%. In many cases, diversion volumes may be increased greatly with perhaps relatively small decreases in reliability. By definition, firm yield has a reliability of 100% and interruptible yield a reliability of less than 100% based on the premises and assumptions reflected in the simulation model. Firm and interruptible water supply commitments from the same reservoir can be combined. Operating rules can include complete curtailment or partial reduction of the interruptible water supply commitment whenever the reservoir storage level drops below a predetermined level.

In this example, a maximum volume of 204,530 acre-feet/year can be supplied from Lake Palestine for municipal use without shortage during a hypothetical repetition of 1940-2023 natural hydrology based on the premises and assumptions reflected in the *SIM* simulation model and WAM input dataset. The 204,530 acre-feet/year is called a firm yield. Water supply commitments greater than 204,530 acre-feet/year can be managed by combining firm and interruptible commitments. WRAP/WAM simulation studies can be performed to analyze relationships between firm and interruptible water supply volumes and reliabilities. Tradeoffs between firm and interruptible supplies and between supply volume and reliability can be evaluated.

In the following example, a reservoir storage trigger of 50% of storage capacity is adopted for curtailing interruptible water supply commitments. The authorized storage capacity of 411,840 acre-feet in Lake Palestine is managed to supply both firm and interruptible water supply commitments. Interruptible commitments will be supplied only when the storage level is above 205,920 acre-feet (50% of capacity). Monthly water use quantities equivalent to a full annual supply of 100,000 acre-feet/year will be supplied to the extent that water is available in storage above 205,920 acre-feet. Annual demands (AMT on *WR* records) for firm and interruptible use are allocated to the 12 months of the year in proportion to the 12 monthly factors on use coefficient *UC* records labeled UMUN and UINT, respectively, in the DAT file of Table 6.4.

Addition of the interruptible diversion commitment will reduce the municipal diversion firm yield to 183,160 acre-feet/year, computed using the DAT file of Table 6.4 with the *FY* record activated. The *FY* record is then deactivated in the DAT file of Table 6.4 by commenting-out the record with **. A new firm diversion is set at the new firm yield of 183,160 acre-feet/year. The annual diversion amount AMT of 183,600 is inserted on the *WR* record.

A *SIM* simulation is performed with the DAT file of Table 6.4 along with a *TABLES* 2REL record analysis of simulation results to assess supply reliabilities for the interruptible water right. *SIM* produces an output OUT file of simulation results read by program *TABLES*. A *TABLES* input TIN file with a reliability 2REL record generates the table of reliability metrics recorded in a TOU file that is replicated as Table 6.5. These water supply reliability metrics serve as estimates of likelihood, probability, or frequency of supplying the specified water use targets. Period reliability [$R_P$=(n/N)100%] and volume reliability [$R_V$=(v/V)100%] are primary measures of supply capabilities.

Table 6.4
DAT File for Monthly *SIM* Simulation

```
**       1         2         3         4         5         6         7
**3456789012345678901234567890123456789012345678901234567890123456789012
**     !       !       !       !       !       !       !       !       !
JD    84    1940       1       1                       4
JO     6
OF     1   0   1   1
OFV    9
**FY       200000.  10000.   1000.    100.       Municipal
UC  UMUN   0.065   0.059   0.068   0.070   0.080   0.095
UC         0.122   0.121   0.100   0.086   0.069   0.065
UC  UINT   0.010   0.022   0.051   0.075   0.087   0.135
UC         0.144   0.160   0.130   0.091   0.068   0.027
CP  NEPA    NENE
CP  NENE     OUT
WR  NEPA 183160.    UMUN19560430                                Municipal
WSPALEST 411840.
WR  NEPA 100000.    UIRR19560430                                Interruptible
WSPALEST 411840.                             205920.
**  Reservoir storage volume (acre-feet) versus surface area (acres).
SVPALEST      0    2450    9750   26750   57550   80875  110050  159000  238109  317343  362620  411840
SAPALEST      0     600    1600    3500    6800    8750   10700   13750   17978   21678   23625   25562
ED
```

Table 6.5
Program *TABLES* Output TOU File With Reliability Summary for Water Rights

| NAME | TARGET DIVERSION (AC-FT/YR) | MEAN SHORTAGE (AC-FT/YR) | *RELIABILITY* PERIOD (%) | *RELIABILITY* VOLUME (%) | PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING 100% | 95% | 90% | 75% | 50% | 25% | 1% | PERCENTAGE OF YEARS PERCENTAGE OF TARGET DIVERSION AMOUNT 100% | 98% | 95% | 90% | 75% | 50% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Municipal | 183160.0 | 0.00 | 100.00 | 100.00 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Interruptible | 100000.0 | 24305.96 | 75.60 | 75.69 | 75.6 | 75.6 | 75.7 | 75.8 | 76.4 | 76.9 | 77.1 | 54.8 | 58.3 | 59.5 | 61.9 | 67.9 | 76.2 |
| Total | 283160.0 | 24305.96 | | 91.42 | | | | | | | | | | | | | |

The water right identifiers on the *WR* records are *"Municipal"* and *"Interruptible*". Monthly diversion targets consist of an annual target from a *WR* record allocated to the 12 months of the year in proportion to the 12 factors on a *UC* record. With the municipal diversion set at the previously computed firm yield, volume and period reliabilities are 100.00% in Table 6.5. The interruptible diversion has period and volume reliabilities of 75.60% and 75.69% in Table 6.5.
[$R_P$=(n/N)100%=(762/1,008)(100%)=75.60% & $R_V$=(100,000-24,305.96)/100,000)(100%)=75.69%]

The percentage of the 1,008 months and 84 years of the 1940-2023 simulation during which at least specified percentages of the monthly or annual targets are supplied are also included in the *TABLES* 2REL record reliability table. The full 100.0% of the monthly interruptible diversion target is supplied during 75.60% of the 1,008 months of the 1940-2023 simulation. At least 75% of the monthly interruptible target is supplied during 75.8% of the 1,008 months. At least 75% of the annual target of 100,000 acre-feet/year is supplied during 67.9% of the 84 years. The full annual target of 100,000 acre-feet/year is supplied during 54.8% of the 84 years.

The addition to the WAM of an interruptible diversion of 100,000 acre-feet/year with reliability metrics shown in Table 6.5 is accompanied by a 21,370 acre-feet/year reduction in the firm municipal water supply. The firm yield is reduced 21,370 from 204,530 to 183,160 acre-feet/year. The reservoir operating plan includes setting the top of inactive (bottom of active) storage level at 205,920 acre-feet (50% of capacity) for the interruptible irrigation water supply. Additional similar analyses can be performed by setting the inactive storage volume on the *WS* record for the interruptible irrigation right at different levels. Each alternative operating plan (storage trigger level) will result in different tradeoffs between firm and interruptible supplies.

Reliability estimates reflect all approximations and premises inherent in the WRAP simulation model *SIM* and WAM datasets. The *TABLES* 2REL reliability statistics in Table 6.5 are based on the *SIM* input DAT file of Table 6.4 with *IN* and *EV* records in the DSS file referenced in Table 6.2. Water managers know that droughts more hydrologically severe than the most severe drought during 1940-2023 will occur sometime in the future but the timing is unknown. Figure 6.1 is a *HEC-DSSVue* plot of *SIM* simulated 1940-2023 reservoir storage volumes generated by the example WAM of Table 6.4. The 1,008 end-of-month reservoir storage contents from the *SIM* simulation provide both a drought index and measure of water availability.

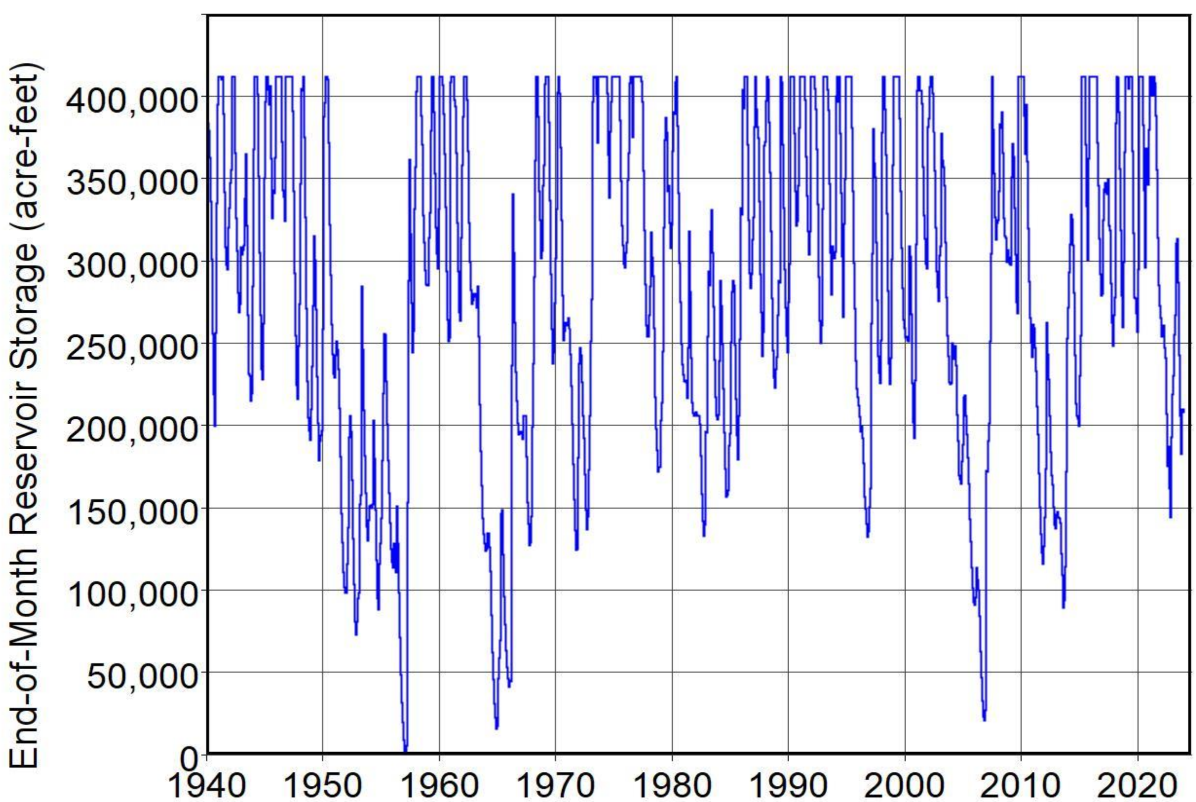


Figure 6.1 Simulated Monthly Reservoir Storage Contents

Monthly naturalized stream flows in acre-feet at control points NEPA and NENE compared in Figure 6.2 were compiled as described in Chapter 9. Control points NEPA and NENE have watershed drainage areas of 839 and 1,145 square miles, respectively. The river channel between the two control points is about 20 miles long [9]. Although considered in certain stream reaches in other WAMs in Table 5.1, channel losses are not considered in the Neches WAM or this example.

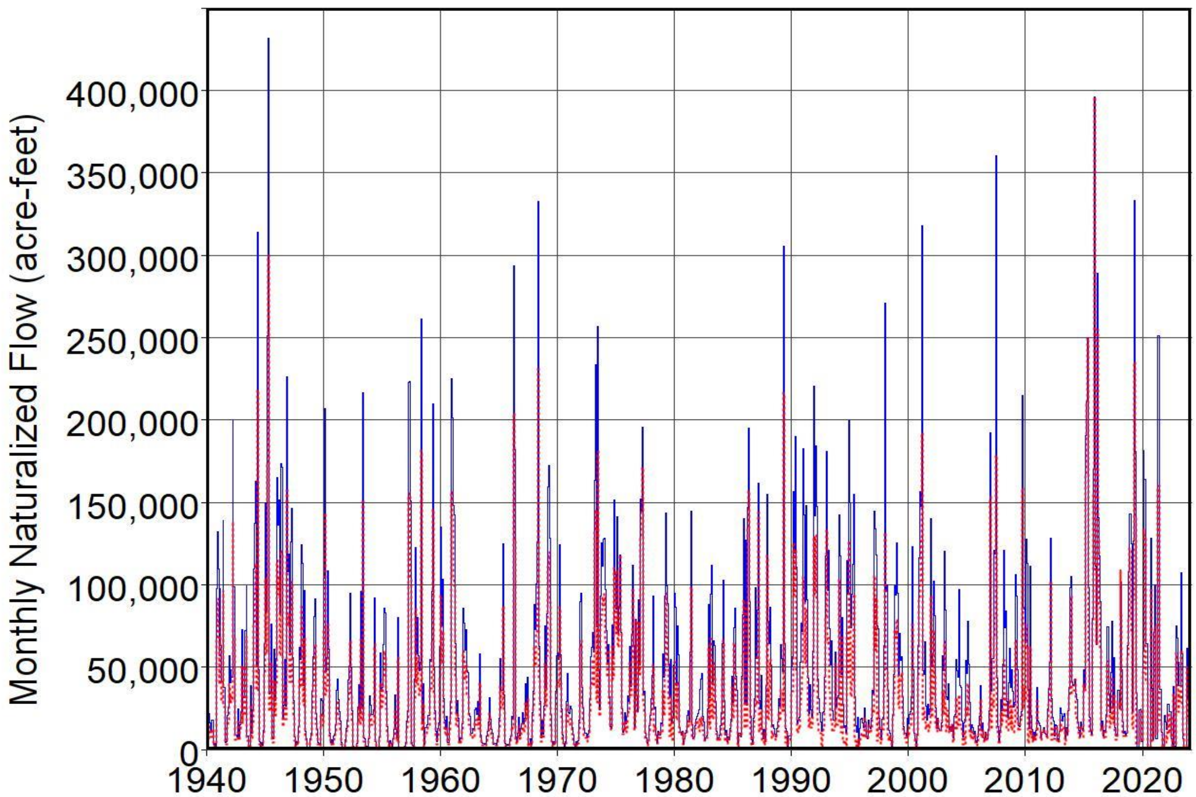

Figure 6.2 Monthly Naturalized Flow (ac-ft) at NENE (**blue line**) and NEPA (**red dots**)

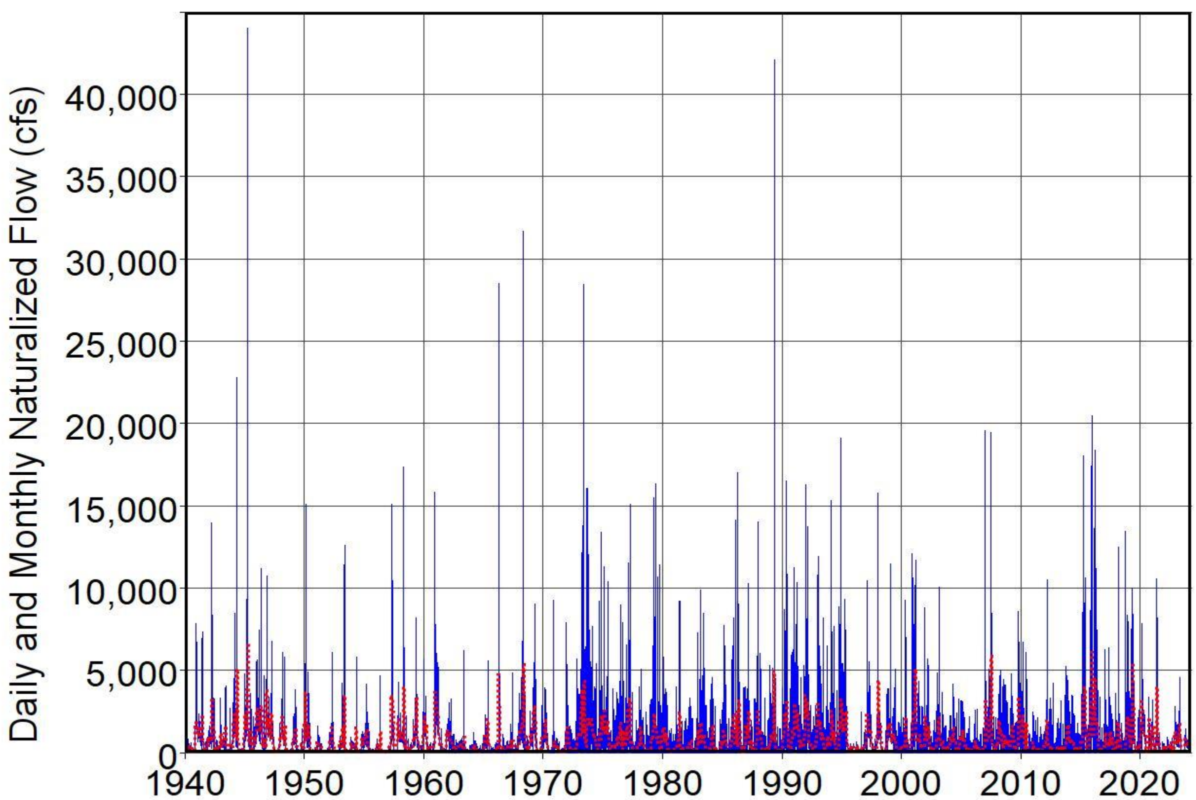

Figure 6.3 Daily (**blue line**) and Monthly (**red dots**) Naturalized Flow (cfs) at NENE

The term ″*negative incremental*″ refers to the monthly naturalized flow at a downstream location being less than flow upstream. There are no negative incrementals in the monthly naturalized flows at the upstream and downstream sites of Figure 6.2. Therefore, no negative incremental flow adjustments are performed in the *SIM* simulation, and ADJINC option 4 specified in column 56 of the *JD* record of Figures 6.1 and 6.4 is not relevant. However, negative incremental flows and associated adjustment options may be a significant complexity in complex WAMs.

Monthly and daily naturalized flows in cubic feet per second (cfs) at control point NENE are compared in Figure 6.3. Monthly and daily volumes in acre-feet are converted within *HEC-DSSVue* to consistent units of cfs for comparison. Monthly naturalized flows at this site and throughout Texas are extremely variable over time even though the within-month variability is removed in the monthly aggregation. Daily flows exhibit much greater variability than monthly flows. Flows over a hourly or 5-minute time step will exhibit greater variability than daily flows.

The following statistics provide a further comparison of the daily versus monthly naturalized flows of the Neches River at the gage near the city of Neches plotted in Figure 6.3. The 30,681 mean daily naturalized flows during 1940-2023 range from 0.000 to 44,013 cfs with a 1940-2023 mean and median (50% exceedance frequency) of 807.4 cfs and 302.6 cfs. The 1,008 mean monthly flows range from 0.000 to a maximum of 6,623 cfs with a 1940-2023 mean and median of 782.4 cfs and 404.0 cfs, respectively. The difference between 1940-2023 means of 807.4 cfs versus 782.4 cfs for daily and monthly means is due to the varying number of days (28, 29, 30, 31) in each month.

Short-Term Conditional Reliability Modeling

Conditional reliability modeling (CRM) is explained in Chapter 8 of the *Reference Manual* [1]. Short-term water availability over the next month, several months, irrigation season, year, or perhaps longer is conditioned upon present or beginning reservoir storage contents. The storage frequency table for Lake Palestine in Table 6.6 is created with *SIM* and *TABLES*. The following conditional reliability *CR* record inserted in the *SIM* DAT file of Table 6.4 activates CRM.

**CR 12 5 0 0.5**

Simulations of length 12 months beginning in May (5) are performed by *SIM* with each simulation beginning with Lake Palestine 50% (0.5) full. *TABLES* is executed with the following TIN file.

```
5CRM
2FRE   4
ENDF
```

Without the *CR* record, execution of *SIM* with the DAT file of Table 6.4 results in a single simulation covering the 1,008 months of the 1940-2023 hydrologic period-of-analysis with, by default, Lake Palestine being full to its capacity of 411,840 acre-feet at the beginning of the 84-year simulation. Options are also availability to start the conventional long-term simulation with beginning reservoir storage contents set at any specified level. With the *CR* record shown above inserted in the DAT file, *SIM* divides the 1940-2023 hydrologic period-of-analysis into 83 sequences of 12 months duration, with each sequence extending from May through the next April. *SIM* performs 83 simulations of 12 months duration with the storage in Lake Palestine set at 205,920 acre-feet (0.50 x 411,840 acre-feet) at the beginning of each simulation.

Table 6.6
Reservoir Storage Frequency

STORAGE-FREQUENCY FOR SPECIFIED CONTROL POINTS

**CONDITIONAL RELIABILITY MODELING: Equal-Weight Option**
**Annual cycles starting in month 5**
**Length of simulation period (CR1) = 12 months**
**Number of simulations and months = 83 and 996 (CR3= 0)**
**Initial storage multiplier (CR4) = 0.500**

| CONTROL POINT | MEAN | STANDARD DEVIATION | 100% | 99% | 98% | 95% | 90% | 75% | 60% | 50% | 40% | 25% | 10% | MAXIMUM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | PERCENTAGE OF MONTHS WITH STORAGE EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE | | | | | | | | | | | |
| NEPA | 227391. | 91428. | 67803. | 82790. | 91163. | 109519. | 127609. | 158167. | 187783. | 204462. | 222701. | 286703. | 387029. | 411840. |
| Total | 227391. | 91428. | 67803. | 82790. | 91163. | 109519. | 127609. | 158167. | 187783. | 204462. | 222701. | 286703. | 387029. | 411840. |

The *CR* record in the DAT file provides various options for organizing the multiple short-term *SIM* simulations having the same specified beginning storage contents. The 5CRM record in the TIN file activates an analysis option in *TABLES* that is based on the results of each *SIM* simulation sequence being weighted equally. Alternatively, 5CRM1 and 5CRM2 records activate *TABLES* options employing a more complex statistical analysis framework. *TABLES* provides a flexible array of analyses of *SIM* input datasets and simulation results. Variations of several of the tables created by *TABLES*, including the frequency 2FRE and reliability 2REL tables, are applicable to CRM as well as conventional long-term simulation results. The 2FRE record creating Table 6.7 specifies inclusion of all control points that have reservoirs, but other 2FRE options allow the table to include any number of either specified reservoirs, control points, or water rights.

The 2FRE frequency table replicated as Table 6.6 begins with the mean and standard deviation of 227,391 ac-ft and 91,428 ac-ft of storage contents of Lake Palestine at the end of each of the 83 twelve-month simulations (end of April) given that each of the 83 simulations begins with a storage content of 411,840 acre-feet at the beginning of May. The other storage volume quantities in the table are storage volumes at the end of the 12-month simulation that are equaled or exceeded in 100%, 99%, 98%, 95%, 90%, 75%, 60%, 50%, 40%, 25%, and 10% of the 83 *SIM* simulations. The last column of Table 6.6 is the maximum storage contents at the end of any of the 83 simulations, which happens to be full to the storage capacity of 411,840 acre-feet. The CRM 2FRE frequency table of Table 6.6 can be interpreted as follows. With the reservoir half (50%) full at the beginning of May, there is an estimated 75% likelihood or probability that the storage content with be at or above 158,167 acre-feet twelve months into the future.

Daily Simulation Model

Development of daily WRAP/WAM modeling capabilities over the past several years has been motivated by the environmental flow standards (EFS) established through the process mandated by the 2007 Senate Bill 3 (SB3). Table 6.7 is the daily version of the DAT file of Table 6.3 with SB3 EFS added. The *JT*, *JU*, and *DF* records in the DAT file of Table 6.7 and the *DF* record in the DSS file of Table 6.2 convert the monthly WAM to daily. SB3 EFS at control point NENE are added as a set of *IF*, *ES*, and *PF* records

Table 6.7
DAT File for Daily *SIM* Simulation

```
**       1         2         3         4         5         6         7
**3456789012345678901234567890123456789012345678901234567890123456789012
**     !       !       !       !       !       !       !       !       !
JD    84    1940       1       1                       4
JO     6
JT
JU
OF     1   0   1   1
OFV    9
UC  UMUN   0.065   0.059   0.068   0.070   0.080   0.095
UC         0.122   0.121   0.100   0.086   0.069   0.065
UC  UIRR   0.010   0.022   0.051   0.075   0.087   0.135
UC         0.144   0.160   0.130   0.091   0.068   0.027
CP  NEPA    NENE
CP  NENE     OUT
WR  NEPA 183160.    UMUN19560430                                Municipal
WSPALEST 411840.
WR  NEPA 100000.    UIRR19560430                                Irrigation
WSPALEST 411840.                         205920.
**  SB3 EFS
IF  NENE     -9.        20091130   2          IF-NENE-ES
ES SUBS     51.     51.     51.     21.     21.     21.     12.     12.     12.     13.     13.     13.
ES BASE    196.    196.    196.     96.     96.     96.     46.     46.     46.     80.     80.     80.
IF  NENE     -9.        20091130   2          IF-NENE-PF
ES PFES
PF   1 0    833.  19104.  10   1       1   3           2
PF   1 0    820.  20405.  12   2       4   6           2
PF   1 0    113   13390.   4   1       7   9           2
PF   1 0    345    5391.   8   2      10  12           2
**  Reservoir storage volume (acre-feet) versus surface area (acres).
SVPALEST      0    2450    9750   26750   57550   80875  110050  159000  238109  317343  362620  411840
SAPALEST      0     600    1600    3500    6800    8750   10700   13750   17978   21678   23625   25562
ED
```

The *JT* record in the daily DAT file activates a daily computational time step. Disaggregation of monthly naturalized stream flows to daily is the key aspect of converting a monthly WAM to daily. Default flow disaggregation option 4 activated on the *JU* record of Table 6.7 disaggregates monthly naturalized flows to daily in proportion to *DF* record daily flows while preserving monthly volumes. The daily flow *DF* record in the DAT file (Table 6.7) connects to the *DF* record in the DSS file (Table 6.2) which contains daily flows in acre-feet/day at control point NENE for the 30,561 days of 1940-2023. Daily flows on *DF* records were compiled for the Neches WAM at 17 control points as explained in Chapter 9, but only the *DF* record for control point NENE is included in this Chapter 6 example.

*SIMD* includes optional capabilities for routing changes in stream flow and forecasting future flows [2, 5]. Routing and forecasting are not adopted for this example and the Neches WAM of Chapter 9 for reasons discussed in Chapter 9 and elsewhere in this report. However, the Neches WAM includes calibrated routing parameters for 19 river reaches connecting 20 control points representing gage sites. The approximately 20-mile long river reach between control points NEPA and NENE is estimated to have a lag of about 1.3 to 1.4 day and attenuation of 1.0 day.

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

The SB3 EFS for control point NENE are included in the DAT file for this example replicated as Figure 6.7. The SB3 EFS at five USGS gage sites described in Table 9.19 adopted on April 20, 2011 with a priority date of November 30, 2009 are described in Chapter 9. Metrics for the five sites are tabulated as Tables 9.20 and 9.21. Sets of instream flow *IF*, environmental standard *ES*, and pulse flow *PF* records modeling the SB3 EFS at each of the five sites are replicated in Table 9.22. *IF*, *ES*, and *PF* records for control point NENE are included in Table 6.7. Although employed in other WAMs discussed in this report, hydrologic condition *HC* records are not needed for the Neches WAM because hydrologic condition was not adopted by the science team, stakeholder committee, and TCEQ in 2011 as a parameter in defining the SB3 EFS.

Statistics for 1940-2023 daily flows and SB3 EFS targets and shortages at the five locations are tabulated in Table 9.26 of Chapter 9. Means of daily quantities from the full authorization daily Neches WAM (Chapter 9) in cfs for control point NENE tabulated in Table 9.26 are as follows: observed flow (699.0 cfs), naturalized flow (807.4 cfs), regulated flow (446.1 cfs), unappropriated flow (188.9 cfs), combined SB3 EFS targets (100.6 cfs), high flow pulse targets (36.18 cfs), subsistence and base flow targets (72.31 cfs), and SB3 EFS target shortages (2.100 cfs).

SB3 EFS are a major focus of the six case studies of Chapters 7 through 12. The following modeling strategy is applied in each case study. A daily *SIMD* simulation is executed to compute daily and aggregated monthly targets for the SB3 EFS. The *SIMD* monthly SB3 EFS targets are added to the monthly *SIM* input dataset as target series *TS* records in the DSS input file. Monthly *SIM* and daily *SIMD* EFS target and shortage statistics for the Neches WAM are compared in Table 9.27. The 1940-2023 mean SB3 EFS target at control point NENE is 100.6 cfs for both daily and monthly simulations. However, the daily *SIMD* and monthly *SIM* simulations results in shortages in meeting the SB3 EFS targets with 1940-2023 means of 2.100 cfs and 0.2224 cfs, respectively. Shortages differ in the daily *SIMD* versus monthly *SIM* simulations because regulated flows differ.

Environmental standard *ES* and hydrologic condition *HC* records can be applied in either monthly *SIM* or daily *SIMD* simulations. Pulse flow *PF* records are applicable only in daily *SIMD* simulations. *ES* records model subsistence and base flow components of SB3 EFS. *PF* records model high flow pulse components. *ES* and *HC* records are included in the *SIM/SIM* chapter of the *Users Manual* [2]. *PF* records are in the *SIMD*-only chapter of the *Users Manual* [2].

The *ES* records for subsistence and base flows in the daily WAM DAT file of Table 6.7 can be inserted into the monthly DAT files of Tables 6.1 and 6.3, allowing these components of the SB3 EFS to be modeled directly in a monthly WAM without developing a daily WAM. However, the strategy employing a daily WAM to develop monthly targets significantly improves the accuracy of the SB3 EFS targets in the modified monthly WAM. *PF* record high flow pulse requirements are modeled only in a daily *SIMD* simulation. Subsistence and base flow components as well as high flow pulse components of SB3 EFS are computed in a simulation based on computed regulated flows. As illustrated by Figure 6.3, monthly and daily stream flows averaged over a month versus a day are significantly different due to greater attenuation or smoothing-out with increasing time interval. Differences between daily versus monthly averaging interval occur with either observed, naturalized, or simulated regulated flows. Other aspects of monthly *SIM* versus daily *SIMD* simulations also affect regulated stream flows and associated SB3 EFS targets.

The statistics tabulated in Table 6.8 provide a comparison of the SB3 EFS targets computed in the following two alternative simulations. The *SIM* simulation reflected in Table 6.8 employs the DAT file of Table 6.4 with the *IF* and *ES* records for water right IF-NENE-ES shown in Table 6.7 added. The *SIMD* simulation employs the DAT file of Table 6.7.

1. Monthly *SIM* simulation with the *IF* and *ES* records modeling the subsistence and base flow components of the SB3 EFS inserted directly into the *SIM* input DAT file. The high pulse flow component of the SB3 EFS is not modeled.

2. Daily *SIMD* simulation with *IF*, *ES*, and *PF* records modeling the subsistence, base flow, and high flow pulse components of the SB3 EFS included in the *SIMD* input DAT file.

Table 6.8
Statistics for SB3 EFS Targets and Shortage

| | Mean | Median | Minimum | Maximum |
|---|---|---|---|---|
| Monthly *SIM* Subsistence/Base Flow (*ES* Record) Targets and Shortages (acre-feet/month) | | | | |
| *ES* record target (acre-feet/month) | 4,518 | 3,136 | 714.0 | 12,052 |
| *ES* record shortage (acre-feet/month) | 66.98 | 0.000 | 0.000 | 3,136 |
| Monthly *SIMD* Summations of Daily SB3 EFS Targets and Shortages (acre-feet/month) | | | | |
| *ES* record target (acre-feet/month) | 4,011 | 3,136 | 714.0 | 12,052 |
| *PF* record target (acre-feet/month) | 2,158 | 0.000 | 0.000 | 30,519 |
| Total combined target (ac-ft/month) | 5,704 | 3,671 | 714.0 | 31,703 |
| Target shortage (acre-feet/month) | 69.51 | 0.000 | 0.000 | 3,080 |
| Daily *SIMD* SB3 EFS Targets and Shortages (acre-feet/day and cubic feet/second) | | | | |
| Daily *ES* record target (acre-feet/day) | 131.8 | 101.2 | 23.80 | 388.8 |
| Daily *PF* record target (acre-feet/day) | 70.92 | 0.000 | 0.000 | 1,652 |
| Combined target (acre-feet/day) | 187.4 | 101.2 | 23.80 | 1,652 |
| Target shortage (acre-feet/day) | 7.990 | 0.000 | 0.000 | 101.2 |
| Daily *ES* record target (cfs)) | 66.44 | 51.00 | 12.00 | 196.0 |
| Daily *PF* record target (cfs) | 35.74 | 0.000 | 0.000 | 833.0 |
| Combined target (cfs) | 94.48 | 51.00 | 12.00 | 833.0 |
| Target shortage (cfs) | 4.028 | 0.000 | 0.000 | 51.00 |

The *SIM* simulation with the DAT file of Table 6.4 with *IF* and *ES* records for water right IF-NENE-ES added results in 1,008 monthly subsistence/base flow (*ES* record) targets ranging from 714.0 ac-ft to 12,052 ac-ft with a 1940-2023 mean of 4,518 ac-ft. The alternative approach adopted in Chapters 7-12 consists of inserting an *IF* record (Table 9.24) in the monthly *SIM* input DAT file that references a *TS* record in the DSS file (Tables 6.2 and 9.23) with monthly targets from the daily *SIMD* simulation.

SB3 EFS total and subsistence/base flow targets at control point NENE generated by the complete basin-wide daily Neches WAM are plotted in Figure 9.23. Statistics are tabulated in Table 9.26. The SB3 EFS targets for the actual basin-wide WAM in Chapter 9 differ from those for this hypothetical example in Chapter 6 since the simulated regulated flows differ.

WRAP/WAM Capabilities Not Covered in the Example

As noted in Chapter 2, WRAP/WAM applications range from simple to very complex. WAM datasets vary in size from relatively small to very large. A "*model water right*" in WRAP and the WAMs is a *WR* or *IF* record with any number of auxiliary supporting records. The twenty full authorization WAMs listed in Table 5.1 contain a total of 10,070 water right *WR* records and 1,993 instream flow *IF* records. The two *WR* record water rights in the DAT files of Tables 6.4 and 6.7 are representative of most of the 10,070 *WR* record water rights in the 20 WAMs. Most of the 10,070 *WR* record water rights are defined simply by a set of connected *WR*, *WS*, and *UC* records as illustrated by the Chapter 6 example. The majority of the 1,993 instream flow *IF* record rights are minimum flow requirements defined by *IF* and *UC* records. However, a significant number of the 10,070 *WR* record and 1,993 instream flow *IF* record water rights in the 20 WAMs listed in Table 5.1 are significantly more complicated.

*WR* record field 6 allows selection among eight alternative types of water rights that simulate different water management tasks. The two default type 1 water rights included in the example supplies diversion targets and refills reservoir storage. Most of the *WR* records in the 20 WAMs also specify type 1 water rights. *WR* and *WS* records include several fields not used in the example that activate optional features. Flexible options for defining water management operations are also controlled by parameters on various auxiliary input records connected to a *WR* or *IF* record including target options *TO*, supplemental options *SO*, flow switch *FS*, cumulative volume *CV*, back-up *BU*, limit options *LO*, monthly varying limits *ML*, and target series *TS* records. *HP* records define hydroelectric power generation targets and rules for supplying the energy targets. Drought index *DI/IS/IP* records allow diversion, hydropower, or instream flow targets to be specified as a function of reservoir storage. Options controlled by entries on these input records are employed individually and in various combinations to model complex water management situations. Each of these type of records is included in many or at least some of the WAMs listed in Table 5.1.

*IF* records and the auxiliary DAT file input records noted in the preceding paragraph have been employed to model minimum instream flow requirements and more recently the more complex SB3 EFS. *ES* and *HC* records added to both *SIM* and *SIMD* and *PF* and *PO* records added only to *SIMD* are designed specifically for more efficiently modeling SB3 EFS in the format in which the SB3 EFS are actually defined. These SB3 EFS records are also applicable for modeling other instream flow requirements not associated with SB3 EFS.

As noted in Chapter 2, WRAP includes capabilities for tracking salinity through a system of stream reaches and reservoirs that has to date been used only in research studies of natural salt pollution in the Brazos River Basin. WRAP salinity simulation capabilities are motivated by natural salt pollution from geologic formations in the upper Red, Brazos, Colorado, and Pecos River Basins and are possibly not relevant for the Neches and other eastern river basins.

Lake Palestine, like the majority of reservoirs in Texas, has no designated flood control pool. The *FR*, *FF*, *FV*, and *FQ* input records added to *SIMD* to model flood control operations are not employed in the example. The monthly *SIM* includes no features for simulating flood control operations. Flood control operations of USACE multipurpose reservoirs are included in four of the six case study daily WAMs. *FV* and *FQ* records can be employed to model surcharge storage as well as gate-controlled flood control pool operations.

## Six Case Study Daily and Modified Monthly WAMs

The six case study WAMs discussed individually in Chapters 7 through 12 are listed in Table 6.8. The original monthly WAMs compiled for TNRRC/TCEQ by contractors during 1998-2002 are referenced in the first and second rows of Table 6.9. The daily WAM reports prepared at TAMU for TCEQ describing the river basins and documenting development of the daily and modified monthly WAMs are referenced in rows 3 and 4. The numbers in brackets in rows 2 and 3 refer to the list of references following the last chapter of this report.

Table 6.9
Six Case Study Full Authorization WAMs

| Daily WAM | Brazos | Trinity | Neches | Colorado | Lavaca | Nueces |
|---|---|---|---|---|---|---|
| 1. Date Original WAM Report | 2001 | 2002 | 2001 | 2001 | 2002 | 1999 |
| 2. Number in Reference list | [86] | [87] | [88] | [89] | [90] | [91] |
| 3. Date of Daily WAM Report | May 2019 | Dec 2019 | June 2020 | Feb 2022 | Jan 2023 | June 2023 |
| 4. Number in Reference List | [7] | [8] | [9] | [10] | [11] | [12] |
| *Hydrologic Period-of-Analysis* | | | | | | |
| 5. Original Monthly WAM | 1940-1997 | 1940-1996 | 1940-1996 | 1940-1998 | 1940-1996 | 1934-1996 |
| 6. Latest Monthly WAM | 1940-2018 | 1940-1996 | 1940-2018 | 1940-2016 | 1940-1996 | 1934-1996 |
| 7. Original Daily WAM | 1940-2017 | 1940-2018 | 1940-2019 | 1940-2016 | 1940-2021 | 1934-2021 |
| 8. 2024/2025 Daily & Monthly | 1940-2023 | 1940-2023 | 1940-2023 | 1940-2023 | 1940-2023 | 1934-2023 |
| *Counts of Simulation Input Records for Latest (2024-2025) Modified Monthly WAMs* | | | | | | |
| 9. Number of Control Points | 4,468 | 1,407 | 380 | 2,424 | 220 | 676 |
| 10. *IN* Record Control Points | 77 | 40 | 20 | 45 | 8 | 41 |
| 11. *EV* Record Control Points | 67 | 50 | 12 | 48 | 7 | 9 |
| 12. *DF* Record Control Points | 58 | 49 | 17 | 45 | 9 | 20 |
| 13. SB3 EFS Control Points | 19 | 4 | 5 | 14 | 5 | 17 |
| 14. Water Right WR Records | 2,470 | 1,073 | 420 | 2,233 | 86 | 481 |
| 15. Instream Flow IF Records | 743 | 76 | 75 | 169 | 61 | 127 |
| *Reservoirs in Latest WAMs - Flood control is included in daily WAMs but not monthly WAMs.* | | | | | | |
| 16. Number Model Reservoirs | 695 | 699 | 206 | 527 | 22 | 122 |
| 17. Authorized Storage (ac-ft) | 4,720,566 | 7,602,144 | 3,904,100 | 5,270,560 | 265,250 | 1,047,020 |
| 18. Number Major Reservoirs | 42 | 31 | 10 | 28 | 1 | 3 |
| 19. Reservoirs w/ Flood Control | 9 | 8 | 2 | 4 | 0 | 0 |
| 20. Flood Control (acre-feet) | 4,102,667 | 1,767,592 | 1,179,295 | 1,526,397 | 0 | 0 |
| *Watershed Area of River Basins* | | | | | | |
| 21. Basin Area (square miles) | 44,305 | 17,913 | 9,937 | 39,428 | 2,309 | 16,700 |

The information in Table 6.9 is for full authorization scenario versions of the WAMs. The metrics in this table are mostly the same but in some cases a little different than the corresponding metrics for the current use scenario versions. Current use scenario daily and modified monthly versions of datasets were previously developed for the Trinity, Neches, Lavaca, and Nueces WAMs [8, 9, 11, 12] but not for the Brazos and Colorado WAMs [7, 10]. Full authorization daily and revised monthly versions of the six WAMs are explored further in Chapters 7 through 12.

Comparison of Features of the Different WAMs

The six WAMs and corresponding river basins vary greatly in size and other characteristics reflecting the dramatically diverse characteristics of the twenty WAMs modeling all the river basins of Texas. Chapters 7 through 12 include results from simulations with the monthly WAMs listed in Table 5.1 of Chapter 5 downloaded from the TCEQ WAM website in October 2023, which are still the latest versions as of December 2024. Record counts in lines 9, 10, 11, 12, 14, and 16 of Table 6.9 are replicated from Table 5.1. Simulations with alternative variations of hydrology data for the six monthly WAMs are also presented in Chapters 7 through 12.

The original hydrologic periods-of-analysis adopted during the 1998-2002 initial compilation of the monthly WAM datasets are shown in row 5 of Table 6.9. The period-of-analysis of the latest official TCEQ WAMs are shown in row 6. The hydrologic periods-of-analysis for the initially reported daily WAMs referenced in rows 3 and 4 and the updated 2024 daily WAMs (Chapters 7-12) are listed in rows 7 and 8 of Table 6.1. Updated periods-of-analysis adopted for the developmental daily WAMs documented in the six previous developmental case study reports [7, 8, 9, 10, 11, 12] are in the seventh row. The hydrologic periods-of-analysis of the six daily WAMs have been further extended through 2023 (row 8) during 2024 in conjunction with the investigation reported in this present report as discussed here in Chapter 6 and in Chapters 7-12.

The *SIMD* message MSS file counts in the 9th through 15th lines of Table 6.9 include the total number of control points (*CP* records), number of primary control points with monthly naturalized flows input on *IN* records, and number of sets of *EV* records with monthly net reservoir less precipitation depths. The number of control points with daily flows on *DF* records added later in converting the month WAM to daily is shown in line 12. The number of control points (gage sites) with SB3 EFS is listed in line 13. The number of water right *WR* and instream flow *IF* records in the monthly WAMs of Table 5.1 of Chapter 5 are also shown in lines 14 and 15 of Table 6.9.

Row 16 of Table 6.9 shows the counts in the message file of the total number of model reservoirs in each of the six full authorization WAMs. The simulation model counts the number of reservoirs identified in the input dataset. The full authorization scenario includes authorized but not yet constructed reservoirs as well as all existing reservoirs licensed by water rights (certificates of adjudication and water use permits). Reservoirs with less than 200 acre-feet of conservation storage capacity are normally not reflected in water rights. Large multiple-owner federal reservoirs may be subdivided into storage components with each component treated as a separate reservoir in the *SIM* simulation model. In addition to actual real reservoirs, the Colorado WAM includes about forty artificial reservoirs used for water budget accounting schemes. Other WAMs include smaller numbers of artificial reservoirs employed in modeling complex system operations.

Row 17 is the total authorized reservoir storage capacity in each WAM. Most reservoirs with at least 200 acre-feet of storage capacity are included in water rights and the WAMs. Major reservoirs are categorized as having at least 5,000 feet of authorized capacity. The number of major reservoirs is tabulated in row 18. The major reservoirs contain most of the total storage capacity. Authorized storage capacity in the WAMs normally exclude flood control and surcharge storage.

The daily WAMs discussed later in Chapters 7, 8, 9, 10 (but not Chapters 11 and 12) include the flood control pools of the multipurpose reservoirs owned and operated by the U.S.

Army Corps of Engineers (USACE). The number of USACE reservoirs and summation of their flood control pool storage capacities are shown in rows 19 and 20 of Table 6.9. Flood control storage pools and their capacities tabulated in Table 6.9 are discussed in the previously cited book [19], daily WAM reports [7, 8, 9, 10], and Chapter 3 and Chapters 7 through 10 of this report.

The watershed area encompassed by each of the river basins from Table 1.1 are tabulated in the last row of Table 6.9. The watershed areas shown for the Brazos and Colorado River Basins include the areas of adjoining coastal basins included in the WAMs. As previously noted, the estimates of areas encompassed by the river basins tabulated in Tables 1.1 and 6.1 are from a TWDB website (https://www.twdb.texas.gov/surfacewater/rivers/river_basins/index.asp).

WAM Time Series Data Files

River system hydrology is represented in the monthly *SIM* and daily *SIMD* simulation models primarily by input sequences of monthly naturalized stream flow volumes in acre-feet (*IN* records) and monthly reservoir net evaporation less precipitation depths in feet (*EV* records) for each month of the hydrologic period-of-analysis at each relevant control point location. Other optional monthly time series input quantities are recorded on flow adjustment *FA*, hydrologic index *HI*, and time series *TS* records. Daily flow pattern series in acre-feet/day (*DF* records) are used within a *SIMD* simulation to disaggregate monthly naturalized flows to daily.

The hydrology time series input datasets for the monthly WAMs discussed in Chapters 7-12 are converted to a single DSS file for each WAM before performing other modifications. All monthly and daily time series input data for each of the six pairs of daily and modified monthly WAMs are stored in a single DSS file in DSS binary format. Simulation results for simulations discussed in Chapters 7 through 12 are also recorded in *SIMD* and *SIM* output DSS files. All time-series plots in this report were prepared with *HEC-DSSVue*.

Hydrology time series for the official TCEQ WAMs are stored in text format in files with filename extensions FLO (*IN* records), EVA (*EV* records), FAD (*FA* records), HIS (*HI* records), and TSF (*TS* records). These *SIM* input records in these text files can be easily transferred to a single DSS hydrology input file which replaces the text files using options included in *SIM* [2].

## Conventional and Intermediate Updates of Naturalized Stream Flows

The conventional approach to developing sequences of naturalized monthly flows at primary control points by adjusting observed flows is described in Chapter 5. As observed data accumulate over time, naturalized flow updates are performed employing the same conventional types of adjustments to observed flows. Major extensions of the WAM hydrology have been performed for TCEQ by consulting engineering firm contractors. These major hydrology extensions require significant time, effort, and funding and consequently are not performed often.

The following two approaches for performing intermediate naturalized flow extensions, also described in the preceding chapter, are generally quicker and less expensive but typically more approximate than conventional adjustments to observed flow: (1) TWDB regression equations relating naturalized flows to observed flows and (2) WRAP program *HYD* hydrologic regression model relating naturalized flows to TWDB quadrangle precipitation and evaporation. These methods are useful for performing intermediate updates that can be replaced later with less frequent but more detailed updates. The Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces WAMs provide opportunities for comparative analyses of results of applying these alternative flow extension methods. Results generated with the alternative methods are compared in later chapters.

The *HYD* hydrologic model generally synthesizes long-term statistics of naturalized stream flows more accurately than the flow it generates in each individual month. As an example illustrating one of many factors contributing to inaccuracies, most of the rainfall during May of a particular year might occur during the last several days of May with most of the resulting increase in stream flow occurring during June. In this case, the monthly *HYD* model will over-estimate the stream flow for May and under-estimate the stream flow during June. A variety of other factors also contribute to inaccuracies.

Hydrologic periods-of-analysis for the Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces WAMs are extended through December 2023 along with preparation of this report. The year 2022 was much hotter and drier than normal. The year 2023 was the hottest and one of the driest years on record for most of Texas and planet Earth. Impacts of extremely dry hydrologic conditions in 2022-2023 on WAM analysis results are particularly relevant. Temperatures and rainfall during 2024 have been closer to normal throughout most of Texas.

Strategy for Updating Monthly Hydrology Time Series Datasets

Reports documenting the six daily WAMs are cited in row 4 of Table 6.9. The period-of-analysis for the original daily WAMs described in these reports are shown in row 7. The daily WAMs were further refined along with preparation of this report. The 2024-2025 refined WAMs have periods-of-analysis listed in row 8 of Table 6.9 labeled "2024/2025 Daily & Monthly".

With the exception of *DF* records of daily flows, the hydrologic time series data included in the WAMs are monthly data employed in both monthly *SIM* and daily *SIMD* simulations. Strategies for compilation of *DF* records of daily flows are summarized in Chapter 5 and discussed further in Chapters 7 through 12. Strategies for extending monthly hydrology through December 2023 for the Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces daily WAMs and associated modified monthly WAMs are as follows. Alternative strategies are compared in the case studies.

- All WAM monthly hydrologic time series data available at the TCEQ WAM website in October 2023 through 2024 are adopted without modification for all six WAMs.
- TWDB 1997-2021 initial (previous reports) and then later 1997-2023 (this report) *IN* and *EV* records were adopted for the Trinity, Lavaca, and Nueces WAMs to extend the hydrologic periods-of-analysis. The TWDB naturalized flow (*IN* record) extensions are based on regression with observed flows [78]. The TWDB net evaporation less precipitation (*EV* record) extensions employ the TWDB quadrangle precipitation and evaporation database.
- *IN* record naturalized flows for 2018-2023, 2019-2023, 2017-2023, and 2020-2023 for the Brazos, Trinity, Neches, and Colorado WAMs are generated with the *HYD* hydrologic regression model which relates naturalized flows to quadrangle precipitation and evaporation.

- *EV* record evaporation-precipitation depths for 2018-2023, 2019-2023, 2017-2023, and 2020-2023 for the Brazos, Trinity, Colorado, and Neches WAMs are compiled employing the WRAP program *HYD* with the TWDB quadrangle evaporation and precipitation database.
- Flow adjustment *FA* records modeling spring flows in the Colorado WAM were extended as discussed in Chapter 10.
- Hydrologic index *HI* records defining hydrologic conditions for SB3 EFS in the Brazos and Colorado WAMs were extended as discussed in Chapters 7 and 10.

<u>USACE FWD Modeling System Unregulated Flows</u>

Unregulated daily flows for the Brazos and Trinity River Basins for 1940-1997 and 1940-2009, respectively, were obtained from the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) in 2013 early in the development of daily WRAP/WAM modeling capabilities [7, 8]. The 1940-1997 and 1940-2009 USACE daily flows at some control points in the Brazos and Trinity WAMs are included in *DF* record daily pattern hydrographs discussed in Chapters 7 and 8. Early daily Brazos and Trinity WAM studies also included aggregation of USACE FWD unregulated flows to monthly for use as monthly naturalized flows. However, monthly unregulated flows generated from USACE daily data are not included in the WAMs discussed in this report.

The 24 reservoirs in Texas owned and operated by the USACE FWD include eight reservoirs in the Trinity River Basin and nine reservoirs in the Brazos River Basin. The USACE FWD has a daily modeling system designed to support operations of their multiple-purpose reservoirs, particularly flood control operations. The modeling system includes incremental daily unregulated flows that are accumulated to obtain total daily unregulated flows at each control point. Unregulated daily flows from the USACE modeling system are analogous to WAM monthly naturalized flows. USACE unregulated flows are similarly developed by adjusting gaged flows to remove the effects of major reservoirs and water users. Although computational details are different, both USACE daily unregulated and WAM monthly naturalized flows are based on adjustments to observed flows. Flood flows are a major focus in the adjustment process for the unregulated flows in the USACE FWD modeling system.

<u>Program *HYD* Input Files for Intermediate Hydrology Extensions</u>

The WRAP program *HYD* was employed in extending both the *IN* and *EV* records for the Brazos, Trinity, Colorado, and Neches WAMs [79, 80, 81, 82]. Separate *HYD* input HIN files and computational routines are employed in extending *EV* record evaporation-precipitation depths and *IN* record naturalized flows. Extension of monthly net evaporation-precipitation depths is covered in Chapters 5 and 8 of the *Hydrology Manual* [4]. Extension of monthly naturalized flows using the hydrologic regression model is covered in Chapters 6 and 8 of the *Hydrology Manual* [4].

*HYD* routines for extending evaporation-precipitation depths and naturalized flows employ monthly quadrangle precipitation and evaporation data from the TWDB database discussed in Chapter 4. Text files with filenames Precipitation.EEE and Evaporation.EEE read by *HYD* contain 1940-2023 monthly precipitation and 1954-2023 monthly evaporation for each of 92 quadrangles encompassing Texas. Program *HYD* includes options to convert these two text files to a single DSS file and to read DSS files. These data files maintained at TAMU as part of WRAP can be easily updated each year following the annual TWDB update of the TWDB online evaporation and precipitation database. Likewise, the *HYD* input HIN files can be quickly updated to further extend the WAM *IN* and *EV* record sequences.

Monthly *IN* and *EV* record hydrology extensions for the Brazos, Trinity, Neches, and Colorado WAMs were performed with program *HYD* input files with the following filenames.

| | |
|---|---|
| BrazosNatFlow.HIN | BrazosEvapPrecip.HIN |
| TrinityNatFlow.HIN | TrinityEvapPrecip.HIN |
| NechesNatFlow.HIN | NechesEvapPrecip.HIN |
| ColoradoNatFlow.HIN | ColoradoEvapPrecip.HIN |

Following specifications in HIN files, *HYD* reads two text files with filenames Precipitation.PPP and Evaporation.EEE or alternatively a single DSS file with filename PrecipEvap.DSS. These files are created from text files of the datasets downloaded from the TWDB website. The TWDB quadrangle datasets in these files consist of monthly precipitation and evaporation depths in inches for each of ninety-two quadrangles encompassing Texas. The *HYD* input HIN files can be quickly updated upon TWDB completion of annual updates of the TWDB online database [4].

Monthly naturalized flow HIN files contain calibrated parameter values for each individual primary control point for the hydrologic regression model [4]. Calibration was performed using the original TCEQ hydrologic periods-of-analysis shown in row 5 of Table 6.9 [79, 80, 81, 82, 83, 84]. Calibration is complex. The computer execution run-time may be multiple hours for a single calibration run for each individual control point. The calibrated models for each primary control point consist of calibration parameter values contained in the HIN files listed above. Although initial development of the HIN files is difficult, the files can be easily updated to apply the same calibrated naturalized flow synthesis models after annual TWDB updates of precipitation and evaporation datasets.

The net evaporation-precipitation *HYD* input HIN files were simpler to develop than the naturalized flow extension HIN files. Net evaporation-precipitation HIN files are also much simpler to apply than to initially create. The *HYD* input HIN files assign evaporation-precipitation control point identifiers to evaporation and precipitation sequences for either a single quadrangle or the weighted average of quantities for two to four quadrangles. *HYD* subtracts adjusted precipitation depths from evaporation depths to obtain net evaporation-precipitation depths. Precipitation depths may be adjusted by a constant multiplier or 12 monthly multiplier factors.

## **Comparison of the Case Studies to Conventional WAM Applications**

The WAMs have been applied by water agencies and consulting engineering firms since before 2002. Conventional routine monthly *SIM* applications have primarily been as follows.

- Water use permit applicants and their consultants and TCEQ staff apply the WAMs in developing and evaluating new water use permit applications, amendments to existing water rights, and developing and updating associated water management plans.

- Senate Bill 1 (SB1) regional planning groups, TWDB staff, and consulting engineering firms apply the WAMs in SB1 regional and statewide planning.

- River authorities and other water management agencies and consulting engineering firms apply the WAMs in operational planning studies and drought management.

The WRAP/WAM modeling system has also been employed in university and agency research studies to investigate a diverse array of water management issues such as environmental flow requirements, impacts of climate change, reservoir storage reallocations, salinity, reservoir evaporation, stream flow synthesis, and short-term forecasting for drought management [1].

The case studies presented in Chapters 7-12 refine and update research studies performed at TAMU sponsored by TCEQ that are documented in much greater detail by previous reports [7, 8, 9, 10, 11, 12]. The case studies explore more recent developments in modeling capabilities that have not yet been fully implemented along with modeling capabilities that have been routinely employed for many years. Differences between the case studies in Chapters 7-12 and conventional past applications of the official monthly TCEQ WAMs are highlighted as follows.

Hydrology Extensions

Hydrologic periods-of-analysis for the 20 WAMs are shown in Table 5.1. Original and updated periods-of-analysis for the six case study WAMs are tabulated in Table 6.9. Conventional TCEQ strategies and methods for updating WAM hydrology are described in Chapters 5 and 6. Other alternative more approximate but less expensive methods explored in Chapters 5-12 are designed for easier intermediate hydrology updates between more expensive conventional updates. TCEQ has prepared a 2023 status report on conventional WAM hydrology updates [15].

Refinements to precipitation adjustment EPADJ options (Table 5.2) developed during 2023-2024 are described in Chapter 5. The Brazos and Neches WAMs discussed in Chapters 7 and 9 reflect the first applications of the new EPADJ feature.

Simulations with a Daily Computational Time Step

Most practical applications of the WAMs have employed the *SIM* simulation model based on a monthly computational time step. Most executions of the daily *SIMD* to date have occurred in research and development endeavors at TAMU sponsored by TCEQ. Likewise, the new environmental standard *ES*, hydrologic condition *HC*, and pulse flow *PF* records for modeling *SB3 EFS* have not been adopted to date in routine conventional applications. A major objective of this report is to support and promote application of daily WRAP/WAM capabilities in combination with *ES*, *HC*, and *PF* record SB3 EFS features within the water agencies and consulting firms. Application of these expanded modeling capabilities is a central focus of the six case studies.

Hydrologic Engineering Center (HEC) Data Storage System (DSS)

The Data Storage System (DSS) developed by the USACE Hydrologic Engineering Center (HEC) includes capabilities incorporated in the WRAP programs for creating and reading binary DSS files. DSS files and the DSS interface program *HEC-DSSVue* are integral components of WRAP as explained in the WRAP *Reference* and *Users Manuals* [1, 2]. However, DSS files and *HEC-DSSVue* have been used only infrequently in past conventional applications of the WAMs. DSS files and *HEC-DSSVue* are important components of WRAP that could be more fully utilized in various aspects of water availability modeling. The utility of HEC-DSS for managing time series datasets is highlighted in this report.

All time series plots and statistical analyses in this report were developed using *HEC-DSSVue*. Although large datasets are investigated, time series plots and statistics are included in this report for only a few selected control point locations, reservoirs, or groups of reservoirs. Readers can apply *HEC DSSVue* with the datasets that accompany the report to display plots, tabulations, and statistics on a computer monitor for any and all other time series of interest.

<u>Measures of Water Availability</u>

The six case studies in Chapters 7-12 explore WRAP/WAM capabilities for assessing water availability and present the results of the water availability assessments. The WRAP/WAM modeling system provides a diverse array of metrics for assessing water availability. Conventional routine applications of the WAMs have typically focused on different WRAP/WAM features for assessing water supply capabilities than those employed in the six case study chapters.

Chapters 7-12 focus on both (1) determination and analysis of SB3 EFS instream flow targets and (2) general basin-wide assessments of water availability. Time series plots and statistics of stream flows, SB3 EFS instream flow targets, and shortages in supplying the instream flow targets are presented. The primary metric for general assessments of water availability adopted in Chapters 7-12 consists of simulated reservoir storage plots. The timing and severity of fluctuations in WRAP/WAM simulated volumes of water in reservoir storage over the hydrologic period-of-analysis provides measures of both hydrologic conditions and water supply capabilities.

Conventional WAM applications are typically primarily concerned with assessments of water supply reliabilities for specific water users for specific plans of action and the impacts of the proposed actions on supply reliabilities of other water users. Reliability analyses are included in the example presented earlier in this chapter. Period and volume reliabilities are the primary metrics adopted to assess water supply capabilities in conventional WAM applications.

Period and volume reliabilities defined by Equations 7.1 and 7.2 of the *Reference Manual* are discussed throughout the WRAP manuals. The likelihood of fully supplying a municipal diversion requirement during 100% of the months, days, or years of the period-of-analysis or the frequency of supplying at least 75% of an agricultural irrigation diversion may be the focus of simulation studies supporting water use permit applications. Reliability tables are developed with the WRAP program *TABLES* from the results of a *SIM* or *SIMD* simulation. Firm yield analysis activated with the *SIM* firm yield *FY* record is a basic metric often adopted in planning studies.

## <u>**Versions of the WAMs Discussed in Chapters 7 through 12**</u>

The Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces WAMs and associated river basins explored in Chapters 7 through 12 reflect the diverse hydrologic conditions and water management practices found in different locations across Texas. Chapters 7 through 12 are similar in purpose and organization. The six case study chapters address water availability modeling issues and complexities commonly shared by the different regions of Texas. Certain other selected topics are highlighted only in certain individual case study chapters.

The six case studies in Chapters 7 through 12 each employ variations of three versions of full authorization WAMs: (1) latest TCEQ monthly WAM with hydrology extended through 2023, (2) daily WAM created by converting a TCEQ monthly WAM to daily, and (3) modified monthly WAM with instream flow targets for SB3 EFS computed in a daily WAM simulation.

The latest versions of the official monthly WAMs last updated by TCEQ as of 10/1/2023 downloaded from the TCEQ WAM website consists of sets of files with the following filenames.

bwam3.DAT, bwam3.DIS, bwam3.FLO, bwam3.EVA, bwam3.HIS
trin3.DAT, trin3.DIS, trin3.FLO, trin3.EVA
C3.DAT, C3.DIS, C3.FLO, C3.EVA, C3.HIS, C3.FAD
Neches3.DAT, Neches.DIS, Neches.FLO, Neches.EVA
lav3.DAT, lav3.DIS, lav3.FLO, lav3.EVA
N_Run3.DAT, N_Run3.DIS, N_Run3.FLO, N_Run3.EVA

The hydrologic periods-of-analysis for each of these six WAMS are tabulated in line 6 of Table 6.9. The first task documented in each of the case study chapters consists of extending the period of analysis through 2023 and recording the time series data (*IN*, *EV*, *HI*, and *FA* records) in a DSS file. The updated versions of the monthly WAMs consist of the following files.

Brazos3.DAT, Brazos3.DIS, Brazos3HYD.DSS
Trinity3.DAT, Trinity3.DIS, TrinityHYD.DSS
Colorado3.DAT, Colorado3.DIS, ColoradoHYD.DSS
Neches3.DAT, Neches3.DIS, NechesHYD.DSS
Lavaca3.DAT, Lavaca3.DIS, LavacaHYD.DSS
Nueces3.DAT, Nueces3.DIS, NuecesHYD.DSS

The Brazos, Trinity, Neches, Colorado, Lavaca, and Nueces daily WAM reports [7, 8, 9, 10, 11, 12] document the previous daily WAMs, which have periods-of-analysis shown in line 7 of Table 6.9. These previous reports also present *SIMD* simulations performed with the daily WAMs to develop daily instream flow targets for the SB3 EFS, which are aggregated to monthly quantities for incorporation into the corresponding monthly WAMs.

Brazos3D.DAT, Brazos3D.DIS, Brazos3D.DIF, BrazosHYD.DSS
Trinity3D.DAT, Trinity3D.DIS, Trinity3D.DIF, TrinityHYD.DSS
Colorado3D.DAT, Colorado3D.DIS, Colorado3D.DIF, ColoradoHYD.DSS
Neches3D.DAT, Neches3D.DIS, Neches3D.DIF, NechesHYD.DSS
Lavaca3D.DAT, Lavaca3D.DIS, Lavaca3DHYD.DSS
Nueces3D.DAT, Nueces3D.DIS, Nueces3D.DIF, NuecesHYD.DSS

The daily WAM datasets documented in the earlier daily WAM reports [7, 8, 9, 10, 11, 12] are used in combination with the TCEQ monthly WAMs, hydrology extensions, and other refinements to develop the versions of the daily WAMs described in Chapters 7 through 12. Daily WAMs are developed based on converting monthly WAMs to daily as described in Chapter 2. Reservoir flood control operations, modeled with *FR*, *FF*, *FV*, and *FQ* records, and SB3 EFS, modeled with *IF*, *ES*, *HC*, and *PF* records, are added to the WAMs as described in Chapter 2. The updated and refined daily WAMs consist of sets of files with the following filenames.

BrazosD.DAT, Brazos.DIS, Brazos.DIF, BrazosHYD.DSS
TrinityD.DAT, Trinity.DIS, Trinity.DIF, TrinityHYD.DSS
ColoradoD.DAT, Colorado.DIS, Colorado.DIF, ColoradoHYD.DSS
NechesD.DAT, Neches.DIS, Neches.DIF, NechesHYD.DSS
LavacaD.DAT, Lavaca.DIS, Lavaca.DIF, LavacaHYD.DSS
NuecesD.DAT, Nueces.DIS, Nueces.DIF, NuecesHYD.DSS

Disaggregation of monthly naturalized flows to daily is a key fundamental component of converting a monthly WAM to daily. Daily flow pattern hydrographs are stored on *DF* records in the hydrology DSS file along with the other time series datasets (*IN*, *EV*, *HI*, and *FA* records).

*SIMD* simulations are performed with the updated and refined daily WAMs listed above. Daily instream flow targets for the SB3 EFS are aggregated within a *SIMD* simulation to monthly targets for incorporation into the corresponding monthly WAMs. The monthly instream flow targets are stored in the hydrology time series DSS files as target series *TS* records. The same DSS record stores all time series data for both the daily and monthly versions of the WAMs. The same DSS file is read by both the monthly *SIM* and daily *SIMD*. The final modified monthly WAMs consist of sets of files with the following filenames.

BrazosM.DAT, Brazos.DIS, BrazosHYD.DSS
TrinityM.DAT, Trinity.DIS, TrinityHYD.DSS
ColoradoM.DAT, Colorado.DIS, ColoradoHYD.DSS
NechesM.DAT, Neches.DIS, NechesHYD.DSS
LavacaM.DAT, Lavaca.DIS, LavacaHYD.DSS
NuecesM.DAT, Nueces.DIS, NuecesHYD.DSS

This report is accompanied by the WAM files listed on this page and the preceding page and auxiliary DSS file datasets as discussed in the last section of Chapter 1. WAM simulation input datasets can be executed with the WRAP models *SIM* and *SIMD*. Datasets stored in DSS files are managed, viewed, and manipulated with *HEC-DSSVue*. The WRAP program *TABLES* performs supply reliability and flow and storage frequency analyses and summarizes *SIM* and *SIMD* input data and simulation results in various tables in flexible arrays of optional formats.

Alternative compilations of time series data from *SIM* and *SIMD* input datasets and simulation results and other DSS datasets are plotted and analyzed in Chapters 7 through 12 and other chapters and appendices of this report employing *HEC-DSSVue*. Only selected *HEC-DSSVue* monthly and daily time series plots and statistics are presented in the report. However, *HEC-DSSVue* provides flexible capabilities for analysis of any compilation of time series data viewed directly on the computer monitor in addition to the graphs and tables included in this report.

This technical report extends and builds upon the WRAP manuals [1, 2, 3, 4, 5, 6]. The preceding daily WAM reports [7, 8, 9, 10, 11, 12] and the datasets discussed throughout this report provide informative auxiliary support and extensions of this report. However, this technical report is designed to be an informative stand-alone document that provides additional new insights from recent research along with synthesizing a broad experience base developed by the water management community over many years.

# CHAPTER 7
# BRAZOS DAILY AND MODIFIED MONTHLY WAMS

The organization and contents of Chapters 7 through 12 covering each of the six case study WAMs are outlined in the preceding Chapter 6. The six WAMs with developmental daily versions created in past TCEQ sponsored research studies at Texas A&M University are listed in Table 6.9. The original monthly Brazos WAM is documented by a 2001 WAM report [86]. The developmental daily Brazos WAM is documented by a 2019 report [7]. The Brazos WAM original 1940-1997 hydrology [86] was extended through 2018 for the TCEQ by a team of consulting firms [74] and through 2023 in conjunction with the present study.

## Brazos River Basin and San Jacinto-Brazos Coastal Basin

The Brazos WAM covers the 45,870 square mile Brazos River Basin and 1,140 square mile San Jacinto-Brazos Coastal Basin. Figure 7.1 is a map of the Brazos River Basin and adjoining coastal basin. The Brazos River flows from the confluence of the Salt Fork and Double Mountain Fork about 920 miles to the Gulf of Mexico. The San Jacinto-Brazos Coastal Basin is located south of the city of Houston between the Brazos and San Jacinto River Basins. The upper Brazos River Basin in and near New Mexico is an arid flat area that rarely contributes precipitation runoff to stream flow. Mean annual precipitation varies from less than 17 inches in areas of the upper basin in the High Plains to more than 45 inches in areas of the lower basin in the Gulf Coast region.

The U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) owns and operates a system of nine multiple-purpose reservoirs in the Brazos River Basin. The Brazos River Authority (BRA) has contracted for the conservation storage capacity in the nine federal reservoirs and owns three other reservoirs. The City of Waco holds water rights for Lake Waco. BRA holds rights for the eleven other reservoirs of the 12-reservoir USACE/BRA system. BRA operations including a system operation permit and water management plan [96] approved by TCEQ in 2016 are described at a BRA website (https://brazos.org/About-Us/Water-Supply/System-Operations).

The 14 largest existing reservoirs and 19 gage sites for environmental flow standards (EFS) established through the process created by the 2007 Senate Bill 3 (SB3) are shown in Figure 7.2. The 15 largest existing reservoirs and the proposed Allen's Creek Reservoir, which is permitted but not yet actually constructed, are listed with descriptive information in Table 7.1 [7]. The proposed off-channel Allen's Creek Reservoir would be filled with water pumped from the Brazos River near the USGS flow gage at Richmond.

The latest Brazos WAM includes about 695 storage facilities with authorized capacities totaling 4,720,566 acre-feet licensed by water rights as documented in certificates of adjudication and water use permits. In several cases a single storage facility is modeled as multiple storage components. The storage facilities have conservation storage capacities of at least 200 acre-feet. Forty-three major reservoirs with conservation storage capacities of 5,000 acre-feet or greater contain most of the total storage capacity of the 695 storage rights. Flood control storage capacity is not included in water rights. The 16 reservoirs in the Brazos River Basin with combined conservation and flood control capacities greater than 75,000 acre-feet are listed in Table 7.1. There are no reservoirs of this size in the San Jacinto-Brazos Coastal Basin. The 16 reservoirs in Table 7.1 contain 79.4% of the total authorized conservation capacity of the 695 storage rights and all the controlled flood control capacity.

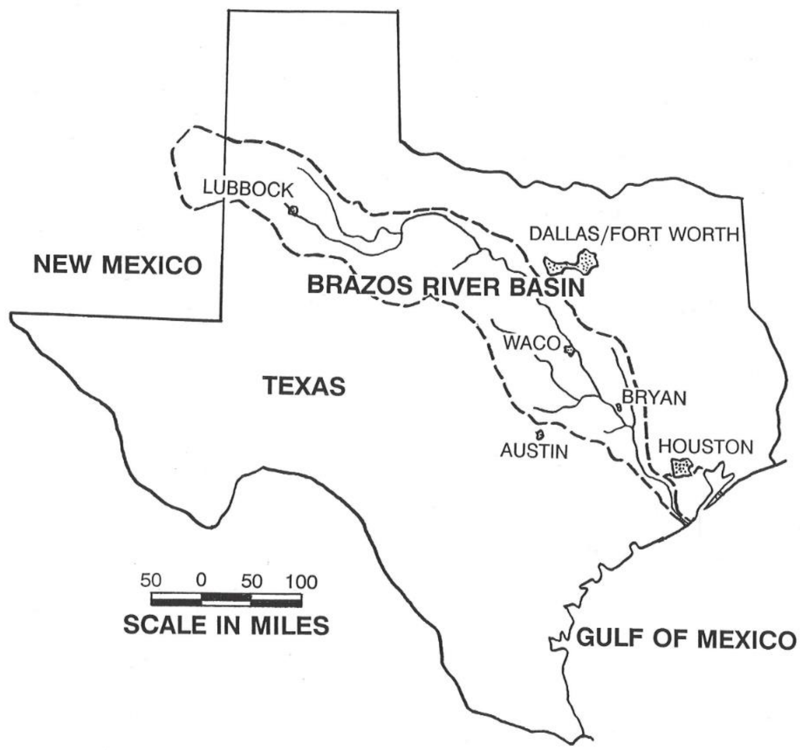


Figure 7.1 Brazos River Basin and San Jacinto-Brazos Coastal Basin

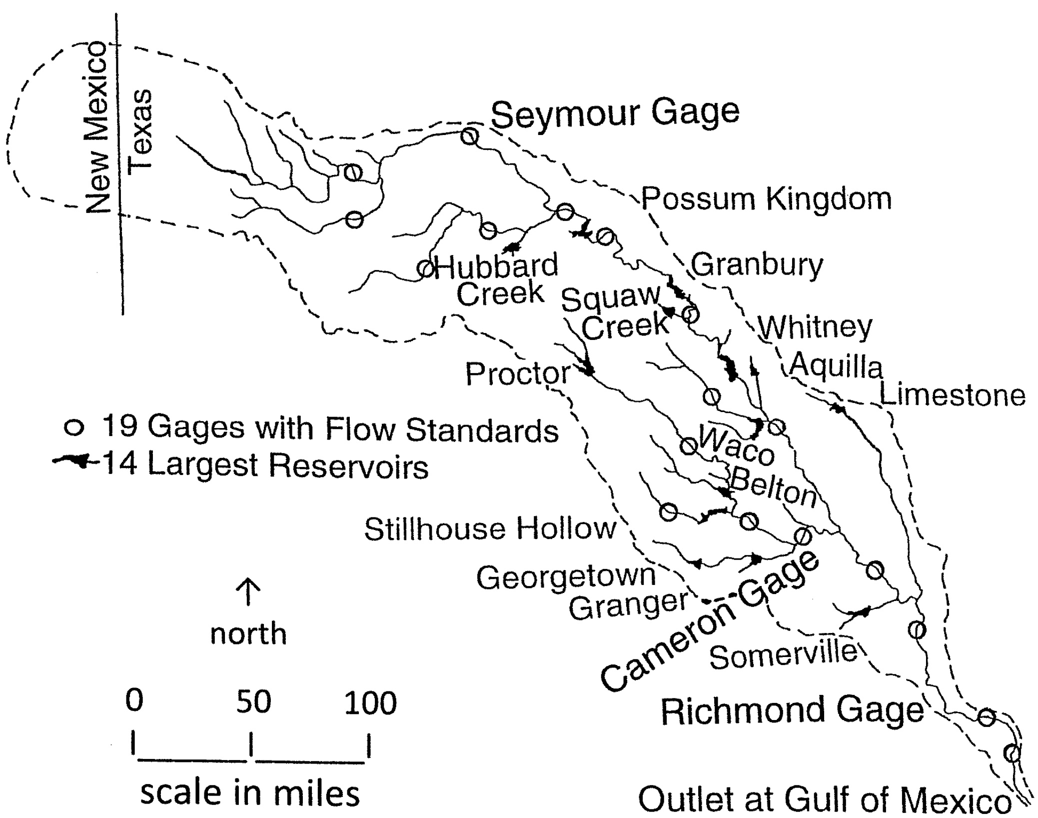


Figure 7.2 Locations of Largest Reservoirs and SB3 Environmental Flow Standards

Table 7.1
Largest Reservoirs in the Brazos River Basin

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

Possum Kingdom Lake has the largest conservation storage capacity in the basin. Lake Whitney has the second largest conservation storage capacity. Considering the total of both flood control and conservation capacity, Lake Whitney is the largest reservoir in the Brazos River Basin and the seventh largest reservoir in Texas. All controlled (gate-operated) flood control storage capacity in the Brazos River Basin is contained in the nine USACE reservoirs listed in Table 7.1.

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

In addition to releases for water supply diversions from the lower Brazos River, Possum Kingdom and Granbury Reservoirs supply water as needed to maintain constant operating levels in Lakes Squaw Creek, Tradinghouse Creek, and Lake Creek which are owned and operated by utility companies to supply water for steam-electric power plant operations.

## Monthly WAM Hydrology

This section employs the latest official TCEQ monthly WAM. The 1940-2018 hydrologic period-of-analysis is extended through 2023 as discussed in this section. The TCEQ WAM 1940-2018 hydrology [74] was adopted without change except for the one small *EV* record correction noted in the next paragraph. Estimates for *IN* record monthly naturalized flows and *EV* record net evaporation-precipitation depths for 2019-2023 were added to the hydrology dataset. *HI* record hydrologic index sequences were also extended through 2023 as discussed later in the SB3 EFS section of this chapter. Several comparative analyses are presented to explore various complexities.

As noted in the preceding paragraph, one minor correction was made to the *EV* record data in the official TCEQ monthly WAM. An evaporation depth of 1.900 feet in September 2016 for Whitney Reservoir was changed to 0.3046 feet, which was computed in the program *HYD* dataset. The 1.9 feet of net evaporation-precipitation for September appears excessive and thus was revised. *HEC-DSSVue* time series plots provide a convenient quick review of general characteristics of time series datasets and identification of various types of potential issues such as this.

The Brazos WAM has 4,468 control points, 77 primary control points with *IN* record naturalized flows, and 67 sets of *EV* evaporation-precipitation rates (Tables 5.1 and 6.9). Each of the 695 WAM reservoirs is assigned one of the 67 sets of *EV* evaporation-precipitation rates.

### Hydrologic Period-of-Analysis Extensions

The Brazos WAM original 1940-1997 hydrology [86] was extended through 2018 for the TCEQ by a team of consulting engineering firms [74]. The 1940-1997 *IN* and *EV* record hydrology input dataset has also been extended from 1998 through 2023 at TAMU using WRAP program *HYD* routines. The *HYD* hydrologic model for synthesizing naturalized flows was calibrated using the original 1940-1997 naturalized flows and applied to generate 1998-2023 flows [79]. The daily and modified monthly Brazos WAMs discussed later in this chapter combine the official TCEQ WAM 1940-2018 hydrology and WRAP program *HYD* 2019-2023 extended hydrology.

Brazos WAM simulations presented in this chapter combine the DAT and DIS files for the TCEQ monthly full authorization WAM with a DSS file containing the two alternative 1940-2023 hydrology datasets listed below. Simulations are performed with alternative variations of these two basic hydrology datasets to support comparative analyses of aspects of WAM hydrology.

- TCEQ WAM 1940-2018 hydrology and *HYD* 2019-2023 extension adopted in the daily and monthly versions of the WAM discussed in this chapter.
- TCEQ WAM 1940-1997 hydrology and *HYD* 1998-2023 extension included only in the comparative analyses of this section.

### Alternative Monthly Naturalized Stream Flow Extensions

Naturalized flows from the two datasets listed above at control point BRRI70 at the USGS gage on the Brazos River at Richmond (Figure 7.2) are plotted in Figures 7.3 and 7.4. Figure 7.3 covers 1940-2023 of which 1940-1997 and 2019-2023 flows are the same in both datasets. Figure 7.4 focuses on 1998-2018 during which the flows differ. This gage site has a watershed area of

35,540 square miles that encompasses portions of 19 TWDB quadrangles. Monthly precipitation and evaporation depths for each of the 19 quadrangles are included in the *HYD* naturalized monthly flow extension. The legend for Figures 7.3 and 7.4 is as follows.

- TCEQ WAM 1940-2018 hydrology and *HYD* 2019-2023 extension adopted in the daily and monthly versions of the WAM (blue solid line in plots)
- TCEQ WAM 1940-1997 hydrology and *HYD* 1998-2023 extension (red dotted lines)

The WRAP program *HYD* includes a hydrologic regression model with many empirical parameters requiring calibration that relates monthly naturalized stream flow to TWDB quadrangle monthly precipitation and reservoir evaporation depths. The TWDB quadrangle precipitation and reservoir evaporation database is described in Chapter 4. The program *HYD* hydrologic model is described in Chapters 6 and 8 of the *Hydrology Manual* [4]. The hydrologic model is calibrated for each individual primary control point using the original WAM period-of-analysis monthly naturalized flows and monthly precipitation and evaporation depths for selected relevant quadrangles. The calibrated model is then applied to synthesize naturalized flows for the extension period based on known precipitation and evaporation depths for the extension period.

Calibration and initial application of the *HYD* naturalized flow extension model is documented by a 2012 report [79]. Models stored as a *HYD* input HIN file have been calibrated for each of the 77 Brazos WAM primary control points based on 1940-1997 monthly naturalized flows and corresponding TWDB monthly precipitation and reservoir evaporation rates for the quadrangles encompassing the Brazos River Basin and adjoining coastal basin [7, 79].

The conventional development of naturalized monthly flows by adjusting observed gaged flows is generally more accurate than the *HYD* model relating naturalized monthly flows to precipitation and evaporation. Although calibration is complicated and requires significant effort, a calibrated *HYD* model can be applied with minimal expense to occasionally update naturalized flows between more accurate but also more expensive conventional extensions [7, 79].

Figures 7.3 and 7.4 and Table 7.2 provide insight regarding differences in the alternative computed naturalized flows. Statistics for the two alternative sets of 1998-2018 monthly naturalized flows are compared in Table 7.2. Both datasets include months during 1998-2018 with zero flow. The median (50% exceedance) and mean of the 252 monthly naturalized flows for 1998-2018 generated with *HYD* is 95.41% and 101.1%, respectively, of the corresponding median and mean of the conventional 1998-2018 naturalized monthly flows.

Table 7.2
Statistics for 1998-2018 Monthly Naturalized Flows at Richmond Gage on Brazos River

| Monthly Flow Statistic in acre-feet | Conventional Adjusted Flows | *HYD* Hydrologic Model Flows |
|---|---|---|
| median (acre-feet) | 267,046 | 254,796 |
| mean (acre-feet) | 521,266 | 526,941 |
| maximum (acre-feet) | 4,018,561 | 4,771,762 |
| standard deviation (ac-ft) | 693,146 | 757,879 |

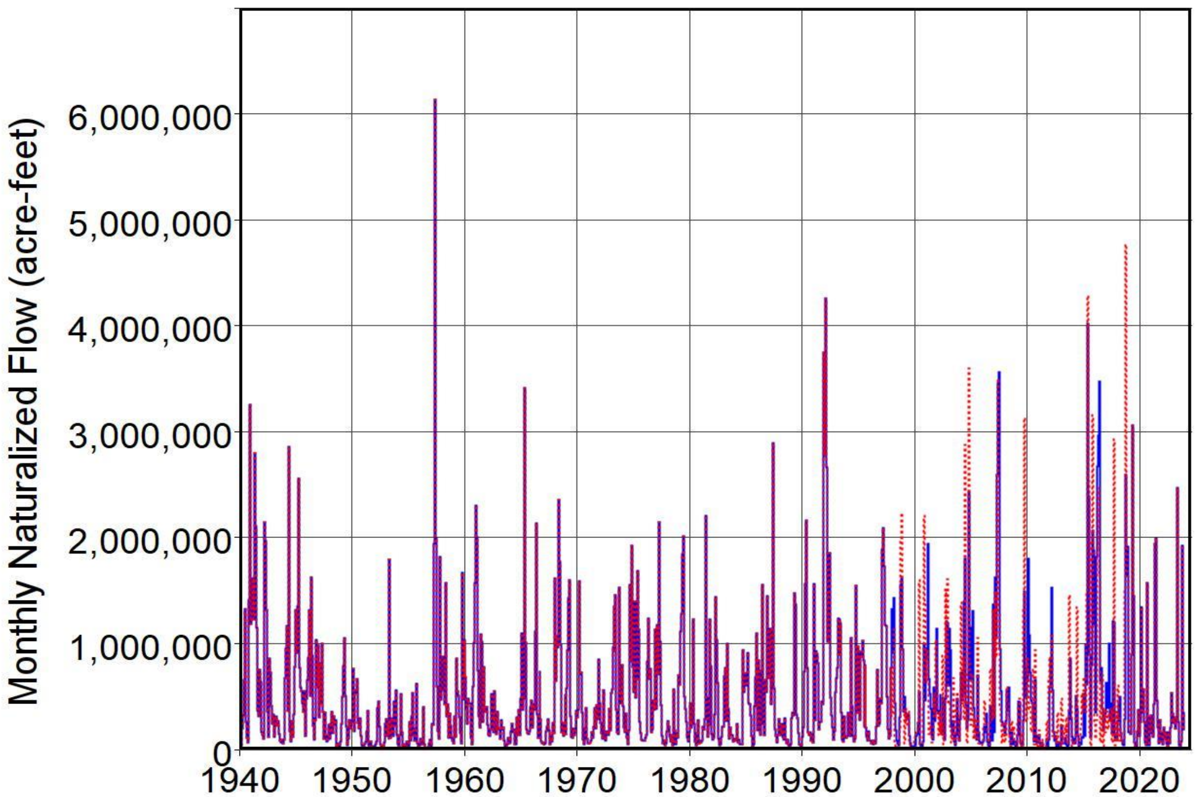


Figure 7.3 Naturalized Flows of Brazos River at Richmond for 1940-2023

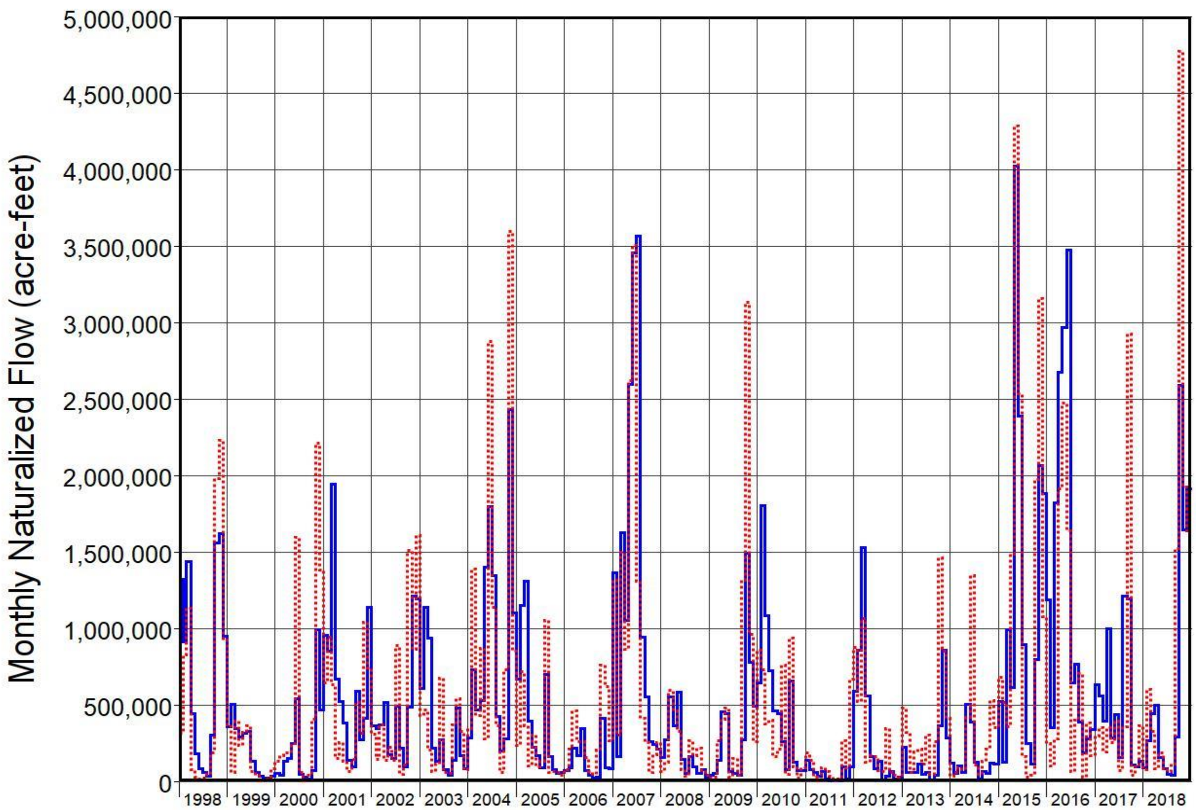


Figure 7.4 Naturalized Flows of Brazos River at Richmond for 1998-2018

Reservoir Net Evaporation Minus Precipitation Depths

The Brazos WAM includes 67 sets of *EV* record net evaporation minus precipitation depths in feet. If evaporation exceeds precipitation, the *EV* record quantities are positive numbers. If precipitation exceeds evaporation in a particular month, the net quantity is negative. Precipitation adjustments activated by EPADJ on the *JD* record are computed within the *SIM* simulation as discussed below in the next sub-section of this chapter.

Evaporation-precipitation depths for ten large reservoirs are from specific precipitation gages and evaporation pans located near the individual reservoirs. The TWDB database is used for these ten reservoirs only for periods of missing data from measurements at the reservoir sites. Thirty-nine of the 67 sequences of net evaporation-precipitation depths are for individual large reservoirs with water surface areas extending into more than one quadrangle. The *EV* record quantities are weighted averages of evaporation-precipitation depths for the relevant quadrangles. The 18 other sets of *EV* records are derived from evaporation and precipitation data from the TWDB database for single individual quadrangles. Many of the 695 reservoirs are assigned the same set of quadrangle net evaporation-precipitation depths [7, 74, 86].

Precipitation Adjustment Options for Net Evaporation-Precipitation Depths

A precipitation adjustment feature controlled by input parameters EPADJ on the *JD* record and EWA(cp) on the *CP* record is described in Chapter 5 of this report as well as the *Reference* and *Users Manuals* [1, 2]. Alternative precipitation adjustment options are defined in Table 5.2. The different precipitation adjustments are variations of the procedure embedded in *SIM* for computing the precipitation depth adjustment term in feet in Equation 5.3 replicated below.

$$\text{Adjusted Net Evaporation-Precipitation Depth} = (\text{Evaporation Depth} - \text{Precipitation Depth}) + (\text{Precipitation Depth Adjustment}) \quad (5.3)$$

The original Brazos WAM has an entry of −1 on the *JD* record for parameter EPADJ. The new option 1 defined in Table 5.2 and discussed in Chapter 5 is adopted for the daily and modified monthly versions of the Brazos WAM described in Chapter 7. Options 1 and 4 were added to *SIM* in 2024. The hydrology dataset adopted in Chapter 7 consists of the TCEQ WAM 1940-2018 *IN* and *EV* record sequences and *HYD* 2019-2022 extensions of the *IN* and *EV* records. *JD* record parameter EPADJ is changed from option −1 to option 1 for the dataset adopted for the 2024 daily and modified monthly versions of the WAM.

Net evaporation-precipitation depths at Possum Kingdom, Whitney, Belton, Limestone, and Somerville Reservoirs are adopted for the comparison of alternative EPADJ options in Tables 7.3 and 7.4. These five reservoirs at diverse locations in the Brazos River Basin account for 41.6% of the authorized storage capacity reflected in the Brazos WAM.

Two alternative sets of unadjusted *EV* record evaporation minus precipitation depths for Possum Kingdom and Whitney Reservoirs are plotted in Figures 7.5 and 7.6. The legend for Figures 7.5 and 7.6 on the next page as well as the earlier Figures 7.3 and 7.4 is as follows.

- TCEQ WAM 1940-2018 hydrology and *HYD* 2019-2023 extension (blue solid line)
- TCEQ WAM 1940-1997 hydrology and *HYD* 1998-2023 extension (red dotted line)

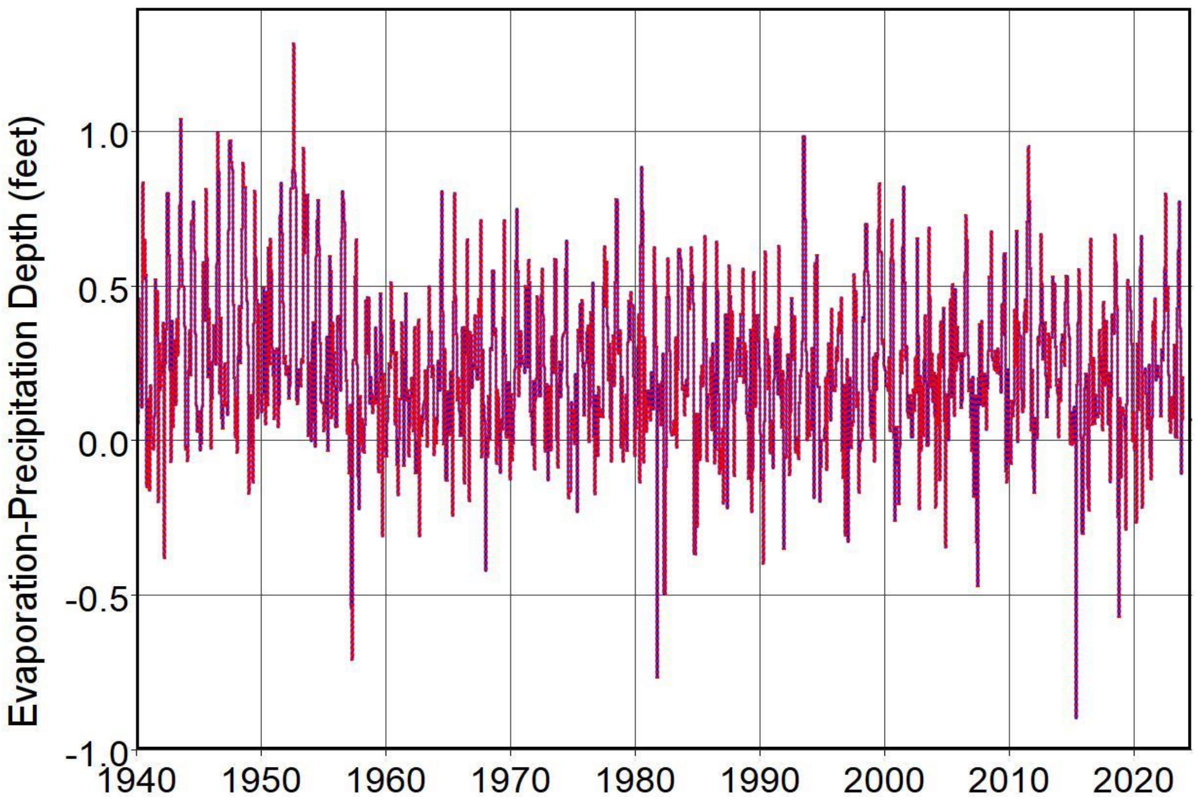

Figure 7.5 Unadjusted *EV* Record Evaporation-Precipitation Depths for Possum Kingdom

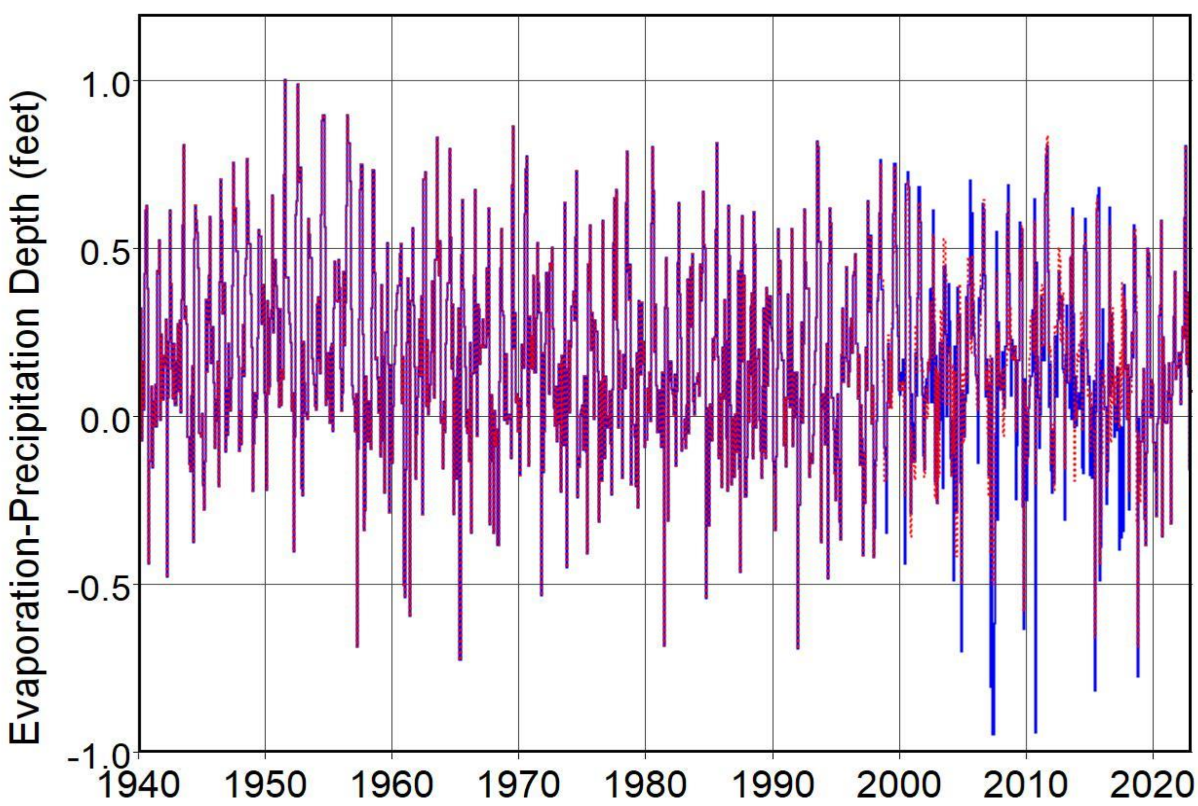

Figure 7.6 Unadjusted *EV* Record Evaporation-Precipitation Depths for Whitney Reservoir

Table 7.3
Minimum, Mean, and Maximum Monthly Net Evaporation-Precipitation Depths during 1940-2017 with Alternative Precipitation Adjustment Options

| Reservoir | | Net Evaporation-Precipitation Depth (feet) | | | |
|---|---|---|---|---|---|
| | | No Adjustment | Option −1 | Option 1 | Option 4 |
| Possum Kingdom | minimum | -0.90000 | -0.89161 | -0.89161 | -0.84463 |
| | mean | 0.22798 | 0.24529 | 0.24947 | 0.23452 |
| | maximum | 1.28400 | 1.29409 | 1.29409 | 1.28460 |
| Whitney | minimum | -0.94500 | -0.76962 | -0.76962 | -0.92201 |
| | mean | 0.15801 | 0.18874 | 0.19161 | 0.16759 |
| | maximum | 1.00300 | 1.01103 | 1.01103 | 1.00533 |
| Belton | minimum | -0.95200 | -0.65863 | -0.65863 | -0.81223 |
| | mean | 0.15543 | 0.18880 | 0.18914 | 0.17438 |
| | maximum | 1.04000 | 1.04084 | 1.04084 | 1.04017 |
| Limestone | minimum | -0.55085 | -0.43578 | -0.43578 | -0.44986 |
| | mean | 0.11560 | 0.16277 | 0.16288 | 0.16322 |
| | maximum | 0.95400 | 0.95407 | 0.95407 | 0.95407 |
| Somerville | minimum | -1.3180 | -1.0933 | -1.0933 | -1.11813 |
| | mean | 0.085085 | 0.12205 | 0.12221 | 0.11596 |
| | maximum | 0.75500 | 0.75500 | 0.75500 | 0.75500 |

Table 7.4
Minimum, Mean, and Maximum Monthly Net Evaporation-Precipitation Depths during 1940-2017 with Alternative Precipitation Adjustment Options

| Reservoir | | No Adjustment (feet) | Percent of Depth with No Adjustment | | |
|---|---|---|---|---|---|
| | | | Option −1 | Option 1 | Option 4 |
| Possum Kingdom | minimum | -0.90000 | 99.1% | 99.1% | 93.8% |
| | mean | 0.22798 | 107.6% | 109.4% | 102.9% |
| | maximum | 1.28400 | 100.8% | 100.8% | 100.0% |
| Whitney | minimum | -0.94500 | 81.4% | 81.4% | 97.6% |
| | mean | 0.15801 | 119.4% | 121.3% | 106.1% |
| | maximum | 1.00300 | 100.8% | 100.8% | 100.2% |
| Belton | minimum | -0.95200 | 69.2% | 69.2% | 85.3% |
| | mean | 0.15543 | 121.5% | 121.7% | 112.2% |
| | maximum | 1.04000 | 100.1% | 100.1% | 100.0% |
| Limestone | minimum | -0.55085 | 79.1% | 79.1% | 81.7% |
| | mean | 0.11560 | 140.8% | 140.9% | 141.2% |
| | maximum | 0.95400 | 100.0% | 100.0% | 100.0% |
| Somerville | minimum | -1.3180 | 83.0% | 83.0% | 84.8% |
| | mean | 0.085085 | 143.4% | 143.6% | 136.3% |
| | maximum | 0.75500 | 100.0% | 100.0% | 100.0% |

Net evaporation less precipitation depths derived from the TWDB database for Possum Kingdom Reservoir are based on weighted-averages of quantities for two adjacent quadrangles. The *EV* record quantities for Possum Kingdom Reservoir throughout 1940-2018 are the same for both of the alternative data sets listed above since the TWDB quadrangle evaporation and precipitation data are employed in the same manner. The depths on the *EV* records assigned to Possum Kingdom Reservoir at control point 515531 are plotted in Figure 7.5.

Whitney is one of ten large reservoirs with *EV* records in the TCEQ WAM compiled from measurements of evaporation and precipitation at the reservoir site for the periods with recorded measurements available [7, 74, 86]. The TWDB database was employed for periods without recorded observations from the relevant sites. The second alternative dataset listed above is based solely on the TWDB database. Whitney Reservoir extends into portions of four quadrangles. Net evaporation less precipitation depths are weighted-averages of depths for four TWDB quadrangles. The depths on the *EV* records assigned to Whitney Reservoir at control point 515731 are plotted in Figure 7.6. The two alternative *EV* record datasets differ during the period 1998-2018.

The TCEQ WAM 1940-2018 hydrology and *HYD* 2019-2023 extension were adopted for the daily and modified monthly versions of the Brazos WAM discussed later. One minor correction was made to the *EV* record data in this dataset. An evaporation depth of 1.900 feet in September 2016 for Whitney Reservoir was changed to 0.3046 feet, which was computed in the program *HYD* dataset. The 1.9 feet of evaporation-precipitation for September appeared to be excessive.

Tables 7.3 and 7.4 are based on simulations with the TCEQ WAM 1940-2018 hydrology and *HYD* 2019-2022 extension. The only difference between the alternative simulations compared in Tables 7.3 and 7.4 is the evaporation-precipitation adjustment option selected by the entry for parameter EPADJ on the *JD* record.

Alternative precipitation adjustment options are defined in Table 5.2 of Chapter 5. The only difference between EPADJ options −1 and 1 is handling of negative computed precipitation adjustments. Option −1 allows negative precipitation depths. Option 1 converts negative depths to zero. Option 2 also converts negative precipitation depths to zero. Option 4 employs total watershed areas from watershed parameter *WP* records and generates no negative quantities. Options −1 and 1 use incremental watershed areas as delineated by flow distribution *FD* records.

The minimum, mean, and maximum of the 1940-2023 monthly net evaporation-precipitation depths in feet at each of the five reservoirs are tabulated in Table 7.3 for no adjustment (EPADJ=0) and EPADJ options −1, 1, and 4. The net evaporation-precipitation depth in feet is also tabulated in Table 7.4, but the depths for EPADJ options −1, 1, and 4 are expressed in Table 7.4 as a percentage of the depths with no precipitation adjustment.

At Possum Kingdom Reservoir, with no EPADJ adjustment, the 1940-2022 mean of the net evaporation-precipitation depth is 0.22798 foot. With EPADJ option −1 activated, the 1940-2022 mean of the net evaporation-precipitation depth is 0.24529 foot (Table 7.3) which is 102.9% (Table 7.4) of the evaporation-precipitation depth of 0.22798 foot with no adjustment. The minimum and maximum net evaporation-precipitation depth occurring in any month during the 996 months of the 1940-1922 simulation are included in Tables 7.3 and 7.4 as well the mean of the 996 depths.

Net evaporation-precipitation depths each month must equal or be greater with EPADJ option 1 than with option −1 since negative adjustments are changed to zero by option 1. Likewise, net evaporation-precipitation depths with EPADJ option 4 must equal or exceed adjustments with option −1 since option 4 generates no negative precipitation adjustments. The minimum evaporation-precipitation depth during the 1940-1922 simulation at each of the five reservoirs are negative quantities indicating adjusted precipitation is greater than evaporation in those months.

Negative precipitation depth adjustments result from negative incremental naturalized flows that occur with EPADJ option −1. Negatives occur in many months at many locations in the Brazos WAM. The same negative quantities are computed with EPADJ options 1 and −1, but the negatives are changed to zero with option 1. Option 4 has no incremental flows and no negative adjustments. With ICHECK option 1, all negative incremental precipitation adjustments are recorded in the *SIM* message MSS file for information if EPADJ options 1 or −1 is activated.

The simulations with alternative EPADJ options employ the TCEQ WAM 1940-2018 hydrology with *HYD* 2019-2022 hydrology adopted in the daily and monthly versions of the WAM described in Chapter 7. EPADJ is changed from −1 to 1 for the simulations in Chapter 7.

Simulated Reservoir Storage with Alternative Hydrology Input Datasets

The summation of simulated end-of-month storage in the 695 reservoirs in the full authorization Brazos WAM (Table 5.1) are plotted in Figure 7.7. The original EPADJ option −1 is activated. The only difference between the two variations of Brazos WAM storage plots in Figure 7.7 is the natural flow and evaporation-precipitation sequences which are based on:

- TCEQ WAM 1940-2018 hydrology and *HYD* 2019-2023 extension (blue solid line)
- TCEQ WAM 1940-1997 hydrology and *HYD* 1998-2023 extension (red dotted line)

The 695 storage facilities in the full Brazos WAM of Tables 5.1 and 6.9 have capacities totaling 4,720,566 acre-feet. The most severe drawdown during the 1940-2023 simulation depletes the storage contents to a minimum storage of 925,067 acre-feet (19.6 percent of capacity) which occurs at the end of November 1952. The second most severe drawdown occurs during the 2010-2015 drought, reaching a minimum storage level of 1,010,908 acre-feet (21.4 percent of capacity) at the end of December 2014 with the adopted hydrology (blue solid line). The storage computed in the alternative simulation with *HYD* 1998-2023 hydrology (red dotted line) reaches a minimum level of 1,662,448 acre-feet (35.2 percent of capacity) at the end of September 2011.

Effects of Assumed Beginning-of-Simulation Storage

The WAMs generally reflect the premise of all reservoirs being full to capacity at the beginning of the simulation, which means that water availability may be higher in the model than actual reality at the beginning of the hydrologic simulation period. This could possibly reduce the severity of simulated draw-downs during the 1950-1957 drought. The *SIM* beginning-ending-storage (BES) option activated by input parameter BES on the job option *JO* record was employed to investigate the effects of beginning-of-simulation storage. The BES feature was used to set the beginning of January 1940 storage contents equal to the end of December 2022 storage level in each of the 695 reservoirs. The results are plotted in Figure 7.8.

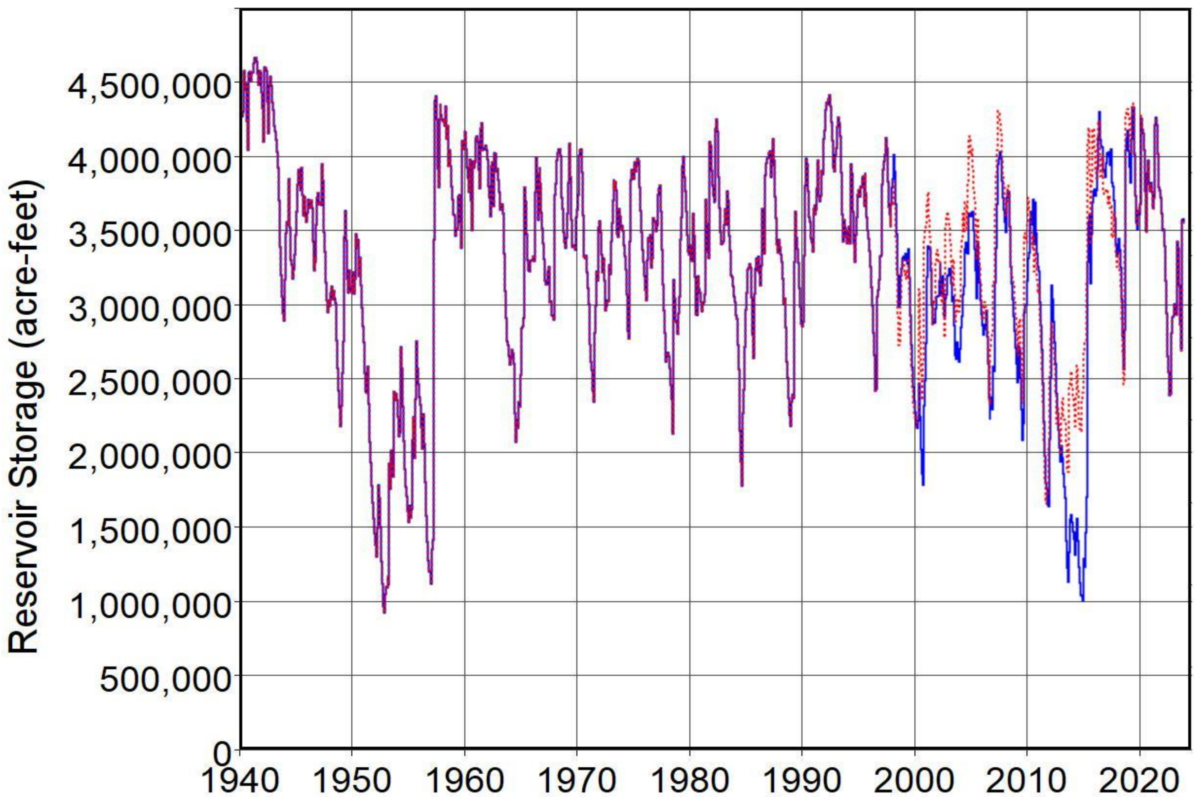


Figure 7.7 Summation of Simulated Storage in the 695 Reservoirs in Brazos WAM

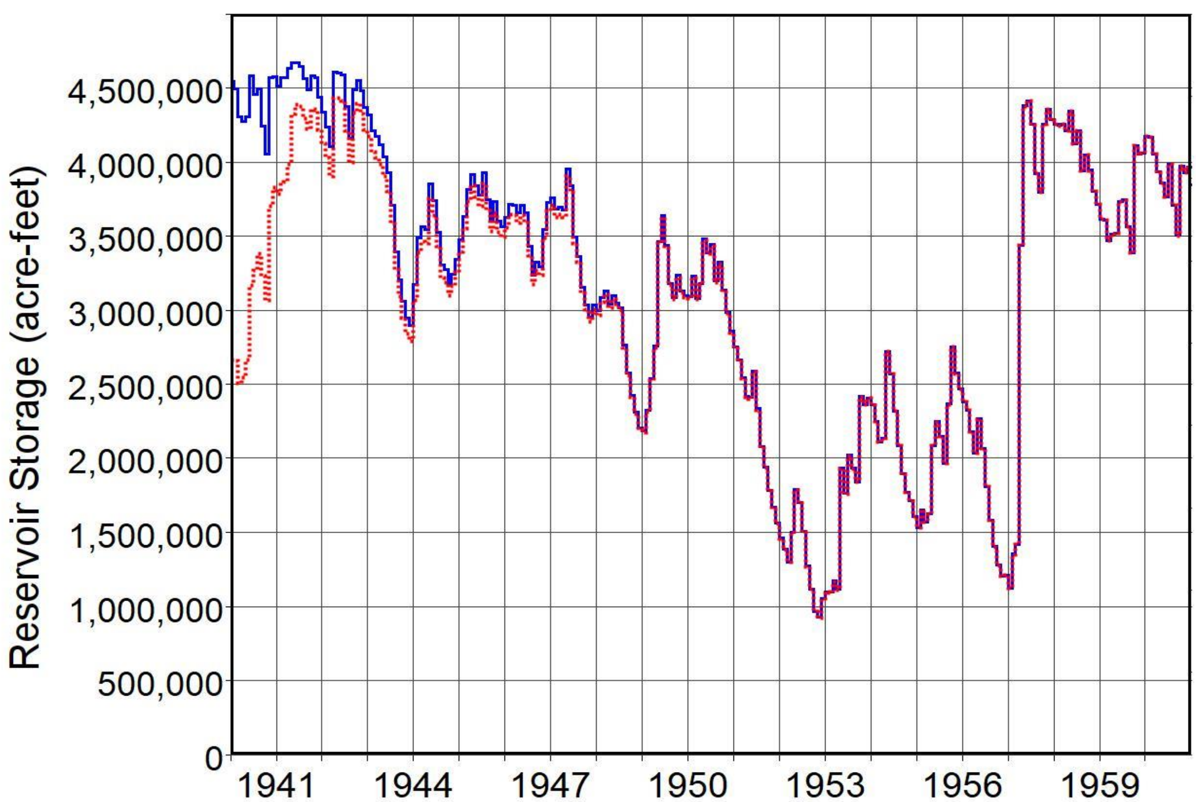


Figure 7.8 Simulated Storage in All Reservoirs in Brazos WAM with and without BES Option

The 1940-1960 storage plots in Figure 7.8 generated with the TCEQ monthly WAM with extended hydrology compare the following simulation premises.

- The TCEQ WAM 1940-2018 hydrology and *HYD* 2019-2023 extension are adopted and all reservoirs are full to capacity at the beginning of the simulation (blue solid line)
- The TCEQ WAM 1940-2018 hydrology and *HYD* 2019-2023 extension are adopted and the storage contents of each reservoir at the beginning of the simulation is equal to its storage capacity at the end of December 2022 (red dotted line in Figure 7.12)

In the second simulation scenario, the beginning of simulation storage contents at the beginning of January 1940 in each of the 695 reservoirs was set equal to the storage contents at the end of December 2022. The year 2022 had the lowest end-of-year storage level since 2015 and was selected somewhat arbitrarily for this comparative analysis. The storage level increased significantly during 2023.

The effects of the beginning-of-simulation storage on later storage levels decrease as the simulation proceeds through the hydrologic period-of-analysis. Thus, only the period from January 1940 through December 1960 is included in Figure 7.12. Only the first several years of this period are affected. With the BES option, the minimum storage level during the 1940-2022 simulation is 920,891 acre-feet in November 1952 compared to 925,067 acre-feet without the BES option. The conventional strategy of setting all reservoirs full to authorized storage capacity is continued in the daily and modified monthly simulations presented in Chapter 7.

<u>Effects on Reservoir Storage of Net Evaporation-Precipitation Adjustment Options</u>

Evaporation-precipitation depths with alternative EPADJ options are compared in the previous Tables 7.3 and 7.4. Storage plots in Figures 7.7 and 7.8 reflect the original EPADJ of −1. The summation of simulated end-of-month storage in all reservoirs in the WAM with alternative EPADJ options are compared in Table 7.5 below. Storage plots with no adjustment and EPADJ options −1 and 1 are compared in Figure 7.9.

Table 7.5
Minimum, Mean, and Maximum Storage Contents of 695 Reservoirs in Brazos WAM during 1940-2017 Simulation with Alternative Precipitation Adjustment Options

| EPADJ Option | Minimum (acre-feet) | Mean (acre-feet) | Maximum (acre-feet) | Legend for Plots in Figure 7.9 |
|---|---|---|---|---|
| 0 | 956,540 | 3,260,040 | 4,676,597 | black solid line |
| −1 | 925,067 | 3,243,655 | 4,670,951 | red dotted line |
| 1 | 923,343 | 3,240,588 | 4,670,292 | blue dashed line |
| 4 | 933,976 | 3,244,615 | 4,670,687 | not included in plot |

Variations of evaporation-precipitation depths with the alternative precipitation adjustment options and no precipitation adjustments are summarized in Tables 7.3 and 7.4 for five reservoirs. Activation of precipitation adjustments increases the mean net evaporation-precipitation depth in each of the five reservoirs by amounts ranging from 9.4% at Possum Kingdom Reservoir in the dry (low rainfall) upper basin to 43.6% at Somerville Reservoir in the wetter lower basin. Differences in Table 7.4 between EPADJ options −1, 1, and 4 are significant but relatively small.

Effects of precipitation adjustments on reservoir storage levels in general are relatively minimal as illustrated by Table 7.5 and Figure 7.8. Total storage in the 695 storage facilities in the Brazos WAM for alternative precipitation adjustment options are compared in Table 7.5 and Figure 7.9. A legend for Figure 7.9 is provided in the last column of Table 7.5.

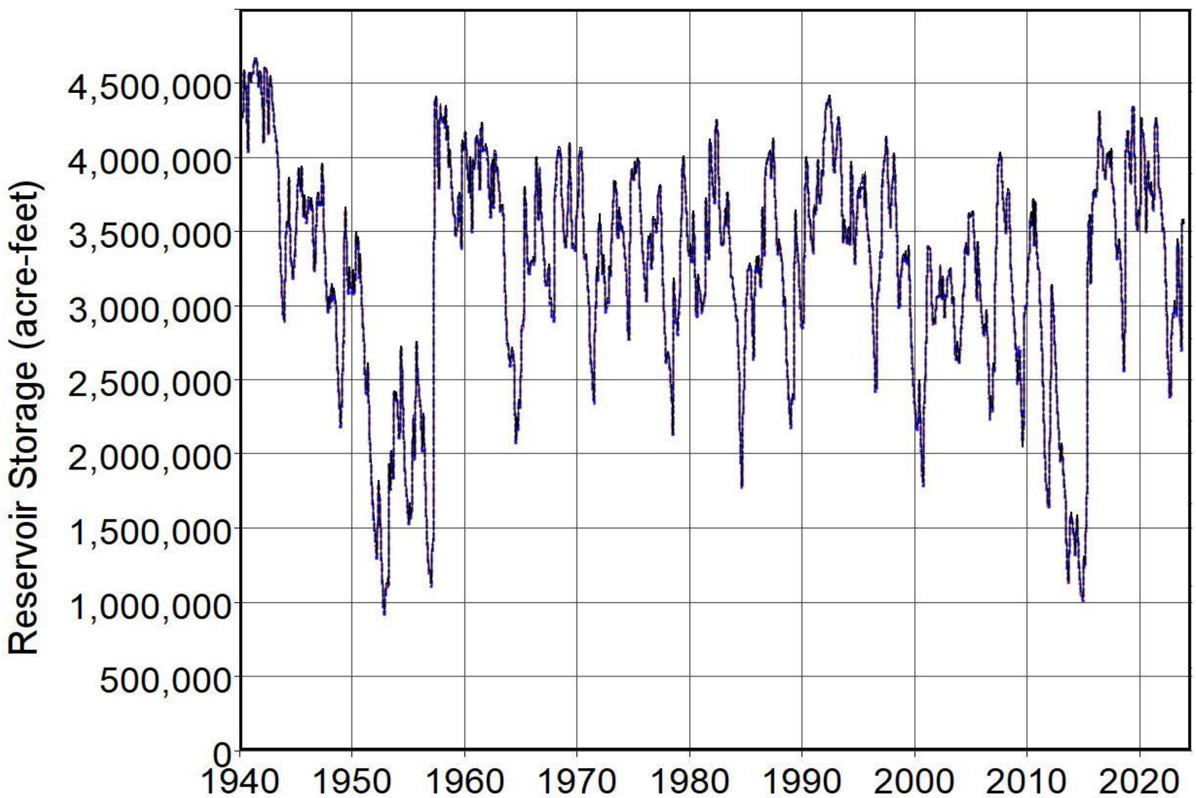


Figure 7.9 Brazos WAM Simulated Storage With Alternative EPADJ Options

The effects of the alternative precipitation adjustment EPADJ options on net evaporation-precipitation depths are indicated by Tables 7.3 and 7.4 to be significant though not dramatic. EPADJ adjustments are indicated by Table 7.5 and Figure 7.9 to have minimal effect on reservoir storage. Precipitation adjustments have the greatest effect in locations and months with high rainfall, which are also the situations in which storage capacity is most likely to be full and spilling.

Simulations presented in the remainder of this chapter use the dataset of *IN* and *EV* records for 1940-2018 included in the official TCEQ Brazos WAM. The hydrologic period-of-analysis extension through December 2023 developed with the WRAP program *HYD* is adopted for the hydrology update. The new EPADJ option 1 described in Chapter 5 is adopted for the simulations presented in the remainder of Chapter 7 rather than option −1 adopted in the previous versions of the WAM. The switch to EPADJ option 1 serves the sole purpose of eliminating negative precipitation adjustments.

## Daily Brazos WAM

The primary motivation for developing daily WRAP/WAM modeling capabilities is to improve capabilities for incorporating Senate Bill 3 (SB3) environmental flow standards (EFS) in the WAMs. Daily *SIMD* capabilities also allow simulation of reservoir flood control operations. A daily WAM includes essentially all monthly *SIM* simulation input data plus additional "daily-only" *SIMD* input records. The components of a daily WAM are summarized in Chapter 2 of this report and explained in detail in the *Daily Manual* [5] and Chapter 4 of the *Users Manual* [2].

Development of the daily WAMs discussed in this report includes the following major tasks described in Chapter 2.

1. Conversion of a monthly WAM to daily.
2. Addition of new environmental standard *ES*, hydrologic condition *HC*, pulse flow *PF*, and other related input records to model SB3 EFS along with removal of the older types of input records approximating the SB3 EFS in the monthly model.
3. Addition of *FR*, *FF*, *FV*, *FQ*, and related records to model reservoir flood control operations in the daily model. Monthly WAMs have no flood control operations.

The 2019 report [7] is the primary reference explaining development of the daily Brazos WAM and associated research studies addressing various modeling issues. The present 2025 report builds upon and references the previous work. As discussed earlier, the preceding monthly WAM has a 1940-2018 period-of-analysis and preceding daily WAM has a 1940-2017 period-of-analysis which have been updated to extend through 2023 in the present study. The *SIMD* simulation model has also been recently refined to add the EPADJ options discussed in the preceding section and reorganize options controlling selection of simulation results to include in output files.

The 2019 daily Brazos WAM report [7] explains in detail the development of the daily Brazos WAM and presents simulation studies that include comparative analyses addressing various modeling complexities and issues. Simulation studies presented in Chapter 10 of the 2019 report explore the effects on simulation results of the following WRAP/WAM features:

- daily versus monthly computational time steps
- negative incremental flow adjustment ADJINC options
- routing versus no routing of flow changes
- alternative flow forecast periods
- reservoir flood control operations
- SB3 EFS

The 2019 daily WAM was developed from an earlier version of the TCEQ monthly WAM with DAT file last updated 9/8/2008, DIS file last updated 8/27/2007, and FLO, EVA, and HIS files last updated 11/3/2017. Although this WAM included 122 *IF* records for older instream flow requirements, the SB3 EFS had not been added. The 2024 daily WAM was developed from this same TCEQ monthly WAM but with updated hydrology and other refinements. The 2019 daily WAM was updated and refined in 2024 rather than converting the latest official TCEQ monthly WAM to daily due to complexities regarding the method of modeling the SB3 EFS in the latest monthly WAM. These complexities are discussed later in the SB3 EFS section of this chapter.

Daily and Monthly Unit Conversions

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 1940-2023 period-of-analysis contains the leap years 1940 and every fourth year thereafter in both reality and the *SIMD* simulation. Monthly volume to mean flow rate conversions vary with number of days in each month. The 1940-2023 time series of simulated reservoir storage content volumes consist of either 1,008 end-of-month volumes or 30,681 end-of-day volumes. The 1,008 end-of-month storage volumes are a subset of the 30,681 end-of-day storage volumes which includes only the end-of-day storage at the end of the last day of each month. Relevant unit conversion factors are as follows.

1.0 acre-feet per day = 1.98347 cubic feet per second (cfs)
1.0 day = 86,400 seconds
1.0 acre-foot (ac-ft) = 43,560 cubic feet ($ft^3$)
1940-2023 contains 84 years = 1,008 months = 30,681 days

Conversion of Monthly WAM to Daily

*SIMD* input parameters controlling simulation options activated in the conversion of the monthly WAM to daily are described on pages 28-29 of Chapter 2 of this report as well as in Chapter 4 of the *Users Manual* and in the 2019 daily Brazos WAM report [7]. The *SIMD* input records in the daily Brazos WAM DAT file containing parameters for controlling daily simulation options are replicated below as Table 7.6.

Table 7.6
SIMD DAT File Input Records Controlling Simulation Options

```
**       1         2         3         4         5         6         7         8
**345678901234567890123456789012345678901234567890123456789012345678901234567890
**-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
JD    84    1940       1       1       0               4               1      13
JO     6                   1                           1                       3
JT
JU     1   1
OF     0   0   2   1                                         Brazos
OFV    9
HI         LOWER  MIDDLE   UPPER
DF        227901  509431  515531  515631  515731  515831  515931  516031  516131
DF        516231  516331  516431  516531  AQAQ34  BGNE71
DF        BRAQ33  BRBR59  BRDE29  BRGR30  BRHB42  BRHE68  BRPP27  BRRI70  BRRO72
DF        BRSB23  BRSE11  BRWA41  CBALC2  CFFG18  CFNU16
DF        CLPEC1  CON070  CON095  CON102  CON129  CON137  CON145  CON147  CON231
DF        DMAS09  DMJU08  EYDB61  GAGE56  GALA57  LAKE50
DF        LEBE49  LEGT47  LRCA58  LRLR53  NABR67  NAEA66  NBCL36  NBVM37  PAGR31
DF        RWPL01  SFAS06  SGGE55  YCSO62
```

The *JT*, *JU*, and *OF* records in Table 7.6 control simulation input, output, and computation options. The *HI* and *DF* records in the DAT file reference *HI* and *DF* record time series datasets in the hydrology input DSS file. The following options activated on the records shown in Table 7.6 are fundamental to the conversion of the monthly WAM to daily.

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

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

- INEV option 6 in *JO* record field 2 (column 8) instructs *SIM* and *SIMD* to read *IN* and *EV* records from a DSS input file. An entry of −6 for INEV activates a routine that converts *IN* and *EV* records from FLO and EVA files to a DSS input file. Other parameters on the *JO* record control transfers of *FA*, *HI*, and *TS* records from FAD, HIS, and TSF files to a DSS file.

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

- DSS(3) option 2 is selected in *OF* record field 4 (column 16) to record both daily and aggregated monthly simulation results in a DSS output file. *OF* record field 4 (column 20) controls the selection of simulation results variables to be included in the DSS output file.

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

- The *JT* record is required for a daily simulation, and the *JU* record activates certain daily options. Defaults are activated for blank fields or entries of zero on the *JT* and *JU* records.

- The *JT* record is the only additional record not included in a monthly WAM that is absolutely required to activate a *SIMD* daily simulation. The *JT* record in Table 7.6 has no entries meaning defaults are selected for all fields of the *JT* record. Some fields of the *JT* record allow optional output tables to be created in the annual flood frequency AFF and message SMM files.

- The *JU* record controls disaggregation and forecasting options. The blank (or zero) *JU* record field 3 (column 12) activates the default DFFILE option 1, meaning daily flow *DF* records are read from the DSS file for the 58 control points listed on the DAT file *DF* records in Table 7.6.

- Flow disaggregation DFMETH option 1 (uniform) is set as the global default in *JU* record field 2 used for computational control points that do not reflect actual real streamflow sites. Three *DC* records placed in the DIF file with REPEAT and DFMETHOD options 2 and 4 activate disaggregation option 4 based on *DF* record pattern hydrographs for all control points on the Brazos River and its tributaries and the streams in the San Jacinto Brazos coastal basin.

- Options for placing routed flow changes at the beginning or within the priority sequenced simulation computations are controlled by entries for WRMETH and WRFCST in *JU* record fields 4 and 5 (columns 16 and 20).

- Forecasting is activated by FCST option 2 in *JU* record field 6 (column 24). The forecast period FPRD set in *JU* record field 7 can be easily set or changed. If FCST=2 is entered in *JU* record field 6 and field 7 is blank, the forecast period FPRD is automatically computed within *SIMD*.

## Disaggregation of Monthly Naturalized Stream Flows to Daily

Disaggregation of monthly naturalized flow volumes to daily volumes is the basic key component of converting from a monthly WAM to a daily WAM. Other variables are also disaggregated from monthly to daily in a *SIMD* simulation by default uniformly.

With the standard default DFMETH option 4 activated, *SIMD* disaggregates monthly naturalized flow volumes to daily volumes in proportion to daily pattern hydrographs while preserving the monthly volumes. Daily flows on *DF* records are initially compiled in units of cfs for the daily WAMs. A *SIMD* simulation is performed with *DF* records for flows in cfs stored in the *SIMD* hydrology input DSS file. *SIMD* simulation results including daily naturalized flows in acre-feet are recorded by *SIMD* in its simulation results DSS output file. The daily naturalized flows in acre-feet in the *SIMD* simulation results DSS file are converted to *DF* records which are copied within *HEC-DSSVue* to the *SIMD* hydrology input DSS file.

The disaggregation of monthly naturalized flow volumes in acre-feet/month to daily volumes in acre-feet/day at the 4,468 control points in the Brazos WAM is controlled by input parameters on the *JO* and *JU* records found in the DAT file and *DC* records in the DIF file along with the 58 daily flow pattern hydrographs stored on *DF* records in the DSS file [7]. Parameter REPEAT option 2 on the *DC* records repeats the DSS file *DF* record flow pattern hydrographs at 58 control points for disaggregating monthly naturalized flows at over 4,400 control points.

The 1940-2017 daily flows on *DF* records for 58 control points in the 2019 daily WAM are adopted without change in the 2024 update. Development of *DF* record daily flows for 1940-2017 at 58 control points is described in detail in Chapter 6 of the 2019 daily Brazos WAM report [7]. The daily flows are extended from January 2018 through December 2023 employing the methods outlined in Tables 6.4, 6.5, and 6.6 of the 2019 report [7]. Daily 2018-2023 daily observed flows at 36 gage sites listed in Table 6.4 [7] represented by WAM control points were downloaded from the USGS National Water Information System (NWIS) website. Daily 2018-2023 flows at the other 22 control points were synthesized as outlined in Tables 6.5 and 6.6 of the 2019 report.

## Routing of Stream Flow Changes and Forecasting in Assessing Stream Flow Availability

The Brazos WAM includes calibrated routing parameters for 67 river reaches stored in the optional *SIMD* input DIF file. Forecast periods are set by two input parameters on the *JU* record in the DAT file. With the calibrated routing parameters already compiled, routing and/or forecasting can be easily activated or deactivated in alternative executions of *SIMD*. Based on simulation studies reported in the 2019 daily WAM report [7] and reassessments in the 2024 studies, routing was adopted with no forecasting. However, forecasting can be easily switched on.

The daily WAMs are valid simulation models without activation of the optional routing and forecasting features of *SIMD*. However, the accuracy of a simulation perhaps may be improved by activating routing with or without forecasting for appropriate stream reaches such as very long reaches. The Brazos River Basin is the largest of the six daily WAM case study river basins with the longest stream reaches. Therefore, routing and forecasting are more likely to be warranted in the Brazos daily WAM than the daily WAMs of other smaller river basins.

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 or attenuation, in a daily *SIMD* simulation in essentially the same manner as in 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* [5]. The routing parameters are stored on *RT* records in the daily input DIF file as 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.

Forecasting is relevant only if routing is employed. Forecasting and accompanying reverse routing, as explained in Chapter 3 of the *Daily Manual* [5], are designed specifically to deal with the effects of water management actions in a particular day on downstream stream flows in future days, as reflected in routing computations. With routing, stream flow depletions, return flows, and reservoir releases in the current day can affect both (1) stream flow availability for downstream water rights in future days and (2) flood flow capabilities for releases from flood control pools. The following two purposes are served by forecasting in the *SIMD* 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 from flood control pools that contribute to flooding in future days.

Routing and forecasting complexities and issues are explored in Chapter 2 (pages 31-37) of this report as well as in the 2019 daily WAM report [7]. Simulation studies presented in Chapter 10 of the daily Brazos WAM report [7] include comparisons of simulation results with and without routing and forecasting. The effects of routing on reservoir storage and other simulation results were found to be noticeable but not dramatic. The forecast period significantly affects the impacts of forecasting on water availability. A long forecast period can result in significant over-constraining of stream flow availability. Studies presented in the 2019 daily WAM report focus on a forecast period of 15 days versus no forecast, while also exploring other forecast periods.

Forecasting should be activated only if routing is employed. Routing can be employed without forecasting. A key major concern is to assure that a reasonably short forecast period is selected in *JU* record field 7 to prevent unreasonable constraints (reductions) in water availability. The default for FPRD in *JU* record field 7 will likely result in a forecast period that is too long. Thus, the default automatic setting of the forecast period should be used very cautiously if at all.

## Simulation of Reservoir Flood Control Operations

Operation of reservoirs in Texas for flood control is explained in a recent book [19]. Simulation of reservoir operations during floods in *SIMD* is explained in Chapter 5 of the *Daily Manual* [5]. Incorporation of flood control operations of nine USACE reservoirs in the Brazos WAM is described in Chapter 4 of the 2019 daily Brazos WAM report [7]. The 2024 version of the daily Brazos WAM incorporates without change the sets of *FR*, *WS*, *FF*, *DI/IS/IP*, and *FV/FQ* records for modeling reservoir flood control operations replicated as Tables 4.7, 4.8, 4.9, and 4.10 of the 2019 daily Brazos WAM report [7]. *FR*, *FF*, *FV*, and *FQ* records are applicable only in daily

*SIMD* simulations. The monthly *SIM* simulation model sets outflows equal to inflows whenever conservation storage is full to capacity.

Flood control operations of the nine USACE reservoirs (Table 7.1) are incorporated in the daily WAM by adding the following information to the *SIMD* input files. With the exception of LAGF and ATTF on *RT* records in the DIF file, these 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. LAGF and ATTF are for routing and reverse routing *FR* record flood pool releases in the determination of remaining flood flow channel capacity.
- *SV/SA* record reservoir storage volume versus area tables are extended to encompass the flood storage pools above the top of conservation pools if and as necessary.
- *FR* and *FF* records are added to model operation of the flood control pools of the nine USACE reservoirs based on flows at downstream gaging station. *WS* records are used with *FR* records to provide reservoir identifiers. Storage or drought index *DI/IS/IP* records are employed with a *FF* record to model the variation of flood flow limits with reservoir storage capacity. Any number of reservoirs can be operated based on flows at any number of downstream gages.
- *FV* and *FQ* records are employed to model outlet structure flow capacity and flow capacity of the stream reach below a dam that is relevant to single individual reservoirs rather than systems of two or more reservoirs.

Routing parameters LAGF and ATTF stored on *RT* records in the DIF file are employed in the *SIMD* simulation to route releases from the flood control pools of *FR* record reservoirs and perform reverse routing in determining available channel capacity associated with *FF* record flow limits. The parameters LAG and ATT are applied for all other routed flow changes.

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

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

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

The records controlling flood control operations of the nine USACE reservoirs are replicated as Table 7.7. Flood control reservoir *FR* records and auxiliary *WR* and *FF* records are treated as water rights analogous to *WR* and *IF* record rights. The group of records in Table 7.7 is inserted with the other water right records in the DAT file. *WS* records provide reservoir identifiers. The storage capacities in acre-feet at the top of flood control pool and conservation pool on the *FR* records are also tabulated in Table 7.1. The maximum release capacities in cfs at the dams are tabulated in columns 33-40 of the *FR* records. The maximum allowable nondamaging flow rate at downstream control points are specified on flood flow *FF* records. Multiple reservoir system operations are controlled by storage and release priorities on the *FR* records.

Table 7.7
SIMD DAT File Records Modeling Flood Control Operations of Nine USACE Reservoirs

```
**       1         2         3         4         5         6         7         8         9        10        11
**3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
**     |       |       |       |       |       |       |       |       |       |               |
FR5157319010000090980000   0   2  25000. 1363400       0       0               WTNYFC-FRSTOR   WTNYFC-FRREL
WSWTNYFC1363400.                                      -1       1      -1
FR5094319020000090970000   0   2  30000.  519838     1.0       0               WACOFC-FRSTOR   WACOFC-FRREL
WSWACOFC 519838.                                      -1       2      -1
FR5158319080000090910000   0   2   3000.  146000           52400               AQUILA-FRSTOR   AQUILA-FRREL
WSAQUILA
FR5159319050000090940000   0   2   2000.  374200           59400               PRCTOR-FRSTOR   PRCTOR-FRREL
WSPRCTOR
FR5160319040000090960000   0   2  10000. 1097600          457600               BELTON-FRSTOR   BELTON-FRREL
WSBELTON
FR5161319040000090960000   0   2  10000.  630400          235700               STLHSE-FRSTOR   STLHSE-FRREL
WSSTLHSE
FR5162319070000090920000   0   2   3000.  130800   37100   37100               GRGTWN-FRSTOR   GRGTWN-FRREL
WSGRGTWN
FR5163319060000090930000   0   2   6000.  244000   65500   65500               GRNGER-FRSTOR   GRNGER-FRREL
WSGRNGER
FR5164319030000090950000   0   2   2500.  507400  160110  160110               SMRVLE-FRSTOR   SMRVLE-FRREL
WSSMRVLE
**  FCDEP option 2 on the FR record for each reservoir specifies that the FF record limits not be employed.
FFLEHS45   2000.
FFLEGT47   5000.
FFLRLR53  10000.           2
FFLRCA58  10000.
FFBRWA41  25000.
FFBRHE68  60000.
FFBRRI70  60000.
```

Flood control operations are not activated in the simulation as long as storage is at or below the conservation pool capacity. If storage exceeds the top of conservation pool (bottom of flood control pool), the flood control pool is emptied as quickly as possible subject to the constraints that reservoir release rates cannot exceed a flow rate at the dam specified on the *FR* record and releases must be limited to levels that do not contribute to flows at downstream control points exceeding the maximum allowable flow rates specified on *FF* records.

However, FCDEP option 2 is activated in column 32 of all nine *FR* records (Table 7.7), meaning flood pool releases are restricted only by *FR* record flow limits at the dams. The *FF* record downstream flow limits are not employed. This simplification is motivated by downstream routing and forecasting issues and other complexities warranting further research. Flood control operations of USACE reservoirs in the Brazos, Trinity, and Colorado WAMs share the same complexities. Issues with applying *FF* record flood flow limits at multiple downstream gage sites are discussed further in Chapters 8 and 10.

The Brazos WAM sets outflows equal to inflows whenever storage exceeds flood control capacity. However, *FV* and *FQ* records can be added to set outflow as a function of storage volume. A varying outlet capacity as a function of storage level can be applied to model surcharge above the flood control pool or above conservation storage for reservoirs with no flood control storage.

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

Environmental flow standards (EFS) established pursuant to the process mandated by the 2007 Senate Bill 3 (SB3) are discussed in Chapter 3 of this report. Table 3.1 on page 57 lists the river systems for which SB3 EFS have been established. SB3 EFS have been established at 19 USGS gage sites in the Brazos River Basin shown in Figure 7.1. SB3 EFS are also discussed in Chapter 5 of the 2019 daily Brazos WAM report [7]. The rules and metrics defining the sets of SB3 EFS for the 19 sites in the Brazos River Basin are tabulated in Tables 5.2 and 5.3 [7]. The sets of *IF*, *HC*, *ES*, and *PF* records modeling the SB3 EFS are replicated in Table 5.5 of the 2019 daily Brazos WAM report [7]. This same group of 19 sets of *SIMD* input records are inserted in the DAT file of the 2024/2025 version of the daily WAM.

### Methodologies for Modeling SB3 EFS

A new approach for simulating SB3 EFS was introduced in the July 2018 versions of *SIMD* and *SIM* that is designed to replicate the format of SB3 EFS [13]. The SB3 EFS format established pursuant to the 2007 SB3 [98] was replicated in *SIMD* by addition of environmental standard *ES*, hydrologic condition *HC*, pulse flow *PF*, and pulse flow options *PO* records. These new records are combined with the old instream flow *IF* record in the DAT file to define the SB3 EFS. The new *ES* and *HC* records function in both monthly *SIM* and daily *SIMD* simulations. The pulse flow *PF* record is applicable only in the daily *SIMD*. The 2019 daily Brazos WAM was the first application of this new approach for modeling instream flow requirements [7].

The *IF* record dates back to the original versions of *SIM*. A variety of supporting record types are combined with *IF* or *WR* records to model instream flow requirements or diversion and storage rights. Instream flow requirements other than the SB3 EFS have been modeled in all versions of the Brazos WAM and the other WAMs with *IF* records long before addition of *ES* and *HC* records in the July 2018 *SIM* and *SIMD and PF* records in earlier pre-2018 versions of *SIMD*.

The SB3 EFS at 19 sites are modeled in the DAT file of the daily WAM by inserting 284 input records consisting of 19 *IF*, 19 *HC*, 76 *ES* (4x19=76), and 170 *PF* records. The 184 added records are grouped together in the DAT file and can be conveniently viewed or altered. Three 1940-2023 sequences of monthly hydrologic index *HI* records are stored in the DSS file. The three sequences of *HI* records representing the upper, middle, and lower regions of the Brazos River Basin are referenced by the *HC* records in defining hydrologic conditions. The DAT file *IF*, *HC*, *ES*, and *PF* records are replicated as Table 5.8 of the 2019 daily WAM report [7].

Monthly instream flow targets for the SB3 EFS at each of the 19 sites are computed in a daily *SIMD* simulation and stored as 19 target series *TS* records in the hydrology DSS file. The SB3 EFS are modeled in the monthly SIM DAT file with a group of 38 input records consisting of 19 *IF* records with corresponding 19 *TS* records referencing the 19 sequences of 1940-2023 monthly targets recorded on *TS* records in the DSS file.

The SB3 EFS are modeled in the 2023 version of the TCEQ monthly WAM available at the WAM website using a large assortment of records without employing the new *ES*, *HC*, *PF*, and *PO* records designed specifically for SB3 EFS. The 19 SB3 EFS are modeled with a group of combinations of about 4,900 *IF*, *WR*, *TO*, *PX*, and *FS* records, along with an additional group of

152 *UC* records, groups of 532 *CP* and 608 *CI* records, and various other records. Nine 1940-2018 sequences of hydrologic index *HI* records in a HIS file represent three alternative conditions (dry, average, wet) in each of three regions (upper, middle, lower).

SB3 EFS modeled with the older types of records are easily removed from other simpler WAMs. However, removal of the massive and complex scheme of SB3 EFS described in the preceding paragraph from the monthly Brazos WAM without inadvertently changing some other functionality that should not change will require significant time and expertise. Upon removal of the old records, the new sets of records developed in the present study can be easily inserted.

The then latest monthly TCEQ WAM described in the 2019 daily WAM report [7] was adopted for conversion to the 2024/2025 daily WAM as well as the preceding 2019 daily WAM. This monthly full authorization Brazos WAM consists of the following *SIM* input files with the dates of the latest revisions shown in parenthesis: bwam3.dat (9/8/2008), bwam3.dis (8/27/2007), bwam3.eva (11/3/20017), bwam3.flo (11/3/2017), and bwam3.his (11/3/2017).

Hydrologic Conditions Defined by Palmer Hydrologic Drought Index

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

Hydrologic conditions are defined in the daily Brazos WAM by hydrologic indices recorded on three hydrologic index *HI* records in the hydrology input DSS file representing three regions (watersheds) of the Brazos River Basin: Upper Basin above Possum Kingdom Dam, Lower Basin below Whitney Dam, and Middle Basin between Possum Kingdom Dam and Whitney Dam. Each *HI* record contains a monthly 1940-2023 (1,008 months) sequence of numbers that are either 1, 2, or 3 signifying dry (1), average (2), or wet (3) conditions in the lower, middle, and upper Brazos River Basin. The hydrologic conditions are defined based on the PHDI.

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

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

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

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

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

The PHDI for the lower (watershed below Whitney Dam), middle (between Whitney and PK), and upper (watershed above Possum Kingdom) Brazos River Basin have been computed as area-weighted averages of monthly PHDI quantities published by the NWS for the ten climatic regions of Texas. The area weighting factors are employed in the computations explained in the 2019 daily Brazos WAM report [7].

The 1940-2018 PHDI and associated *HI* record hydrologic indices in the 2023 WAM were extended through 2023 in conjunction with the present work. Time series of monthly PHDI quantities for the ten climatic regions were downloaded from the NWS website. Area weighting factors and PHDI ranges defining dry, average, and wet hydrologic conditions published in the Brazos EFS chapter of the Texas Administrative Code are employed in the computations to extend the hydrologic index *HI* records for the period from January 2019 through December 2023.

<u>*IF* Record Rights Modeling SB3 EFS in the Daily Brazos WAM</u>

Input data inserted into a *SIMD* input DAT file to model instream flow requirements specified by SB3 EFS are illustrated by the set of input records for the site of the USGS gage on the Brazos River at Richmond replicated as Figure 7.8. The sets of *IF*, *HC*, *ES*, and *PF* records are similar for each of the 19 sites though the numbers vary in magnitude between sites.

Table 7.8
SB3 EFS at the Richmond Gage on the Brazos River (Control Point BRRO72)

```
**      1       2       3       4       5       6       7       8       9       10
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234
**      !       !       !       !       !       !       !       !       !       !
IFBRRO72     -9.       20120301   2          EFS-BRRO72
HC LOWER      HI      M   J   N     0.0     1.5     2.5     -9.
ES SF501    430.    430.    430.    430.    430.    430.    430.    430.    430.    430.    430.    430.
ES BASE1   1140.   1140.   1250.   1250.   1250.   1250.    930.    930.    930.    930.   1140.   1140.
ES BASE2   2090.   2090.   2570.   2570.   2570.   2570.   1420.   1420.   1420.   1420.   2090.   2090.
ES BASE3   4700.   4700.   4740.   4740.   4740.   4740.   2630.   2630.   2630.   2630.   4700.   4700.
**
IFBRRO72     -9.       20120301   2         PF-BRRO72
HC LOWER      HI      M   J   N     0.0     1.5     2.5     -9.
ES PFES
PF     1   9090.  94700.  12   1   0  11   2   0   0   2
PF     2   9090.  94700.  12   3   0  11   2   0   0   2
PF     3  13600. 168000.  16   2   0  11   2   0   0   2
PF     1   6580.  58500.  10   1   0   3   6   0   0   2
PF     2   6580.  58500.  10   3   0   3   6   0   0   2
PF     3  14200. 184000.  18   2   0   3   6   0   0   2
PF     1   2490.  14900.   6   1   0   7  10   0   0   2
PF     2   2490.  14900.   6   3   0   7  10   0   0   2
PF     3   4980.  39100.   9   2   0   7  10   0   0   2
```

The pulse flow and subsistence/base flow components of the SB3 EFS are treated as two separate *IF* record water rights in Table 7.8 which allows simulation results for the pulse flow component and combined subsistence and base flow component of the SB3 EFS to be examined separately. Pulse flow *PF* and subsistence/base flow *ES* records are combined into a single *IF* record instream flow water right at a control point by allowing the set of *PF* records to follow directly after the after *ES* records by removing the extra *IF/HC/ES* records. Combining the records has no effect on the computed final combined instream flow targets. Alternative *SIMD* simulations with the SB3 EFS components combined versus separated are explored later in this chapter.

Any number of instream flow *IF* record water rights can be located at the same control point. Combining instream flow targets for multiple *IF* record rights at the same control point is controlled with *IF* record parameter IFM(if,2) with the following options: (1) a junior target replaces a senior target; (2) the largest target is adopted; the smallest target is adopted; or targets are added. The largest target (option 2) is adopted on the *IF* records of Table 7.8.

Instream flow targets are managed in the same manner as all water right targets within the *SIMD* simulation computations and output files. Options controlled by *IF* record field 3 and *PF* record field 15 create tables in the MSS and SMM message files that provide additional supplemental information that facilitates tracking the *HC*, *ES*, and *PF* record computations. These message file options are not activated in the dataset of Table 7.8.

*HC*, *ES*, *PF*, and *PO* Records

Hydrologic condition *HC* and environmental standard *ES* records are applicable for either a monthly *SIM* simulation or daily *SIMD* simulation. Pulse flow *PF* and pulse options *PO* records are applicable for only a daily *SIMD* simulation. *ES* records describe subsistence and base flow components of environmental flow standards. *PF* and *PO* records model high pulse flow components of environmental flow standards. Hydrologic conditions defined by *HC* records are applicable for both *ES* and *PF* record quantities. The purpose of *HC*, *ES*, and *PF* records is to control computation of a minimum instream flow target for each month of a monthly *SIM* or each day of a daily *SIMD* simulation. With these records employed, an *IF* record water right in a monthly *SIM* simulation input dataset consists of an *IF* record followed by a *HC* record and a set of *ES* records. A set of *PF* and *PO* records can be added for a daily *SIMD* simulation. *IF*, *HC*, and *ES* input records are described in Chapter 3 of the *Users Manual* [2]. *PF* and *PO* input records are covered in Chapter 4 of the *Users Manual*.

SB3 EFS are modeled with *IF*, *HC*, *ES*, and *PF* records in the daily Brazos WAM and five other daily WAMs (Chapters 8-12). Supplemental pulse options *PO* records are not needed. With no *PO* records, defaults are activated for all parameters defined by *PO* record entries.

The computation of a SB3 EFS target consists of computing a subsistence and base flow target as specified by *ES* records and a pulse flow target as specified by *PF* records. The larger of the two targets in each individual day is adopted as the final target applied in the simulation. However, both target components can be recorded in the simulation results for information.

The *IF* records in Table 7.8 include the control point identifier of the EFS, priority of 20120301 (March 1, 2012), and water right identifier. The −9 for AMT in *IF* record field 3 signals that *HC*, *ES*, and *PF* records are being employed to model the instream flow right.

The identifier LOWER, MIDDLE, or UPPER in *HC* record field 2 references the relevant *HI* record in the hydrology input DSS file. The hydrologic condition (dry, average, wet) is defined by the hydrologic index (1, 2, or 3) read from the relevant (lower, middle, upper basin) hydrologic index *HI* record in the DSS file for the first month of the seasons defined in *HC* record fields 6 through 17. The M, J, and N on the *PF* records of Table 7.8 refer to updating the hydrologic index in March, July, and November for application throughout the seasons March-June (Spring), July-October (Summer), and November-February (Winter).

<u>Subsistence and Base Flow Limits</u>

The subsistence flow limit is a constant for each SB3 EFS site in the Brazos WAM. The base flow limits are functions of season of the year and hydrologic condition defined based on Palmer hydrologic drought index (PHDI) quartiles. The subsistence and base flow limits are applied differently in the Brazos WAM for dry hydrologic conditions than for average and wet hydrologic conditions. A 50% rule is applied if the hydrologic condition is dry as measured by the PHDI being in the lowest quartile. A target for a particular day at a particular location is set based on subsistence and base flow requirements as follows.

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

SF501 in *ES* record fields 2 and 3 of Table 7.8 specifies determination of subsistence flow limits using the 50% rule [5, 7] for dry hydrologic conditions. BASE1, BASE2, and BASE3 in *ES* record fields 2 and 3 refer to base flows (ESF=BASE) for dry, average, and wet hydrologic conditions (ESHC = 1, 2, 3). *ES* record fields 4 through 15 consist of twelve subsistence or base flow limits in cfs.

<u>High Flow Pulse Components of SB3 EFS</u>

Each *PF* record defines a set of high flow characteristics to be preserved in one or more high flow events initiated in the specified season if such events occur in the simulation. Regulated flow is the default recommended standard *PF* record field 2 PVF option adopted for the Brazos WAM and the five other case study daily WAMs of Chapters 8-12. Naturalized flow is another *SIMD* PVF option. Hydrologic condition 1, 2, or 3 (dry, average, wet) is specified in field 3 of each *PF* record. The trigger $Q_P$ in cfs, volume limit in acre-feet, and duration in days are entered in *PF* record fields 4, 5, and 6. The target number of events (frequency) for each tracking period are set in *PF* field 7. The March-June (Spring), July-October (Summer), and November-February (Winter) tracking periods are defined in *PF* record fields 8-12.

*PF* record fields 12, 13, and 14 are left blank with defaults being activated. Regulated flow changes in the *SIM/SIMD* simulation as each water right is considered in the priority sequence computations. With the default flow option 1 (blank field 12), the final regulated flow at the end of the priority-sequence computations is used to determine the accumulated flow used with the volume termination criterion. The target limit option 2 in *PF* record field 13 (column 56) means that the computed target each day is limited to not exceed the trigger $Q_P$ entered in *PF* field 4. The default target selection option 2 in *PF* record field 14 (column 60) means that the *IF* record instream flow target computed each day is the maximum of the different computed *ES* and *PF* record intermediate component targets.

Default target limit option 1 in *PF* record field 13 was employed in the daily WAM described in the 2019 daily WAM report [7] and changed to option 2 in the updated daily WAM described in this chapter to be consistent with the actual SB3 EFS. With option 2 adopted in column 56 of the *PF* records, the pulse flow target is limited to not exceed the trigger level in *PF* record field 4. The volume and duration termination criteria remain unchanged. The mean of the high flow pulse targets over the 30,681 days of the 1940-2023 simulation and the number of days with non-zero high flow pulse targets are compared below for four control points described later in Table 7.10. The 30,681-day averages and number of days with high flow pulse targets for the updated daily WAM with option 2 are included in both Table 7.11 and the comparison below.

| control point | LRCA58 | BRSE11 | BRWA41 | BRRI70 |
|---|---|---|---|---|
| option 2 with target limited | 74.45 cfs | 6.643 cfs | 112.1 cfs | 391.6 cfs |
| to not exceed trigger level | 1,963 days | 574 days | 1,159 days | 1,953 days |
| option 1 without limiting | 141.6 cfs | 10.14 cfs | 173.6 cfs | 611.5 cfs |
| to not exceed trigger level | 1,957 days | 1,744 days | 1,151 days | 1,941 days |

Daily and Monthly Instream Flow Targets for the EFS

The simulation procedure described in the next paragraph was performed with 1940-2017 hydrology as reported in the 2019 daily Brazos WAM report [7] and repeated with 1940-2023 hydrology in conjunction with the present report. Simulation studies presented in Chapter 10 of the 2019 Brazos WAM report include analyses of the daily and monthly instream flow targets for the SB3 EFS that includes plots in Figures 10.92 through 10.110 of the simulated 1940-2017 daily instream flow targets in cfs at each of the 19 sites. Daily and monthly subsistence/base flow and pulse flow targets at four of the sites are plotted in Figures 10.111-10.118. Relevant statistics for 1940-2017 stream flows and instream flow targets and shortages are presented in Table 10.12.

A daily *SIMD* simulation was performed with the set of *IF*, *HC*, *ES*, and *PF* records incorporated in the DAT file to control computation of daily instream flow targets for the SB3 EFS at the 19 USGS gaging stations (WAM control points). The daily instream flow targets in acre-feet/day were summed within *SIMD* to monthly quantities in acre-feet/month, which are included in the simulation results DSS file. The DSS records of monthly targets were copied from the daily *SIMD* simulation results DSS output file to the *SIM/SIM* hydrology input DSS file and the pathnames were revised using *HEC-DSSVue*. The *TS* records in the monthly *SIM* DAT file reference the DSS file target series employed by the *IF* record water rights.

The 1940-2023 monthly SB3 EFS instream flow targets and shortages in acre-feet/month at the 19 USGS gage locations are plotted as Figures C1 through C19 of Appendix C of this report. The monthly instream flow targets plotted in Appendix C were computed within *SIMD* by summing simulated daily instream flow targets. These instream flow targets stored on *TS* records in the hydrology DSS input file are read by *SIM*. The monthly shortages are *SIMD* summations of daily shortages, which differ from shortages computed in a monthly *SIM* simulation.

Stream Flow and *IF* Record Instream Flow Target Quantities

A table accompanying the *OF* record description in the WRAP *Users Manual* [2] defines 43 time series variables that may be included in *SIM* and *SIMD* simulation results output files. Labels defining the quantities in *SIM/SIMD OF* records, *TABLES* input files, and *DSS* simulation results files are shown in Table 7.9 for eight of the 43 variables. The eight variables listed below in Table 7.9 are discussed in the next subsection of this chapter. These flow rate quantities are forms of stream flow, instream flow targets, or shortages in meeting instream flow targets. The first five quantities listed in Table 7.9 are associated with control points. The other three quantities are connected directly to individual instream flow *IF* record water rights located at control points. Multiple *IF* record water rights may be located at the same control point.

Table 7.9
Instream Flow Targets and Shortages in *SIM/SIMD* Simulation Results

| Instream Flow<br>Target or Shortage | *SIM/SIMD*<br>*OF* Record | DSS Record<br>Part C | *TABLES*<br>Monthly | *TABLES*<br>Daily |
|---|---|---|---|---|
| naturalized flow at a control point | 1. NAT | NAT-CP | 2NAT | 6NAT |
| regulated flow at a control point | 2. REG | REG-CP | 2REG | 6REG |
| unappropriated flow at a control point | 3. UNA | UNA-CP | 2UNA | 6UNA |
| final flow 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 |

Statistics for Daily Stream Flow and SB3 EFS Targets

Statistics for daily streamflow and instream flow targets in cfs for 1940-2023 time series of 30,681 daily quantities occurring at four control points (USGS gage sites) listed in Table 7.10 are compared in Table 7.11. The locations of the gage sites are included on the basin map of Figure 7.2. The gage on the Brazos River at Waco is located at the downstream edge of the city. The four gage locations represent a diverse range of watershed and river flow characteristics.

Table 7.10
Four Control Points Representing USGS Gage Sites

| Location | Control<br>Point | USGS<br>Gage | Watershed Area<br>(square miles) |
|---|---|---|---|
| Little River at Cameron | LRCA58 | 08106500 | 30,016 |
| Brazos River at Seymour | BRSE11 | 08082500 | 5,996 |
| Brazos River at Waco | BRWA41 | 08096500 | 20,065 |
| Brazos River at Richmond | BRRI70 | 08114000 | 35,454 |

Table 7.11
Statistics for Daily Stream Flows and SB3 EFS Targets and Shortages

| Daily Flow Variable | Variable (Table 7.9) | Control Point LRCA58 | BRSE11 | BRWA41 | BRRI70 |
|---|---|---|---|---|---|
| | | **Mean of Daily Quantities (cfs)** | | | |
| Observed Flows | - | 1,742 | 290.30 | 2,255 | 7,593 |
| Naturalized Flows | NAT-CP | 1,878 | 301.2 | 2,629 | 8,176 |
| Regulated Flows | REG-CP | 1,478 | 282.1 | 1,813 | 6,487 |
| Unappropriated Flows | UNA-CP | 773.9 | 37.30 | 749.4 | 3,609 |
| Final Total Instream Flow Targets | IFT-CP | 443.9 | 26.49 | 484.6 | 2,632 |
| SB3 EFS Targets* | IFT-CP | 316.5 | 26.49 | 394.5 | 2,104 |
| Pulse Flow Targets | TIF-WR | 74.45 | 6.643 | 112.1 | 391.6 |
| Subsistence/Base Flow Targets | TIF-WR | 258.5 | 20.15 | 294.1 | 1,836 |
| Total Instream Flow Shortages | IFS-CP | 140.5 | 3.927 | 164.4 | 787.8 |
| SB3 EFS Target Shortages* | IFS-CP | 60.13 | 3.927 | 107.1 | 472.0 |
| | | **Median (50% Exceedance Frequency) of Daily Quantities (cfs)** | | | |
| Observed Flows | - | 425.0 | 44.00 | 730.0 | 2,760 |
| Naturalized Flows | NAT-CP | 479.7 | 45.24 | 650.5 | 3,015 |
| Regulated Flows | REG-CP | 238.6 | 38.88 | 211.9 | 1,520 |
| Unappropriated Flows | UNA-CP | 0.000 | 0.000 | 0.00 | 0.00 |
| Final Total Instream Flow Targets | IFT-CP | 460.0 | 19.00 | 480.0 | 1,899 |
| SB3 EFS Targets* | IFT-CP | 190.0 | 19.00 | 250.0 | 1,650 |
| Pulse Flow Targets | TIF-WR | 0.000 | 0.000 | 0.000 | 0.000 |
| Subsistence/Base Flow Targets | TIF-WR | 160.0 | 19.00 | 250.0 | 1,650 |
| Total Instream Flow Shortages | IFS-CP | 60.37 | 0.000 | 81.20 | 387.3 |
| SB3 EFS Target Shortages* | IFS-CP | 0.000 | 0.000 | 0.000 | 0.000 |
| | | **Maximum of Daily Quantities (cfs)** | | | |
| Observed Flows | - | 84,200 | 46,798 | 121,000 | 120,000 |
| Naturalized Flows | NAT-CP | 149,425 | 46,798 | 210,023 | 327,392 |
| Regulated Flows | REG-CP | 145,209 | 46,284 | 207,835 | 325,963 |
| Unappropriated Flows | UNA-CP | 86,726 | 22,314 | 72,149 | 155,329 |
| Final Total Instream Flow Targets | IFT-CP | 4,790 | 1,040 | 13,600 | 16,300 |
| SB3 EFS Targets* | IFT-CP | 4,790 | 1,040 | 13,600 | 16,300 |
| Pulse Flow Targets | TIF-WR | 4,790 | 1,040 | 13,600 | 16,300 |
| Subsistence/Base Flow Targets | TIF-WR | 760.0 | 46.00 | 690.0 | 3,980 |
| Total Instream Flow Shortages | IFS-CP | 1,020 | 46.00 | 690.0 | 5,341 |
| SB3 EFS Target Shortages* | IFS-CP | 760.0 | 46.00 | 690.0 | 3,980 |
| | | **Minimum Daily Quantities (cfs)** | | | |
| Observed Flows | - | 0.000 | 0.000 | 0.120 | 55.00 |
| Final Total Instream Flow Targets | IFT-CP | 127.5 | 1.000 | 96.56 | 833.1 |
| SB3 EFS Targets* | IFT-WR | 32.00 | 1.000 | 56.00 | 550.0 |
| Subsistence/Base Flow Targets | TIF-WR | 32.00 | 1.000 | 56.00 | 550.0 |
| Minimum of 0.00 at all control points for naturalized, regulated, unappropriated flows and EFS shortages. | | | | | |
| | | **Number of Days with Non-Zero Pulse Flow Targets During the 30,681 Days of 1940-2023** | | | |
| Pulse Flow Targets | TIF-WR | 1,963 | 574 | 1,159 | 1,953 |

The mean, median, maximum, and minimum daily flow rates are included in Table 7.11 for the 30,681 days of the 1940-2023 period-of-analysis for observed, naturalized, and simulated regulated and unappropriated stream flows, and various forms of instream flow targets and shortages in meeting the targets. The median is the magnitude that is exceeded during 50 percent of the 30,681 days. The number of days during the 30,681-day 1940-2023 simulation with high flow pulse targets greater than zero are tabulated as the last row in Table 7.11.

The datasets represented in Table 7.11 were managed and analyzed with *HEC-DSSVue*. The times series of observed daily flows were downloaded from the USGS NWIS website. The other quantities in Table 7.11 are from DSS output files created with *SIMD*. The quantities were generated with two alternative simulations of *SIMD*, with the only difference being alternative strategies for dealing with the situation of SB3 EFS being located at the same control points as other instream flow requirements established earlier independently of the SB3 EFS process. Two simulation results variables marked with an asterisk in their labels in Table 7.11 were generated with a second simulation designed to separate SB3 EFS targets and shortages from other instream flow requirements at the same control points that are not associated with the SB3 EFS. For the other WAMs covered in case study Chapters 8-12, almost all the additional pre-existing instream flow requirements are assigned to control points in the WAMs other than SB3 EFS control points.

About 120 of over 1,200 certificates of adjudication and water use permits modeled in the Brazos WAM contain special conditions regarding minimum instream flow requirements [7]. The 122 *IF* records in the version of the DAT file last updated 9/8/2008 are listed in in Table 2.7 of the 2019 daily WAM report [7]. Priorities for the 122 *IF* records range from November 1947 to May 2005. The SB3 EFS have a priority date of March 2014. One or more of the 122 more senior *IF* records are located at each of nine of the 19 control points with *IF* records modeling SB3 EFS.

Any number of instream flow *IF* record water rights can be located at the same control point in a *SIM* or *SIMD* simulation. Combining instream flow targets for multiple *IF* record rights at the same control point is controlled with *IF* record parameter IFM(if,2) with the following options: (1) the junior target replaces the senior target in the water right priority sequence computations; (2) the largest target is adopted; or (3) the smallest target is adopted.

The computation of an *IF* record instream flow target for SB3 EFS consists of computing a subsistence and base flow target as specified by *ES* records and a high flow pulse target as specified by *PF* records. The default is for the larger of the two targets in each individual day to be adopted as the SB3 EFS target applied in the simulation. However, both target components can be recorded in the simulation results for information using labels listed in Table 7.9. The combined SB3 EFS instream flow target in all cases in the six case study WAMs is the larger of the *ES* record component or *PF* record component.

Referring to the last line of Table 7.11, high flow pulse events are tracked as specified by PF records at control points control points LRCA58, BRSE11, BRWA41, and BRRI70 during 1,957 days, 1,744 days, 1,151 days, and 1,941 days of the simulation. The *PF* record component of the SB3 EFS is zero during the other days of the 30,681-day simulation. The *ES* record component of the SB3 EFS is greater than zero during all 30,681 days. The *PF* record component is generally larger during the high pulse flow tracking days. The *ES* record component is larger during all other days.

The six simulation results quantities dealing with *IF* record instream flow requirements included in Table 7.11 are defined below. The 2nd and 6th variables flagged with an asterisk * are generated in an alternative *SIMD* simulation employing IFM(if,2) option 1 (based on priority sequence) for combining targets for multiple *IF* record water rights at the same control point. The other variables are from a *SIMD* simulation employing IFM(if,2) option 2 (largest adopted).

1. Final Total Instream Flow Targets (IFT-CP): The final target each day at the completion of the water rights priority sequence computations combining all *IF* record targets at the control point, including non-SB3 EFS, with IFM(if,2) option 2 based on adopting the largest.
2. SB3 EFS Targets* (IFT-CP): The final target employing IFM(if,2) option 1 for combining SB3 EFS and non-SB3 EFS targets. With IFM(if,2) option 1, a senior *IF* record target is replaced with a junior *IF* record target in the water rights priority sequence computations. The daily targets are plotted in Figures 7.10-7.13. Monthly summations of the daily targets are incorporated in the modified monthly WAM and plotted in Figures C1-C19 of Appendix C.
3. High Flow Pulse Targets (TIF-WR): The high flow pulse target as specified by *PF* records.
4. Subsistence/Base Flow Targets (TIF-WR): The target computed as specified by *ES* records.
5. Total Instream Flow Shortages (IFS-CP): The first target variable defined above minus the regulated flow at completion of the priority sequence when the target exceeds regulated flow.
6. SB3 EFS Target Shortages* (IFS-CP): The second target variable defined above minus the regulated flow at completion of the priority sequence whenever the target exceeds the regulated flow. Monthly summations of this target shortage are included in the plots in Appendix C.

Referring to Tables 7.10 and 7.11, control points LRCA58, BRWA41, and BRRI70 have other more senior *IF* record requirements as well as the *IF* records modeling SB3 EFS. The only *IF* record located at control point BRSE11 is the *IF* records modeling SB3 EFS. The means for the first versus second instream flow targets defined above at control points LRCA58, BRSE11, BRWA41, and BRRI70 are compared as follows: 443.9/316.5 cfs, 26.49/26.49 cfs, 484.6/394.5 cfs, and 2,632/2,104 cfs. The first quantity includes all *IF* records at the control point. The second quantity includes only *IF* records modeling SB3 EFS. Control point BRSE11 has no *IF* records other than the *IF* record modeling SB3 EFS.

The non-zero daily quantities for the high flow pulse component of the EFS targets are much larger than the subsistence and base flow quantities but occur only during infrequent flood or high flow events. The subsistence and base flow component of the EFS targets are relatively small quantities in each day compared to high flow pulse components but occur continuously. Figures 7.10, 7.11, 7.12, and 7.13 plot the combined SB3 EFS targets and only the subsidence/base flow component. The difference between the two plots is the high flow pulse component.

Monthly summations of the daily SB3 EFS instream flow targets computed by *SIMD* are plotted for each of the19 SB3 EFS sites in the 1940-2023 time series plots in Appendix C. The means of either the 30,681 daily or 1,008 monthly SB3 EFS instream flow targets at control points LRCA58, BRSE11, BRWA41, and BRRI70 are 21.4%, 9.4%, 21.8%, and 32.4% of the means of the regulated flows (Table 7.11). The means of the daily *SIMD* simulated shortages reflected in failures to meet the SB3 EFS targets are 19.0%, 14.8%, 27.1%, and 22.4% of the means of the SB3 EFS targets at control points LRCA58, BRSE11, BRWA41, and BRRI70.

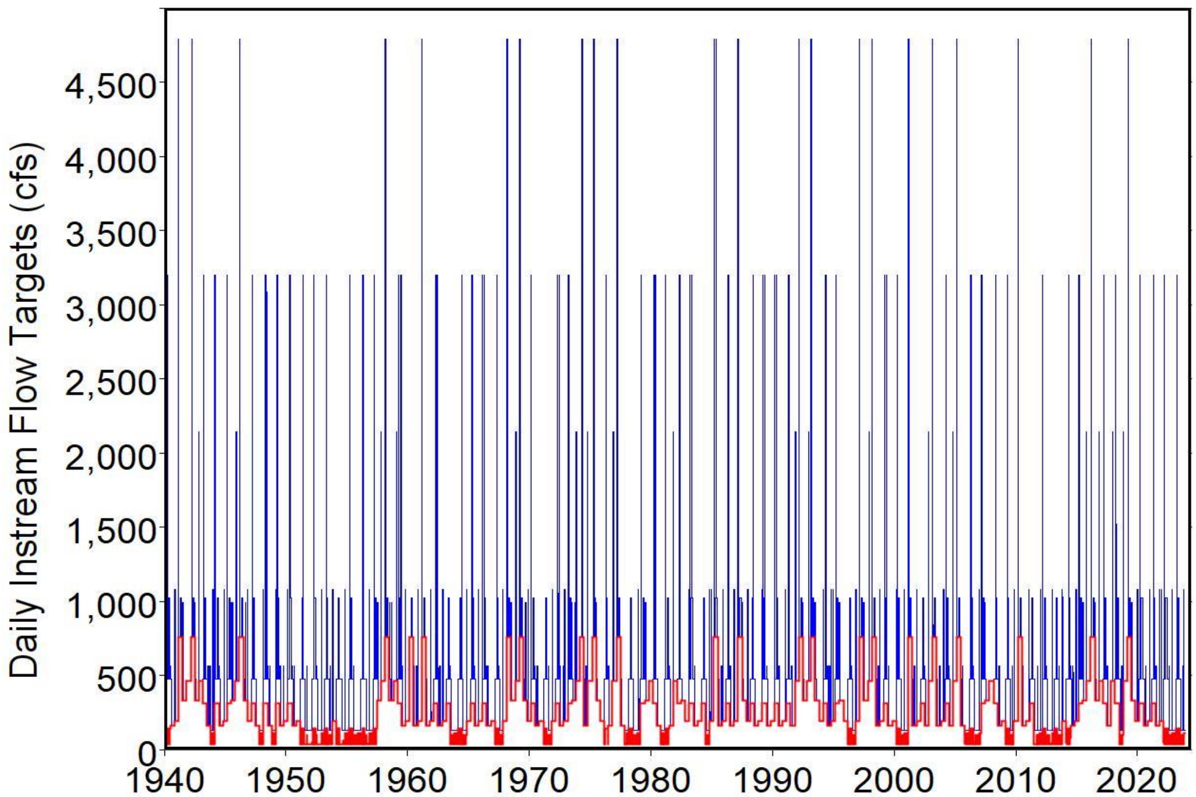

Figure 7.10 SB3 EFS Combined Total (blue) and Subsistence/Base (red) Targets at LRCA58

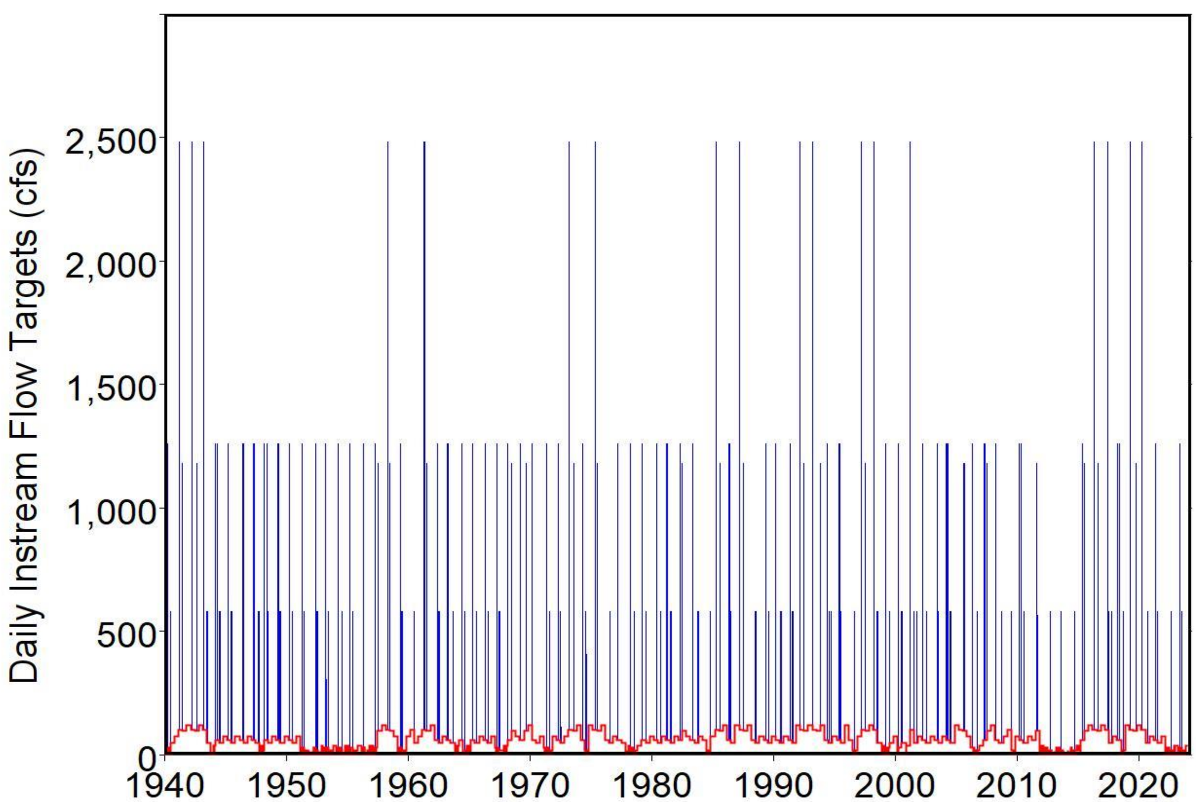

Figure 7.11 SB3 EFS Combined Total (blue) and Subsistence/Base (red) Targets at BRSE11

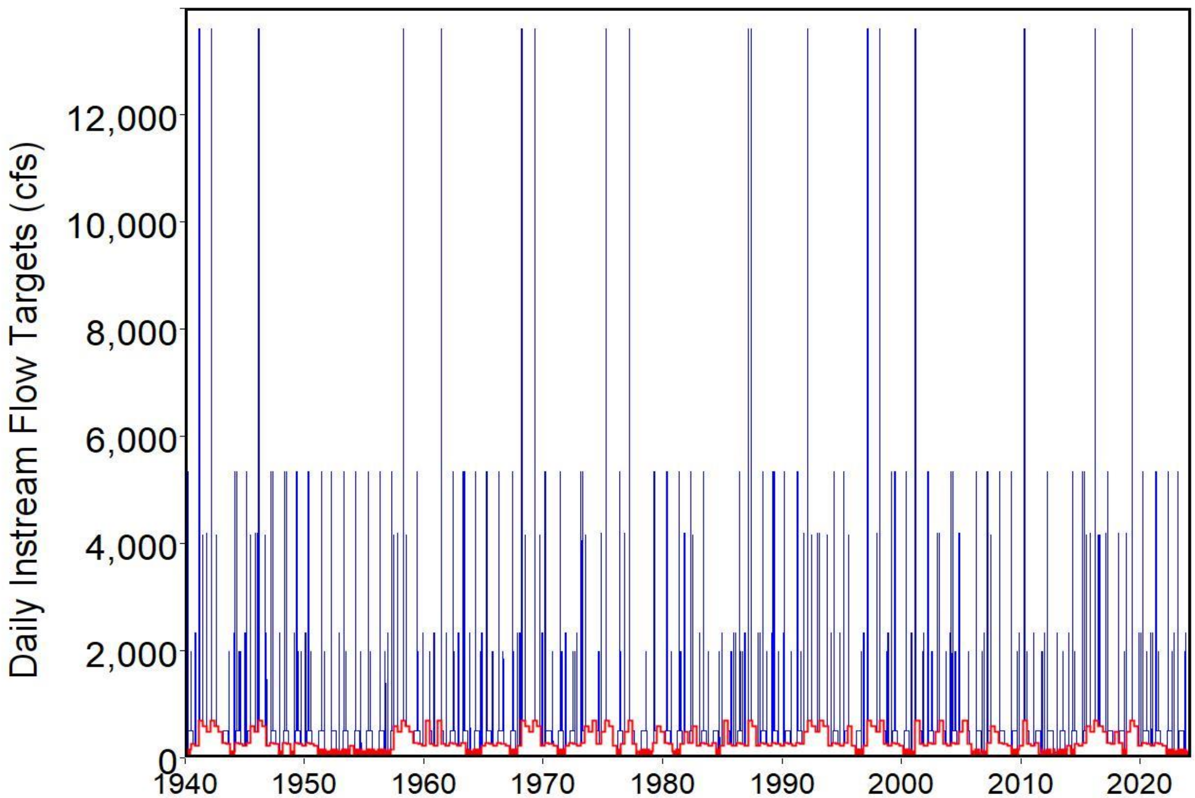

Figure 7.12 SB3 EFS Combined Total (blue) and Subsistence/Base (red) Targets at BRWA41

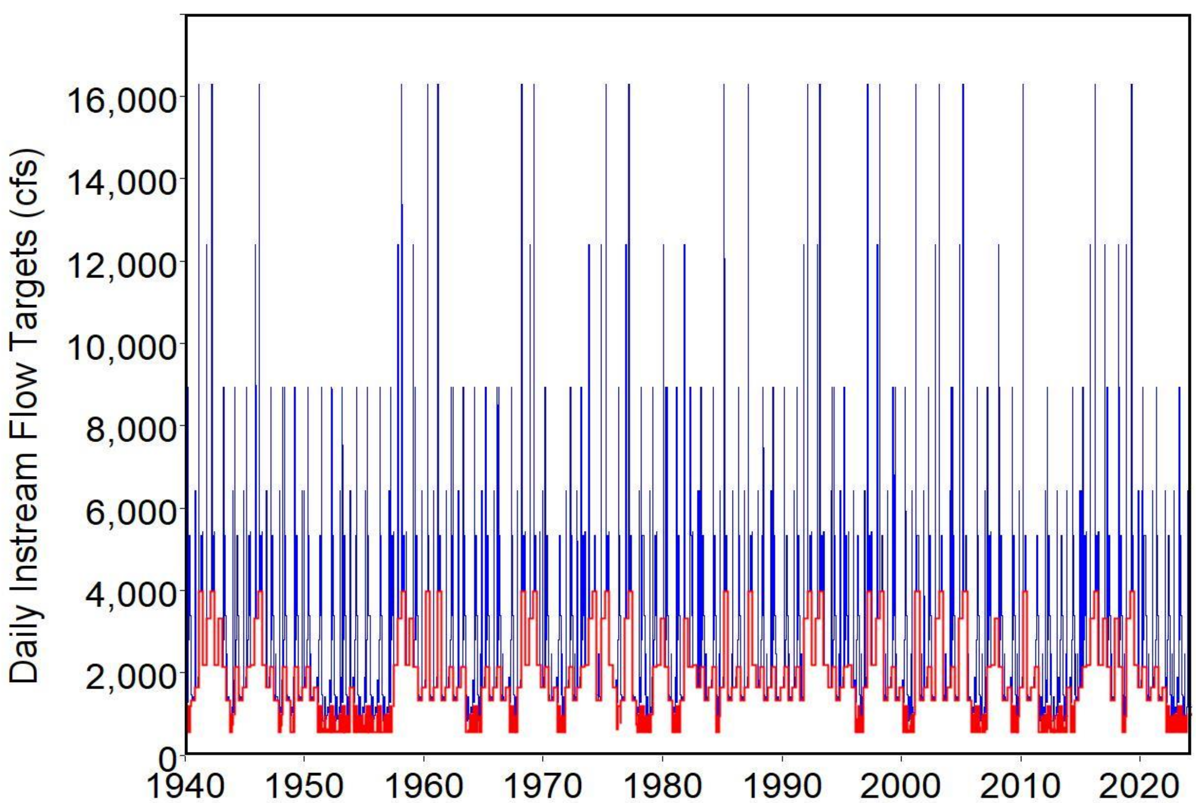

Figure 7.13 SB3 EFS Combined Total (blue) and Subsistence/Base (red) Targets at BRRI70

## Monthly WAM with Instream Flow Targets from the Daily WAM

The strategy for incorporating monthly instream flow targets computed in a daily *SIMD* simulation into the *SIM* input dataset for a monthly WAM is described in Chapter 2 of this report and in Chapter 6 of the *Daily Manual* [5] and illustrated in an example in Chapter 8 of the *Daily Manual*. The method has been applied for each of the case study WAMs as discussed in Chapters 7 through 12 of this report. Daily targets computed by *SIMD* are aggregated within *SIMD* to monthly targets which are included in the *SIMD* simulation results. These time series of monthly targets are converted to target series *TS* records incorporated in the *SIM/SIMD* hydrology input DSS file. The process is illustrated by the *SIM* DAT file input records and pathnames of *TS* records in the DSS input files of Tables 7.12 and 7.13.

Table 7.12
Pathnames for Target Series *TS* Records in Hydrology Input DSS File

| Part A | Part B | Part C | Part D | Part E |
|---|---|---|---|---|
| BRAZOS | SFAS06 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | DMAS09 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRSE11 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | CFNU16 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | CON026 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRSB23 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRPP27 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRGR30 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | NBCL36 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRWA41 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | LEGT47 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | LAKE50 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | LRLR53 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | LRCA58 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRBR59 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | NAEA66 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRHE68 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRRI70 | TS | 31Jan1940-31Dec2023 | 1MON |
| BRAZOS | BRRO72 | TS | 31Jan1940-31Dec2023 | 1MON |

The 1940-2023 sequences of monthly instream flow targets in acre-feet/month stored as DSS records labeled by the pathnames listed in Table 7.12 model the SB3 EFS at the 19 sites. The *TS* records in the DSS input file with the pathname identifiers of Table 7.12 are referenced by the *TS* records in the DAT file of Table 7.13. These 19 DSS records are stored along with the other time series records (*IN*, *EV*, *HI* records) in a DSS file with filename BrazosHYD.DSS that can be read by *SIM*, *SIMD*, *HEC-DSSVue*, or any other computer program with DSS capabilities.

The group of 19 *IF* and 19 *TS* records replicated in Table 7.13 are inserted in the DAT file read by *SIM* in the same manner as for all *IF* and *WR* record water rights. These are the only input records included in the *SIM* input DAT file to model the SB3 EFS. The 1940-2023 time series of monthly targets are read by *SIM* from the records in the DSS input file labeled with the pathnames listed in Table 7.12 as specified by the *IF* and *TS* records in Table 7.13. Model users can apply the monthly WAM without being concerned with the daily WAM.

Table 7.13
Instream Flow Rights that Model the EFS in the Monthly Brazos WAM DAT File

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

Computing monthly SB3 EFS targets by aggregating *SIMD* daily targets allows the improved accuracy of a daily *SIMD* simulation to be incorporated in a monthly WAM. Daily target volumes are precisely replicated in the monthly targets. The accuracy of the *SIM* simulation of constraints of SB3 EFS on junior water rights is significantly improved. This improvement is a key fundamental consideration in WAM support of the water use permit application evaluation process. Shortage amounts for failures in meeting the SB3 EFS are computed within the monthly *SIM* simulation based upon monthly regulated flows computed in the simulation. Thus, the benefits of the daily WAM are reduced significantly in monthly *SIM* based assessments of capabilities for meeting SB3 EFS.

This report focuses on the strategy in which the daily WAM is applied occasionally to develop or update monthly SB3 EFS instream flow targets for incorporation in a monthly WAM dataset used in routine applications with the *SIM* simulation model. However, daily WAMs can be applied directly, instead of using monthly versions of the WAMs, in various diverse applications involving assessments of capabilities for meeting SB3 EFS requirements, flood control operating considerations, or integration of multiple water management purposes and objectives.

## Alternative Versions of the Full Authorization Brazos WAM

The alternative monthly and daily versions the Brazos WAM discussed in this chapter are reiterated as follows. Reservoir storage volumes generated with alternative versions of the WAM are compared later in the last section of the chapter.

### 2008/2017 and 2023 Monthly WAMs

The original Brazos WAM is documented by a 2001 report [86] prepared by a consulting firm for TNRCC (later renamed TCEQ). The original WAM dataset has a period-of-analysis of 1940-1997. Previous daily and modified monthly versions of the Brazos WAM were developed as described in a 2019 report [7] by modifying a 2008/2017 monthly WAM comprised of files with the following filenames and dates of latest updates: bwam3.DAT (9/8/2008), bwam3.DIS (8/27/2007), bwam3.FLO (11/3/2017), bwam3.EVA (11/3/2017), and bwam3.HIS (11/3/2017).

The Brazos River Authority (BRA) has contracted for the conservation (water supply) storage capacity in nine USACE reservoirs and owns three other reservoirs. BRA operations including a system operation permit and water management plan are described at a BRA website (https://brazos.org/About-Us/Water-Supply/System-Operations). The system operation permit was approved by TCEQ by final order dated November 30, 2016. The accompanying water management plan (WMP) is described by a BRA report [96] and other technical documents available at the BRA website. The WMP was approved by TCEQ on April 2, 2018. An update of the WAM is described by a 2021 technical report prepared by a team of consulting firms for TCEQ [74].

The system operation permit and WMP combine multiple-reservoir system operations, use of unregulated flows entering the river system below the dams, return flows, firm and interruptible water supply commitments, and other practices to improve water supply capabilities [96]. The expanded water right features add to the complexity of the Brazos WAM.

The official TCEQ full authorization (run 3) monthly Brazos WAM last updated 10/1/2023 and accessible at the TCEQ WAM website during 2024 is comprised of five *SIM* input files with filenames bwam3.DAT (last update 10/1/2023), bwam3.DIS (undated), bwam3.FLO (8/30/2021), bwam3.EVA(8/30/2021), and bwam3.HIS (undated). As noted in Table 6.9 of Chapter 6, this dataset has a hydrologic period-of-analysis of 1940-2018. This 2023 WAM was modified as described earlier in Chapter 7. The 1940-2018 period-of-analysis was extended through 2023. The *IN*, *EV*, and *HI* records in the FLO, EVA, and HIS files were converted to a single DSS hydrology *SIM/SIMD* input file. The net evaporation-precipitation adjustment method controlled by EPADJ on the *JD* record was changed from option −1 to option 1. The resulting WAM is comprised of three files with filenames Brazos3.DAT, Brazos3.DIS, Brazos3HYD.DSS.

The SB3 EFS are modeled in the 2023 (last update 10/1/2023) version of the monthly WAM available at the TCEQ WAM website using a large assortment of records without employing the new *ES*, *HC*, *PF*, and *PO* records designed specifically for SB3 EFS. The 19 SB3

EFS are modeled with a group of combinations of about 4,900 *IF*, *WR*, *TO*, *PX*, and *FS* records, along with an additional group of 152 *UC* records, groups of 532 *CP* and 608 *CI* records, and various other records. Nine 1940-2018 sequences of hydrologic index *HI* records in a HIS file represent three alternative conditions (dry, average, wet) in each of three regions (upper, middle, lower). Old records modeling SB3 EFS were removed and replaced with sets of *IF*, *ES*, *HC*, and *PF* records fairly easily for the other case study WAMs described in Chapters 8-12. However, removal of the SB3 EFS in the 2023 monthly Brazos WAM without inadvertently changing some other functionality would be much more difficult.

### 2019 and 2024/2025 Daily WAMs

The 2023 monthly WAM described in the preceding paragraphs incorporates a complicated scheme for modeling SB3 EFS with numerous record types rather than the newer *ES*, *HC*, and *PF* records designed specifically for simulating SB3 EFS. Rather than removing the several thousand records representing the SB3 EFS in the 2023 monthly WAM, the earlier 2008/2017 version of the monthly WAM adopted again for conversion to a daily WAM. The 2008/2017 monthly WAM used to create the 2019 daily WAM described in the 2019 daily Brazos WAM report [7] was adopted again for creating a daily WAM.

The 2008/2017 monthly WAM was converted to a daily WAM as explained in this chapter. The resulting 2024/2025 daily WAM is comprised of four files with filenames BrazosD.DAT, BrazosD.DIS, BrazosD.DIF, and BrazosHYD.DSS.

### 2024/2025 Modified Monthly WAM

Daily instream flow targets for the SB3 EFS at 19 gage sites were computed in a daily *SIMD* simulation. The daily instream flow targets were aggregated to monthly targets within *SIMD*, which were recorded in the *SIMD* simulation results DSS output file. The monthly SB3 EFS instream flow targets were then copied from the *SIMD* output DSS file to the *SIM/SIMD* shared DSS input file as *TS* records labeled with the pathnames listed in Table 7.11. The earlier version of the monthly WAM employed as reported in the 2019 WAM report [7] was updated as described in this chapter. The resulting monthly WAM with a period-of-analysis of 1940-2023 is comprised of three files with filenames BrazosM.DAT, BrazosM.DIS, and BrazosHYD.DSS.

## Reservoir Storage Volumes

Reservoir storage capacities and contents provide insightful water availability metrics for assessing hydrologic conditions and water management capabilities. The first subsection of this last section of Chapter 7 explores daily and monthly simulated 1940-2023 reservoir storage contents generated with daily and monthly WAMs. The second sub-section explores differences between WRAP/WAM simulation results and actual observed reservoir storage volumes.

### Simulated Storage Volumes Generated with the Daily and Monthly WAMs

The following discussion explores 1940-2023 end-of-month and end-of-day reservoir storage contents computed in *SIM* and *SIMD* simulations with the following alternative versions of the full authorization WAM.

1. Simulation 1 uses the updated version of the latest TCEQ WAM comprised of files with filenames Brazos3.DAT, Brazos3.DIS, and BrazosHYD.DSS.
2. Simulation 2 uses the daily WAM comprised of *SIMD* files with filenames BrazosD.DAT, BrazosD.DIS, BrazosD. DIF, and BrazosHYD.DSS.
3. Simulation 3 uses the monthly WAM with SB3 EFS instream flow targets computed with the daily WAM. The *SIM* input files used in simulation 3 have filenames BrazosM.DAT, BrazosM.DIS, and BrazosHYD.DSS.

Summations of 1940-2023 simulated storage contents of the 15 largest existing reservoirs in the Brazos WAM from the alternative *SIM* and *SIMD* simulations defined above are compared in Figures 7.14, 7.15, and 7.16 and Table 7.14. End-of-day and end-of-month storage contents of the 15 reservoirs from the daily *SIMD* simulation 2 are compared in Figure 7.14. Monthly storage from *SIM* simulation 3 is compared with daily storage from simulation 2 in Figure 7.15. End-of-month storage sequences generated in *SIM* simulations 1 and 3 are plotted in Figure 7.16.

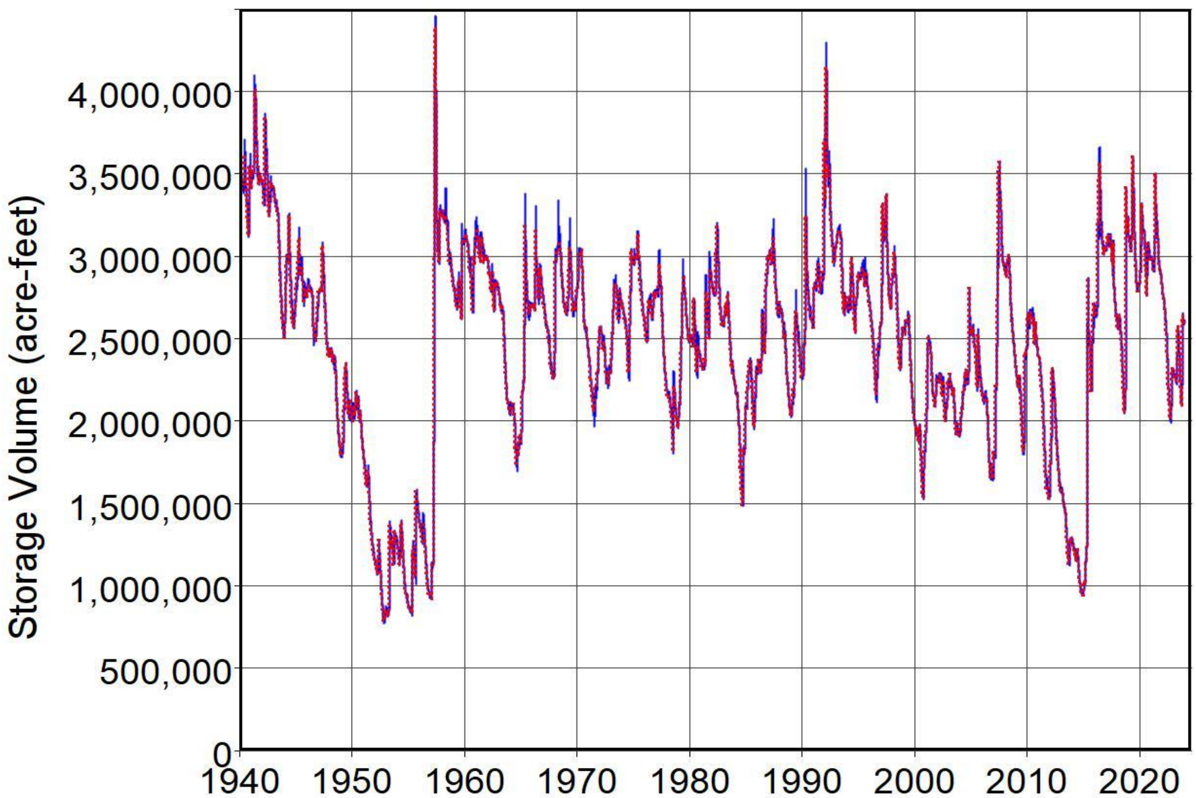


Figure 7.14 Daily (**blue solid**) and Monthly (**red dots**) Reservoir Storage from Simulation 2

The 16 largest reservoirs in the full authorization Brazos WAM are listed in Table 7.1. Summations of storage contents of the 15 largest existing reservoirs are plotted in Figures 7.14-7.16. The proposed Allen's Creek Reservoir in Table 7.1 is authorized but has not been constructed. The locations of the reservoirs are shown in the basin map of Figure 7.2. The 15 largest existing reservoirs contain 76.3 percent of the total authorized storage capacity in the Brazos WAM. Flood control storage capacity is not included in the monthly WAMs. The daily WAM includes the flood control storage capacity of the nine USACE reservoirs listed in Table 7.1.

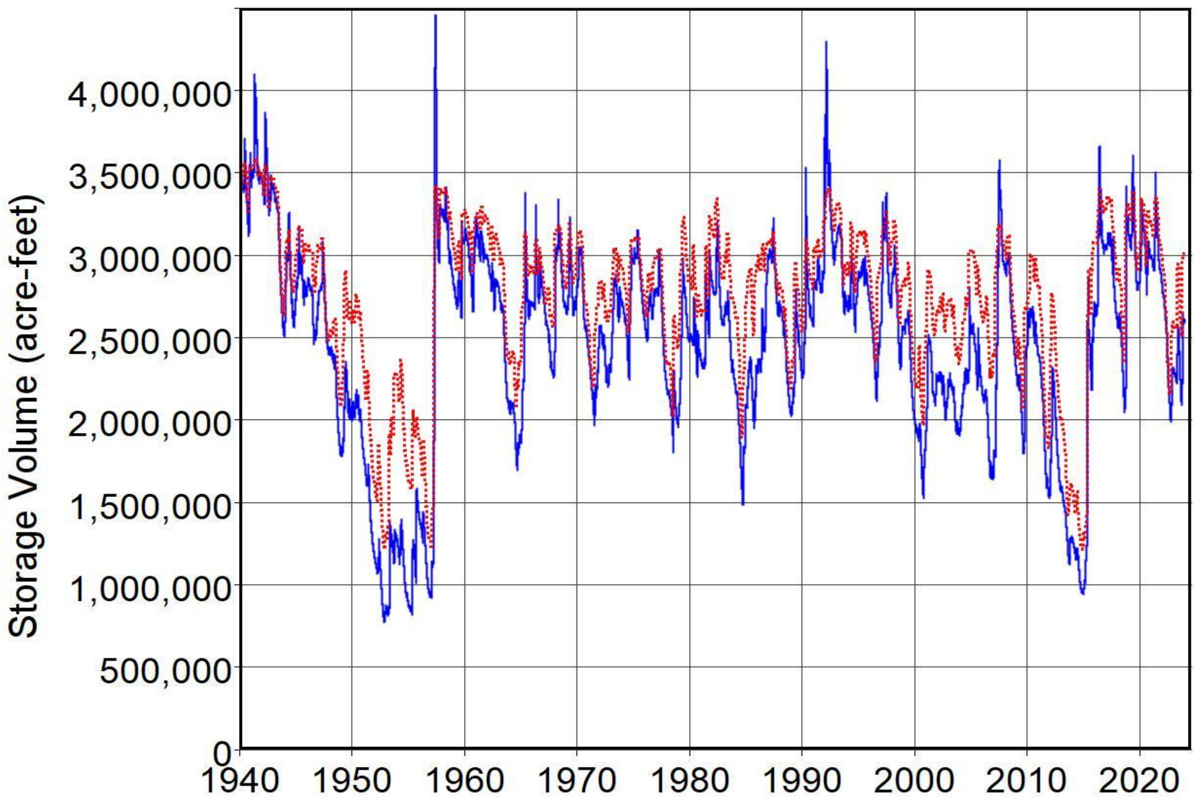


Figure 7.15 Simulation 2 Daily (**blue solid**) and Simulation 3 Monthly (**red dots**) Storage

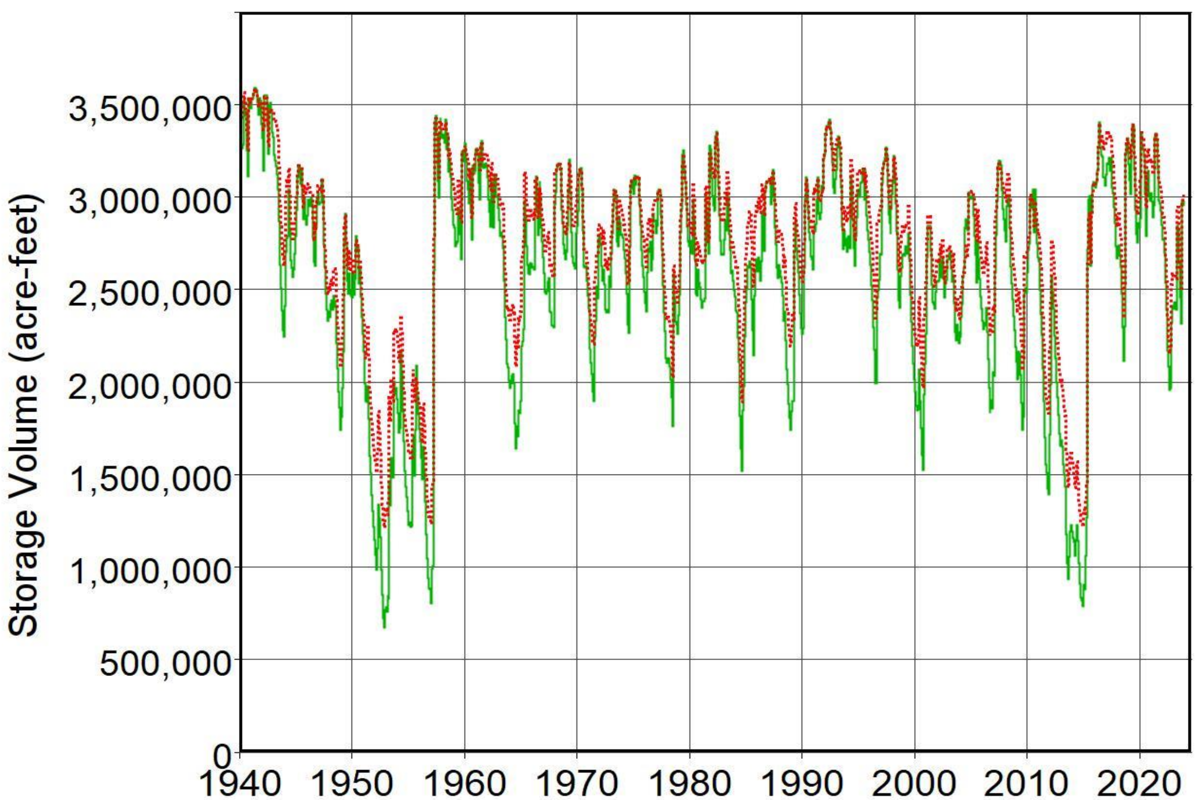


Figure 7.16 Simulation 1 (**green solid**) and Simulation 3 (**red dots**) Storage

Table 7.14
Statistics for Simulated 1940-2023 Storage Contents of 15 Largest Reservoirs

| | | Summation of Storage in 15 Reservoirs (acre-feet) | | | |
|---|---|---|---|---|---|
| Simulation | Time Step | Mean | Median | Minimum | Maximum |
| 1 | month | 2,581,060 | 2,695,059 | 674,584 | 3,587,677 |
| 2 | day | 2,469,000 | 2,577,543 | 772,555 | 4,459,370 |
| 2 | month | 2,472,005 | 2,577,457 | 790,969 | 4,390,008 |
| 3 | month | 2,751,159 | 2,853,254 | 1,212,551 | 3,583,907 |

The 1940-2023 sequences of the summations of end-of-day and end-of-month storage contents of the 15 reservoirs generated in the daily *SIMD* simulation (labeled simulation 2) are compared in Figure 7.14. The 1,008 end-of-month storage volumes are a subset of the 30,681 end-of-day storage volumes which includes only the end-of-day storage at the end of the last day of each month. The two plots are almost the same. Peak storage levels during floods that occur within the month may be higher than the end-of-month storage levels. Minimum daily flows during dry periods may also occur within the month but tend to be not as noticeable as the flood peaks.

The 1940-2023 sequence of summations of end-of-month storage contents of the 15 reservoirs generated in a simulation (labeled simulation 3) with the final modified monthly WAM with monthly SB3 EFS targets from the daily *SIMD* simulation (simulation 3) are plotted as red dotted lines in both Figures 7.15 and 7.16. Results from the modified monthly WAM and daily WAM are compared in Figure 7.15. Results from the modified monthly WAM and preceding version of the monthly WAM are compared in Figure 7.16.

Comparison of WRAP/WAM Simulated and Observed Reservoir Storage

Full authorization WAMs simulate a modeling scenario in which all water right holders appropriate the full amounts of water to which they are legally entitled subject to water availability. Actual water use typically varies with hydrologic conditions and may be significantly less than authorized use during periods of above normal rainfall. Return flows are generally not included in the full authorization scenario. Authorized storage capacities in the certificates of adjudication, water use permits, and WAMs include active and inactive conservation storage capacities typically unadjusted for sedimentation occurring in recent decades. Surcharge storage and designated flood control storage capacity is not included in the monthly WAMs (Figure 3.1).

Many hydrologic, hydraulic, and other types of computer models include parameters that are calibrated based on comparisons between computed model results and actual observed measured data. However, such calibration is not generally applicable for the WAMs due to: (1) the non-stationarity of observed reservoir storage with increased water development and use over time and (2) the modeling premises noted in the preceding paragraph and other aspects of model construction. However, the following storage comparisons of storage contents since 1994 contribute insight to understanding water availability and assessments thereof. Although many other relevant conditions have continued to change, construction and initial filling of storage capacity for most currently existing major reservoirs occurred before 1994.

The TWDB database of observed reservoir storage is discussed in the last sections of both Chapters 3 and 4. Figures A1 and A28 in Appendix A are plots of the summation of storage quantities in the 28 reservoirs in the Brazos River Basin included in the TWDB database. The reservoir projects were constructed at different times over several decades. Figure A1 indicates that completion of construction and initial impoundment of stream flow in the 28 largest reservoirs in the Brazos River Basin occurred between 1941 and 1998. Possum Kingdom, with initial impoundment in 1941, was the only reservoir of the 28 largest reservoirs that existed at the beginning of the 1950-1957 drought. Construction of all 28 reservoirs was completed before 1999.

Figure A28 in Appendix A is a plot of the summation of daily storage quantities in the 28 largest reservoirs in the Brazos River Basin during the period from January 1, 1994 through May 21, 2024. Figure A28 is replicated in Figure 7.13 along with the summation of simulated storage contents of 15 reservoirs generated in a daily *SIMD* simulation with the Brazos WAM. This daily *SIMD* simulation is labeled simulation 2 in Table 7.14 and Figures 7.14 and 7.15.

The 15 largest existing reservoirs in the daily Brazos WAM listed in Table 7.1 and reflected in the storage plots of Figures 7.14-7.17 are discussed in the preceding section. The 15 largest reservoirs have authorized conservation storage capacities totally 3,600,798 acre-feet which is 76.4% of the total authorized storage capacity of all storage facilities in the full authorization Brazos WAM.

The 28 reservoirs in the Brazos River Basin included in the TWDB reservoir storage database and Figures A1, A28, and 7.17 include the 15 largest existing reservoir listed in Table 7.1 and 13 other smaller reservoirs. The 15 largest reservoirs have current active storage capacities in the TWDB database that total 3,123,197 acre-feet which is 87.4% of the total active conservation capacity of 3,574,237 acre-feet in the 28 reservoirs. The active conservation storage capacity of the 28 reservoirs recorded in the TWDB database increased from 3,208,761 acre-feet in January 1994 to a maximum of 3,624,549 acre-feet in December 2002 and then decreased with updated sedimentation estimates to 3,574,237 in December 2017, with no further updates since 2017.

Summations of average daily quantities from the TWDB database for 28 reservoirs are plotted in Figure 7.17 with blue solid, red dashed, and black lines. The summations of simulated end-of-day reservoir storage contents from the daily WAM are plotted with a green solid line. The following reservoir storage volume quantities in acre-feet are plotted in Figure 7.17.

1. Summation of observed daily storage contents of 28 reservoirs in the Brazos River Basin (**solid blue line** in graphs of Figure 7.17 and Appendix A)
2. Portion of the observed storage contents that is contained in active conservation pools which excludes inactive storage for hydropower head and other purposes (**red dashed line**)
3. Active conservation storage capacity (black line in Figure 7.17 and Appendix A)
4. Summation of *SIMD* daily WAM simulated total storage contents of the 15 largest existing reservoirs (**solid green line**).

The total authorized conservation capacity of 3,600,798 acre-feet in the 15 reservoirs is larger than the active conservation capacity of 3,574,237 acre-feet of the 28 reservoirs. The active conservation contents and active conservation capacity quantities in the TWDB database does not include portions of conservation pools designated as inactive storage. Both the total reservoir storage volumes from the TWDB database and the *SIMD* simulated total storage volumes include water stored in the flood control pools of the eight USACE reservoirs listed in Table 7.1. The actual storage contents (blue solid line) represents total storage including surcharge storage (Table 3.1). The *SIMD* simulated storage does not include surcharge storage.

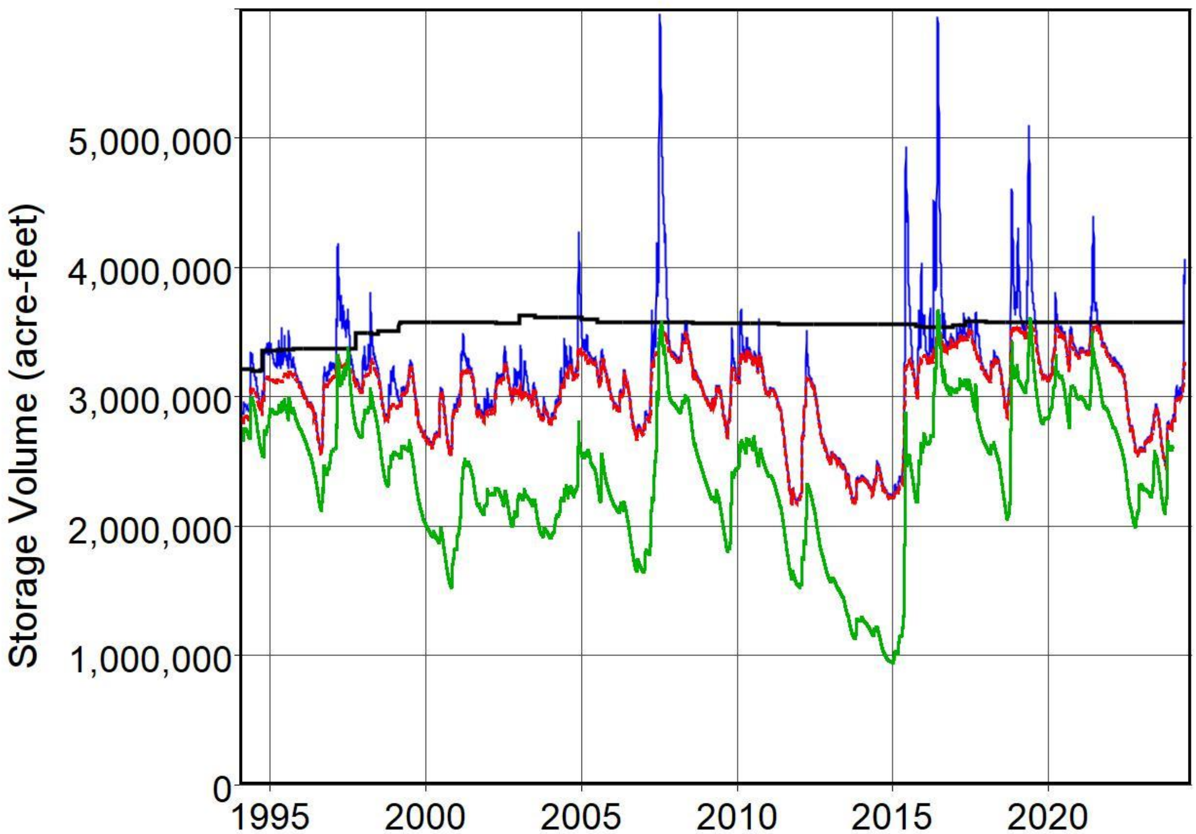


Figure 7.17 Comparison of Observed and WAM Storage Volume Quantities

## CHAPTER 8
## TRINITY DAILY AND MODIFIED MONTHLY WAMS

The original Trinity WAM is documented by a 2002 report [87]. A developmental daily version is documented by a 2019 report [8]. The organization and contents of Chapters 7 through 12 covering each of the six case study WAMs are outlined in Chapter 6. The six WAMs with developmental daily versions created in past TCEQ sponsored research studies at Texas A&M University are listed in Table 6.9 of Chapter 6. Chapter 8 is organized as the following tasks.

1. The original January 1940 through December 1996 hydrologic period-of-analysis of the Trinity WAM is extended through December 2023.
2. An updated daily WAM is developed by converting the version of the monthly Trinity WAM last updated by TCEQ effective 10/1/2021 to daily.
3. Daily flood control operations of eight USACE multipurpose reservoirs are added.
4. Environmental flow standards (EFS) have been established pursuant to the 1997 Senate Bill 3 (SB3) at four sites. SB3 EFS in the monthly WAM are replaced in the daily WAM using the new environmental standard *ES*, hydrologic condition *HC*, and pulse flow *PF* records.
5. Monthly instream flow targets for a modified monthly *SIM* input dataset are developed by summing daily targets computed in a daily *SIMD* simulation using the daily Trinity WAM.

### Trinity River Basin

The basin map of Figure 8.1 shows the location and size of the Trinity River Basin relative to the other major river basins of Texas. The Trinity Basin encompasses an area of approximately 18,000 square miles that transitions from rolling plains in the upper basin, through central Texas prairies and East Texas piney woods, into coastal prairies.


Figure 8.1 Major River Basins of Texas

Most of the population of the Trinity River Basin reside in the Dallas-Fort Worth (DFW) metropolitan area, which has a 2020 census population of 7.64 million people, which is 26.2 percent of the 2020 population of Texas. Dallas and Fort Worth have populations of 1,300,000 and 978,000. Seventy other cities in the DFW metropolitan area have populations exceeding 10,000 people. Mean annual rainfall increases from west to east from less than 30 inches at the northwestern extreme of the basin to over 50 inches at the southeastern-most portion of the basin.

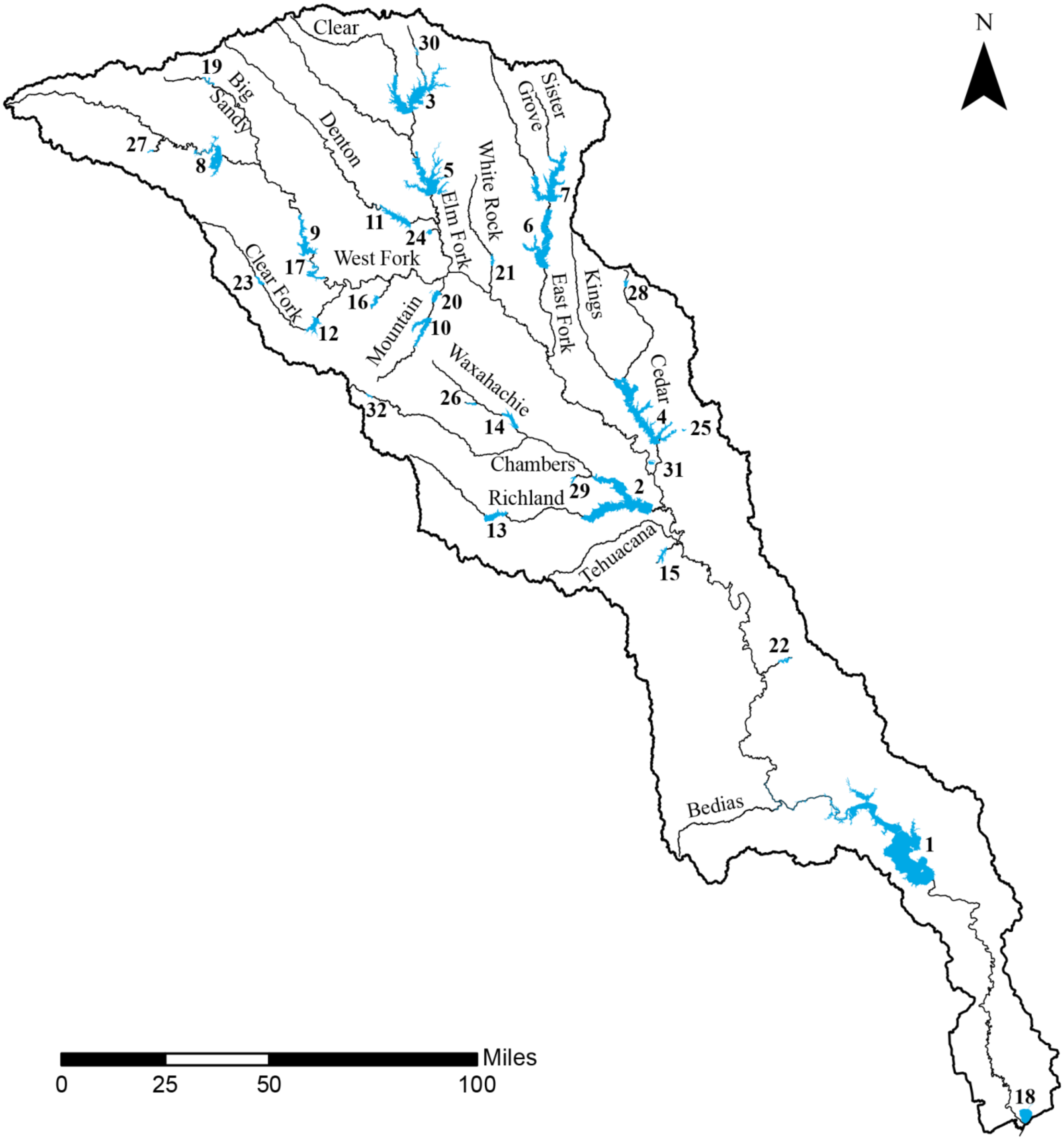


Figure 8.2 Major Tributaries and the 32 Largest Reservoirs

Major tributaries including the West Fork, Elm Fork, and East Fork of the Trinity River, Cedar Creek, Chambers Creek, and Richland Creek and other smaller tributaries are shown in Figure 8.2. The major reservoirs in Figure 8.2 and Table 8.1 include the 31 reservoirs with permitted storage capacities exceeding 5,000 acre-feet and a 32nd with almost 5,000 acre-feet. The numbers in the first column of Table 8.1 refer to the reservoir labels on the map of Figure 8.2. The reservoirs are listed in Table 8.1 in descending order of authorized storage capacity. The reservoirs with "multiple" in the third column have each been divided into multiple components in the WAM.

Table 8.1
Major Reservoirs in the Trinity River Basin

| Map ID | Reservoir | Reservoir Identifier | WAM CP ID | Initial Impound | WAM Storage Capacity Authorized (acre-feet) | WAM Storage Capacity Current (acre-feet) |
|---|---|---|---|---|---|---|
| 1 | Lake Livingston | LIVSTN | B4248B | 1969 | 1,750,000 | 1,739,743 |
| 2 | Richland-Chambers | RICHCH | B5035A | 1987 | 1,135,000 | 1,109,368 |
| 3 | Ray Roberts Lake | multiple | B2335A | 1987 | 799,600 | 796,474 |
| 4 | Cedar Creek Lake | CEDAR | B4976A | 1965 | 678,900 | 630,550 |
| 5 | Lewisville Lake | multiple | B2456A | 1954 | 618,400 | 613,957 |
| 6 | Lake Ray Hubbard | HUBBRD | B2462A | 1968 | 490,000 | 484,495 |
| 7 | Lavon Lake | multiple | B2410A | 1953 | 456,500 | 421,028 |
| 8 | Lake Bridgeport | BRIDGE | B3808A | 1932 | 387,000 | 370,468 |
| 9 | Eagle Mountain Lake | EGLMTN | B3809A | 1934 | 210,000 | 195,941 |
| 10 | Joe Pool Lake | JOPOOL | B3404A | 1986 | 176,900 | 172,678 |
| 11 | Grapevine Lake | multiple | B2362A | 1952 | 162,500 | 162,500 |
| 12 | Benbrook Lake | multiple | B5157P | 1952 | 88,250 | 85,568 |
| 13 | Navarro Mills Lake | NAVARO | B4992A | 1963 | 63,300 | 41,335 |
| 14 | Bardwell Lake | BARDWL | B5021A | 1965 | 54,900 | 44,199 |
| 15 | Fairfield Lake | FAIRFD | B5040A | 1969 | 50,600 | 43,884 |
| 16 | Lake Arlington | ARLING | B3391A | 1957 | 45,710 | 37,792 |
| 17 | Lake Worth | WORTH | B3340A | 1914 | 38,124 | 37,077 |
| 18 | Lake Anahuac | ANAHUA | B4279C | 1914 | 35,300 | 25,781 |
| 19 | Lake Amon G. Carter | CARTER | B3320B | 1956 | 28,589 | 20,050 |
| 20 | Mountain Creek Lake | MTNCRK | B3408A | 1937 | 22,840 | 22,840 |
| 21 | White Rock Lake | WHITER | B2461A | 1911 | 21,345 | 7,937 |
| 22 | Houston County Lake | HOUCTY | B5097A | 1966 | 19,500 | 17,561 |
| 23 | Lake Weatherford | WTHRFD | B3356A | 1957 | 19,470 | 18,630 |
| 24 | North Lake | NORTH | B2365A | 1957 | 17,100 | 16,985 |
| 25 | Forest Grove | FOREST | B4983A | 1976 | 16,348 | 16,348 |
| 26 | Lake Waxahachie | WAXAHC | B5018A | 1956 | 13,500 | 11,790 |
| 27 | Lost Creek Reservoir | LOSTCK | B3313B | 1990 | 11,961 | 11,882 |
| 28 | New Terrell City Lake | TERREL | B4972A | 1955 | 8,712 | 8,512 |
| 29 | Lake Halbert | HALBRT | B5030A | 1921 | 7,357 | 5,982 |
| 30 | Lake Kiowa | KIOWA | B2334A | 1970 | 7,000 | 6,513 |
| 31 | Trinidad Lake | TRINDD | B4970A | 1925 | 6,200 | 6,200 |
| 32 | Alvarado Park Lake | B5001 | B5001A | 1966 | 4,781 | 4,781 |

Actual reservoir storage capacities decrease over time due to sedimentation. The conservation storage capacities from the full authorization and current use WAM datasets are listed in the last two columns of Table 8.1 [8]. The authorized storage capacities are from the certificates of adjudication and water use permits. The version of the current use scenario dataset last updated in October 2012 includes adjustments of storage capacities for sedimentation. The full authorization dataset includes permitted but not yet constructed reservoirs; the current use dataset does not. The current use dataset includes term permits; the full authorization dataset does not.

The total authorized storage capacity of 7,445,687 acre-feet of the 32 largest reservoirs account for 97.94% of the total authorized capacity of 7,602,146 acre-feet in the 699 "model" reservoirs (about 677 actual reservoirs) in the full authorization WAM. The total storage capacity of 7,188,849 acre-feet of these 32 reservoirs account for 97.73% of the total storage capacity of 7,356,202 acre-feet in the 700 model reservoirs in the 2012 version of the current use WAM.

Flood control storage capacity is not included in the water right authorizations and monthly WAM. However, the following flood control pool storage capacities for the eight USACE reservoirs are added to the daily WAM: Lakes Lewisville (340,770 acre-feet), Lavon (291,700), Ray Roberts (265,000), Grapevine (244,400), Navarro Mills (148,900), Joe Pool (127,100), Bardwell (85,100), and Benbrook (76,550 acre-feet). Operation of the flood control pools of these eight USACE reservoirs is incorporated in the daily WAM but not included in the monthly WAM.

Lake Livingston owned and operated by the Trinity River Authority under contract with the City of Houston and located on the lower Trinity River is the largest reservoir in the basin. Water is transported by pipeline from Lake Livingston through a regional water supply system to Houston in the adjoining San Jacinto River Basin and water users in the lower Trinity Basin. The Trinity River Authority supplies its customers in the upper and middle Trinity Basin from Lakes Bardwell, Navarro Mills, and Joe Pool, owned by the USACE.

Richland-Chambers, Cedar Creek, Bridgeport, and Eagle Mountain, which are ranked among the nine largest water supply reservoirs in the basin, are owned and operated by Tarrant Regional Water District to supply water to Fort Worth and other cities. Lakes Bridgeport and Eagle Mountain are operated as a system, along with Lake Worth which is located immediately below Eagle Mountain Lake. Lake Worth is operated by the City of Fort Worth as a pass-through reservoir and is used for recreation and water supply. Tarrant Regional Water District also supplies water to the cities of Fort Worth, Weatherford, and Benbrook from Lake Benbrook which is owned by the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD).

The City of Dallas (Dallas Water Utilities) supplies water to about 30 cities in addition to Dallas from Lakes Ray Roberts, Lewisville, and Grapevine owned by the USACE and Lake Ray Hubbard and White Rock Lake owned by the City of Dallas. The North Texas Municipal Water District supplies its customers from Lavon Lake under a water supply storage contract with the USACE. The other major reservoirs are owned by various cities and electric power companies.

Lake Lewisville is currently the only reservoir in the Trinity River Basin with capabilities for hydropower energy generation. A low-head run-of-river hydropower unit located in the river below the dam operates using water supply releases through the dam. Recreation is popular at most of the lakes in the basin.

USACE Fort Worth District owns and operates eight of the 14 largest reservoirs (Ray Roberts, Lewisville, Lavon, Joe Pool, Grapevine, Benbrook, Navarro Mills, and Bardwell). The eight multiple-purpose reservoirs are operated by the USACE for flood control. Nonfederal sponsors hold contracts for the water supply storage capacity. The nonfederal water supply sponsors for the eight federal reservoirs include the Trinity River Authority, Tarrant Regional Water District, North Texas Municipal Water District, Dallas, Fort Worth, and other cities.

USACE Lakes Ray Roberts, Lewisville, Grapevine, and Benbrook are modeled in the WAM input DAT file using component reservoirs [8]. The conservation storage capacities of these federal reservoirs are divided between multiple nonfederal water supply sponsors. The cities of Denton and Dallas have contracted separately with the USACE for the water supply storage of both Lake Ray Roberts and Lake Lewisville. Lake Grapevine is shared by the Dallas County Park Cities (a group of several communities) and the cities of Grapevine and Dallas. The conservation pool of Lake Benbrook is also modeled as a multiple-owner reservoir in the monthly Trinity WAM. The reservoir counts in the *SIM/SIMD* message MSS file count each of the "component reservoirs" as a reservoir. For this and other reasons, the number of actual reservoirs is less than the counts of "model reservoirs" listed in the *SIM* message file and Tables 5.1 and 6.9 of this report.

A flood control pool in each of the four reservoirs noted above is combined with only one of the component reservoirs of that actual reservoir in the daily WAM [8]. The flood control pool in each reservoir must be set on top of a single component reservoir conservation pool [8]. With the selected component reservoir full and stream flows at flood levels, all component reservoirs are reasonably expected to be full or essentially full to capacity in the *SIMD* simulation. However, the *SIMD* requirement to connect a flood pool to only one conservation pool could be a significant modeling issue in some cases when component conservation pools do not all fill at the same time.

## Trinity Monthly WAM Hydrology

The Trinity WAM has 1,407 control points, 40 primary control points with *IN* record naturalized flows, 50 sets of *EV* evaporation-precipitation rates, and 699 authorized storage facilities (Tables 5.1 and 6.9). The 50 sequences of monthly reservoir net evaporation less adjusted precipitation rates were developed from the TWDB quadrangle evaporation and precipitation depth database. As indicated in Tables 5.1 and 6.9, the original Trinity WAM hydrologic period-of-analysis of 1940-1996 has been extended through 2023 as discussed in this section.

### Alternative Intermediate 1997-2023 Hydrology Extensions

Monthly *IN* record naturalized flows and *EV* record evaporation-precipitation for the daily and associated modified monthly WAMs discussed in this chapter are comprised of a combination of the original TCEQ WAM 1940-1996 hydrology and a 1997-2023 extension developed using approximate methods discussed in Chapter 5. The following two alternative Trinity WAM hydrology datasets of *IN* and *EV* records are reflected in Figures 8.3-8.8 and Tables 8.2-8.3.

- TCEQ WAM 1940-1996 hydrology and TWDB 1997-2023 extension adopted for later simulations in this chapter (blue solid line in Figures 8.3, 8.4, 8.5, 8.6, 8.7, and 8.8)
- TCEQ WAM 1940-1996 hydrology and WRAP program *HYD* 1997-2023 extension developed for comparison (red dotted line in Figures 8.3, 8.4, 8.5, 8.6, 8.7, and 8.8)

Differences and similarities between the two alternative 1940-2023 hydrology datasets are illustrated by Figures 8.3-8.8 and Tables 8.2-8.3. The set of 1940-2023 sequences of monthly *IN* record naturalized flows and *EV* record net evaporation-precipitation depths adopted for the simulations presented in later sections of this chapter consist of the 1940-1996 official TCEQ WAM hydrology combined with a TWDB 1997-2023 extension. Data from this alternative dataset, which is adopted for the simulations presented later in the chapter, are plotted as blue solid lines in Figures 8.3-8.8.

The other alternative hydrology dataset explored in this chapter is comprised of the TCEQ WAM 1940-1996 hydrology and WRAP program *HYD* 1997-2023 extended hydrology [80]. The *HYD* models for synthesizing monthly naturalized stream flows at each of the 40 primary control points were calibrated using 1940-1996 naturalized flow, precipitation, and evaporation [4, 8, 80]. The TWDB evaporation and precipitation database was used to extend the 50 sequences of *EV* records. Data from this alternative dataset are plotted as red dotted lines in Figures 8.3-8.8.

TWDB has extended monthly *IN* record naturalized flows and *EV* record net evaporation-precipitation depths for several WAMs as discussed on page 121 of Chapter 5. The TWDB intermediate naturalized flow extensions are based on linear regression with observed flows at the same site or other nearby sites [78]. TWDB staff employ the TWDB quadrangle evaporation and precipitation database discussed in Chapter 3 to extend *EV* records. The *IN* and *EV* record extensions are available online. TWDB had earlier posted a 1997-2021 *IN* and *EV* record extension online before later further updating the extension to cover 1997-2022. As of August 2024, the TWDB has extended the Trinity WAM *IN* record naturalized flows and *EV* record net evaporation-precipitation depths through December 2023.

The 1997-2018 hydrology extension incorporated in the 2019 version of the daily and modified monthly Trinity WAMs is described in the 2019 report [8]. As noted in Chapter 6 of the present report, the USACE Fort Worth District in 2013 provided unregulated daily flows from their reservoir system operations models for selected sites in the Brazos and Trinity River Basins for use at TAMU in developing daily WAMs. Naturalized monthly flows for the sub-period 1997-2009 in the 2019 daily Trinity WAM consist of monthly summations of USACE unregulated flows at 17 sites, *HYD* synthesized flows at 17 control points, and USGS gaged flows at 9 control points. Naturalized monthly flows for the sub-period 2010-2018 in the 2019 daily Trinity WAM consist of *HYD* synthesized flows at 32 control points and USGS gaged flows at 8 control points [8].

Monthly Naturalized Flows

Naturalized monthly flows from the two datasets at control point 8TRRO representing the USGS gage on the Trinity River at Romayor are plotted in Figures 8.3 and 8.4. This gage site is included on the maps of Figures 4.1 and 8.22. The 1940-1996 flows are the same in both datasets. The only differences are the flows during 1997-2023. Naturalized flows for the entire 1940-2023 simulation period are plotted in Figure 8.3. Figure 8.4 focuses on 1997-2023. Statistics for the two alternative sets of 1997-2023 monthly naturalized flows are compared in Table 8.2 along with statistics for observed flows. The Trinity River at the Romayor gage site has a watershed area of 8,340 square miles that encompasses portions of ten TWDB precipitation and evaporation quadrangles. Monthly precipitation and evaporation depths for each of the ten quadrangles are included in the *HYD* hydrologic model naturalized monthly flow extension.

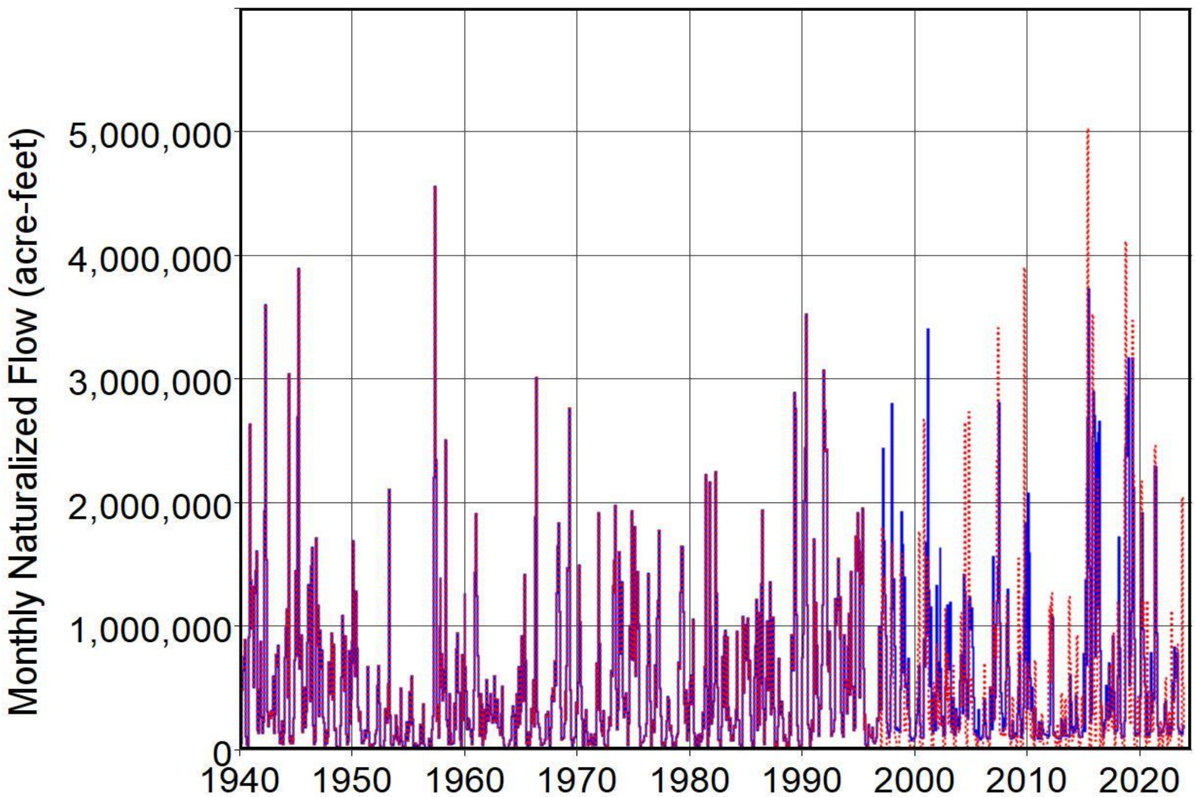


Figure 8.3 Naturalized Flows of Trinity River at Romayor for 1940-2023

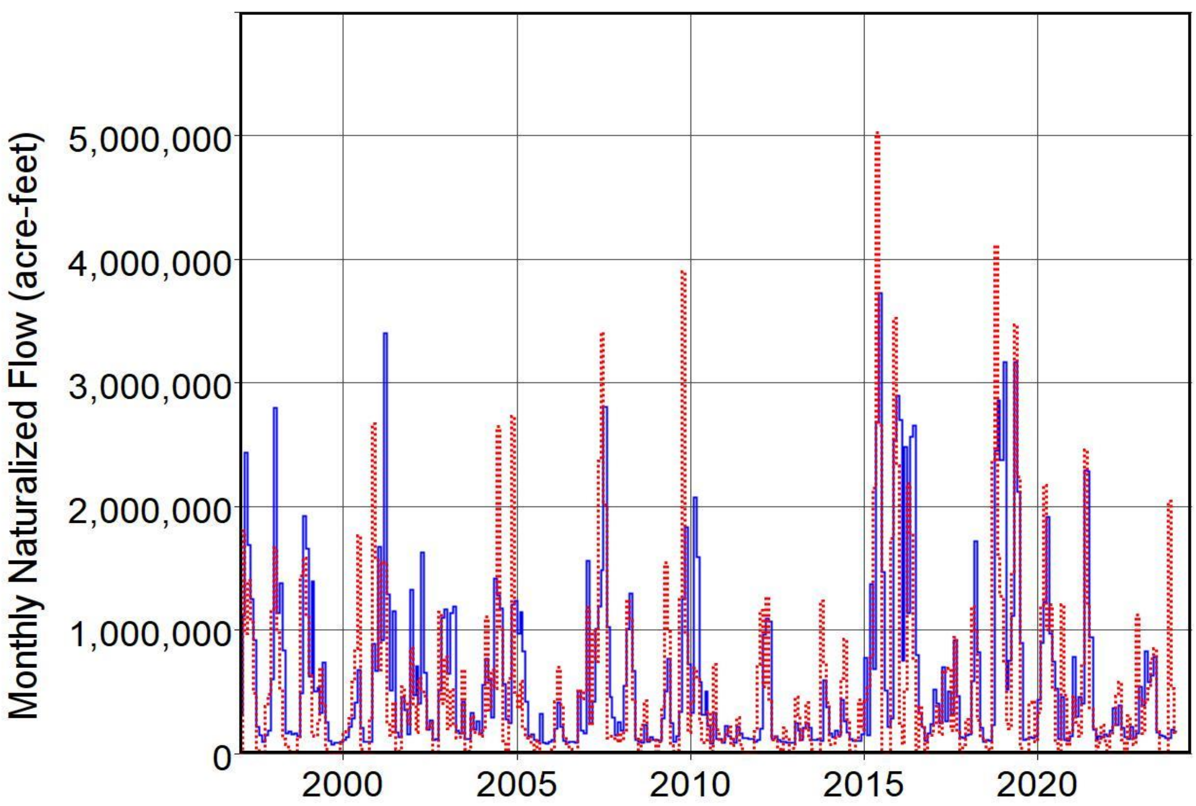


Figure 8.4 Naturalized Flows of Trinity River at Romayor for 1997-2023

Table 8.2
Statistics for 1997-2023 Monthly Flows at Romayor Gage on Trinity River

| Monthly Flow Statistic in acre-feet | USGS Observed Flows | TWDB Regressed Flows | *HYD* Hydrologic Model Flows |
|---|---|---|---|
| median (acre-feet) | 227,491 | 257,977 | 230,953 |
| mean (acre-feet) | 550,181 | 588,051 | 533,670 |
| minimum (acre-feet) | 47,699 | 73,799 | 0.0 |
| maximum (acre-feet) | 3,612,694 | 3,725,751 | 5,020,073 |
| standard deviation (ac-ft) | 683,684 | 700,167 | 746,074 |

Statistics for monthly observed flows during 1997-2023 at the Romayor gage near the outlet of the Trinity River and monthly 1997-2023 naturalized flows generated with the two different methods are compared in Table 8.2. The 1997-2023 median (50% exceedance frequency) of naturalized flows developed with the TWDB and HYD regression models are 113.4% and 101.5% of the observed flow median of 227,491 acre-feet/month. The naturalized flows developed with the TWDB regression model have a 20% larger median and 12% larger mean (average) than the flows generated with the WRAP *HYD* regression model. The 1997-2023 TWDB regressed flows range from 73,799 to 3,725,751 acre-feet. The 1997-2023 *HYD* synthesized flows range from zero to 5,020,073 acre-feet. Standard deviations are also compared in Table 8.2.

Comparative observations regarding variability characteristics of monthly naturalized flows at the Romayor gage site are generally illustrative of flows at the other primary control points in the Trinity WAM. The TWDB flows exhibit less variability than the flows generated with *HYD*. The differences in median, mean, and variability are consistent with what might be reasonably expected considering the two different modeling methodologies. The TWDB methodology is based on regressing naturalized flow with observed flow using standard least-squares linear regression. The *HYD* model is a nonlinear regression of naturalized flow with precipitation and evaporation with adjustments to improve replication of variability.

The 2019 Trinity daily WAM report [8] includes a 1997-2018 extension of naturalized flows developed by combining flows synthesized with the program *HYD* hydrologic model at selected control points that had stream flows significantly affected by water resources development and management and unadjusted observed flows at other control points reflecting no significant effects of water resources development and management. This 1997-2018 flow extension was completed in 2019 before TWDB 1997-2021 and later 1997-2023 hydrology extensions became available. The 2019 report [8] includes comparisons of 1940-2018 observed and naturalized flows.

Reservoir Net Evaporation-Precipitation Depths

The Trinity WAM includes fifty sets of *EV* record monthly net evaporation-precipitation depths. Nineteen of the *EV* record sequences are for individual quadrangles. The other thirty-one sets of net evaporation-precipitation depths are for individual large reservoirs with water surface areas extending into more than one quadrangle. The *EV* record data are weighted averages of evaporation-precipitation depths for the relevant quadrangles.

As discussed in Chapter 5, *SIM* and *SIMD* include an optional feature activated by EPADJ on the *JD* record or EWA(cp) on a *CP* record to account for the portion of the rain falling on a reservoir water surface that is also reflected in the naturalized flows. The adjustment computations are performed during the *SIM/SIMD* simulation based on computed reservoir surface areas and naturalized flows. However, this option is not employed in the Trinity WAM. Rather, the net evaporation-precipitation rates are adjusted during the process of creating the input data file as explained in the original WAM report [87]. A modified methodology for performing these adjustments is explained in a 2013 hydrology extension report [80]. The modified adjustment strategy consists of applying multiplier factors computed from the original 1940-1996 data to the precipitation depths in the process of extending the monthly net evaporation-precipitation depths past 1996 [8, 80]. An alternative strategy not adopted here is noted in the following paragraph.

The feature activated by EPADJ on the *JD* record or EWA(cp) on a *CP* record in the 2024 version of *SIM* and *SIMD* includes a new option added in 2024 activated by the new *JD* record parameter EPYEAR that allows the selected adjustment option to be applied to only a selected portion of the hydrologic period-of-analysis. This option could be adopted to treat the 1997-2023 extension differently than the original 1940-1996 *EV* record net evaporation-precipitation depths.

The *EV* records assigned to Livingston Reservoir (control point label B4248B) are plotted in Figure 8.5. Livingston Reservoir (Figures 4.1 and 8.1 maps) extends into portions of four quadrangles. Net evaporation less precipitation depths are area-weighted averages of evaporation and precipitation depths for the four TWDB quadrangles.

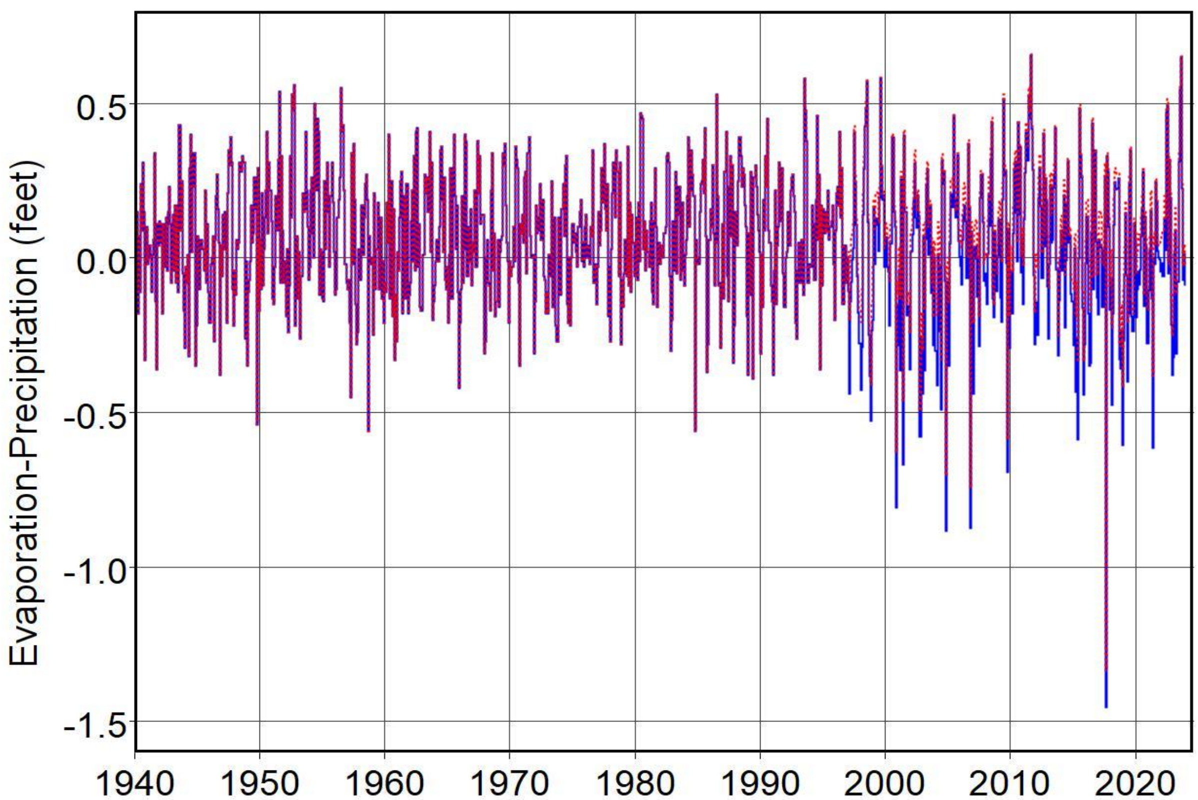

Figure 8.5 Net Evaporation-Precipitation Depths for Livingston Reservoir

Referring to the **blue solid line** in Figure 8.5 and TWDB column of the Table 8.3 below, the net evaporation less adjusted precipitation for Lake Livingston during 1940-2023 with the TWDB-extended *EV* records range from 7.87 inches in August 2011 to −17.87 inches in August 2017. Hurricane Harvey occurred in August 2017. The corresponding maximum and minimum monthly net evaporation minus precipitation depths in the alternative dataset developed with *HYD* as described in the 2019 report (**red dotted line** in Figure 8.5) are 7.91 inches and −16.03 inches as indicated in Table 8.3. Mean monthly depths are also compared below.

Table 8.3
Statistics for 1940-2023 Net Evaporation-Precipitation Depths at Lake Livingston

| | With TWDB Extension | With HYD Extension |
|---|---|---|
| maximum month | 0.656 foot (7.87 inches) | 0.660 foot (7.91 inches) |
| minimum month | -1.453 feet (-17.87 inches) | -1.336 feet (-16.03 inches) |
| 1940-1996 mean | 0.0652 foot (0.783 inch) | 0.0652 foot ((0.783 inch) |
| 1997-2023 mean | 0.01155 foot (0.139 inch) | 0.0859 foot (1.031 inch) |

Alternative Versions of the Trinity WAM

Water availability models (WAMs) are input datasets for the *SIM* and/or *SIMD* simulation models. As of July 2024, the latest version of the full authorization monthly Trinity WAM accessible at the TCEQ WAM website was a version last updated by TCEQ on 10/1/2023. This WAM consists of a set of four files with the following filenames.

trin3.DAT, trin3.DIS, trin3.FLO, trin3.EVA

The 1940-1996 hydrology referenced in the preceding subsections and the daily and modified monthly WAMs presented later in this chapter were created by modifying this version of the TCEQ full authorization WAM last updated by TCEQ on 10/1/2023.

*IN* and *EV* records are stored in FLO and EVA files in text format. The WRAP program *SIM* was executed with the dataset described in the preceding paragraph with the *OF* record DSS(5) option activated to convert the files with filenames trin3.FLO and trin3.EVA to a single DSS file of *IN* and *EV* records with filename TrinityHYD.DSS. Figures 8.3, 8.4, and 8.5 were created with *HEC-DSSVue* directly from this hydrology DSS file.

The two alternative sets of *IN* and *EV* records discussed in this chapter are stored in the same file with filename TrinityHYD.DSS. Any number of time series records can be stored, organized, and managed in the same DSS file. The WRAP programs *HYD*, *SIM*, and *SIMD* read only those DSS records that are applicable in a particular model execution, skipping the rest.

TWDB extensions of *IN* and *EV* records were downloaded from the TWDB website as text files and then copied directly into the FLO and EVA files. The 1940-2023 *IN* and *EV* records in the FLO and EVA files were then converted to binary DSS records in a DSS file using the *SIM* option described in the preceding paragraph. The 1997-2023 *IN* and *EV* record extensions performed with WRAP program *HYD* were combined with the 1940-1996 *IN* and *EV* records within *HYD*. The complete extended datasets were output by *HYD* as a DSS file.

The following filenames are assigned to the dataset with updated 1940-2023 hydrology.

Trinity3.DAT, Trinity3.DIS, TrinityHYD.DSS

The extension through 2023 and converting the hydrology to a DSS file are the only modifications reflected in this version of the full authorization monthly Trinity WAM. The reservoir storage plots presented later as Figure 8.6 were developed with *SIM* and *HEC-DSSVue* using this WAM dataset.

Two other versions of the Trinity WAM are developed later in this chapter. The daily full authorization *SIMD* input dataset consists of a set of files with the following filenames.

TrinityD.DAT, TrinityD.DIS, TrinityD.DIF, TrinityHYD.DSS

The daily WAM was executed with *SIMD* to generate monthly instream flow targets stored as *TS* records in the file TrinityHYD.DSS that model the four sets of SB3 EFS. A modified version of the monthly WAM replaces the old strategy for simulating SB3 EFS with this new methodology. This modified monthly WAM discussed later in this chapter is comprised of a set of *SIM* input files with the following filenames. The same hydrology DSS file with filename TrinityHYD.DSS can be read by *SIM* and *SIMD* in various versions of the WAM input dataset.

TrinityM.DAT, TrinityM.DIS, TrinityHYD.DSS

Simulated Total Reservoir Storage with Alternative Hydrology Input Datasets

As noted above, the *SIM* input dataset with updated 1940-2023 hydrology but no other changes is comprised of a set of files with the following filenames: Trinity3.DAT, Trinity3.DIS, TrinityHYD.DSS. The simulated end-of-month reservoir storage volumes in Figures 8.6 through 8.21 were generated with *SIM* using this WAM dataset.

The summations of the simulated end-of-month storage in the about 677 reservoirs in the full authorization Trinity WAM are plotted in Figure 8.6. The SIM message MSS file includes a count of 699 reservoirs (Table 5.1). However, these 699 "model" reservoirs are located at 677 control points, indicating that some of the actual reservoirs are comprised of multiple components reservoirs in the WAM that are included in the count of 699 reservoirs. The authorized storage capacities of the 699 model reservoirs at 677 control points total 7,602,146 acre-feet.

The storage contents of Livingston and Richland-Chambers Reservoirs are plotted in Figures 8.7 and 8.8. These two largest reservoirs in the Trinity River Basin have authorized storage capacities of 1,750,000 and 1,135,000 acre-feet. Their locations are shown in Figures 4.1 and 8.2.

The legend for Figures 8.3 through 8.8 is as follows.

- TCEQ WAM 1940-1996 hydrology and TWDB 1997-2023 extension adopted for later simulations (blue solid line in Figures 8.3, 8.4, 8.5, 8.6, 8.7, and 8.8)
- TCEQ WAM 1940-1996 hydrology and WRAP program *HYD* 1997-2023 extension developed for comparison (red dotted line in Figures 8.3, 8.4, 8.5, 8.6, 8.7, and 8.8)

Figures 8.3-8.8 illustrate the differences and similarities between the two alternative hydrology datasets. The first alternative hydrology dataset listed in the legend above is adopted for the simulations presented in the remaining sections of this chapter.

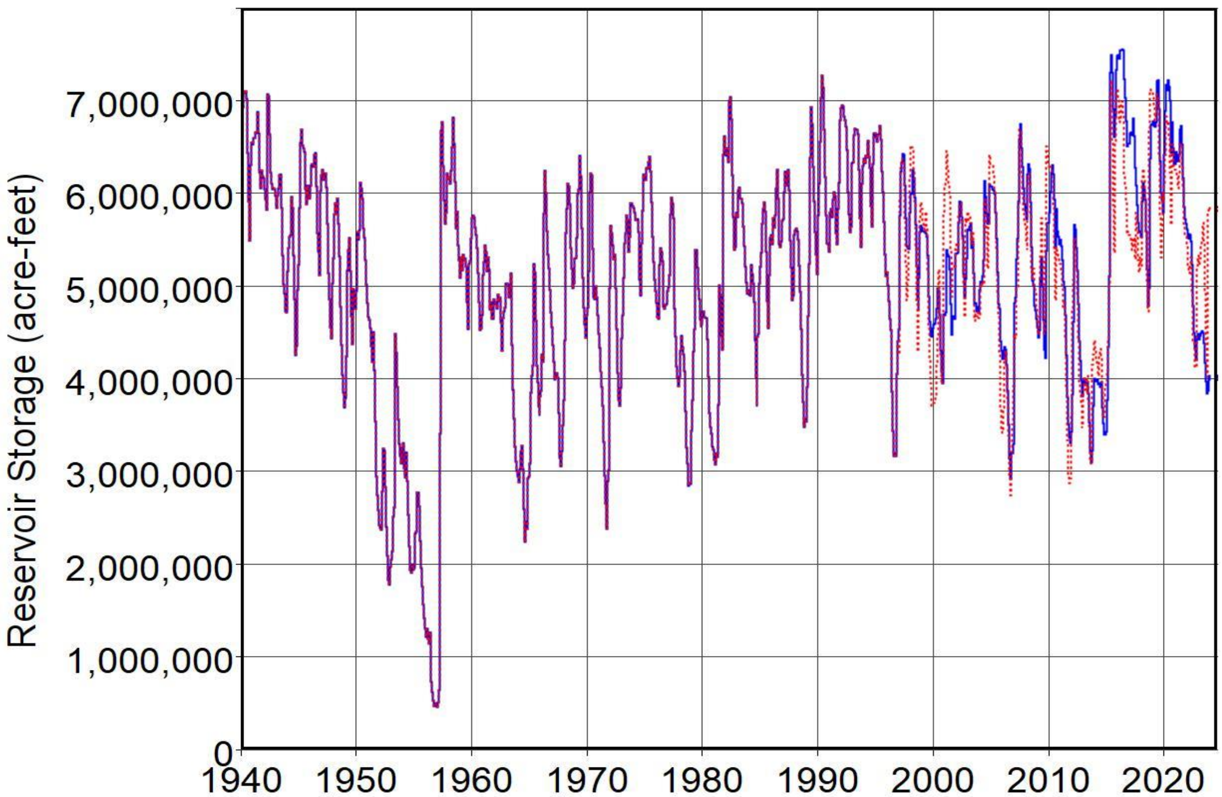


Figure 8.6 Summation of Simulated Storage in All Reservoirs in Trinity WAM

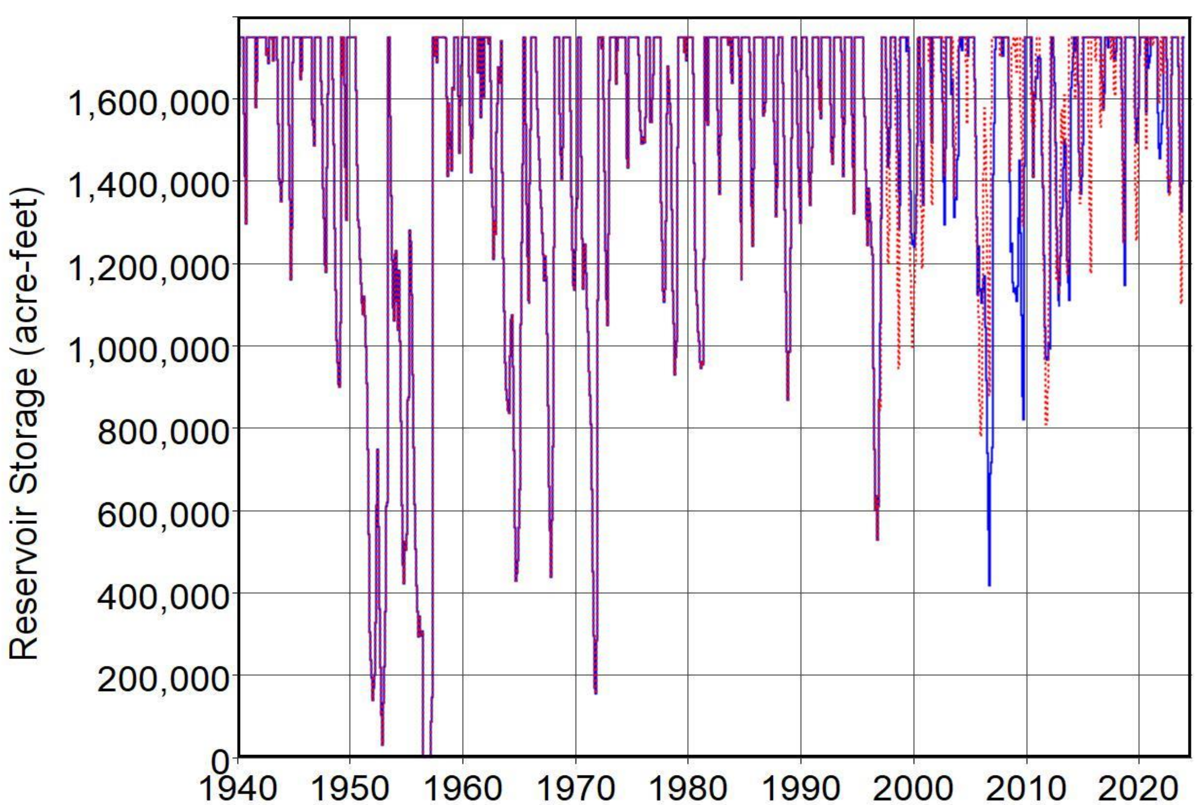


Figure 8.7 Simulated Storage in Lake Livingston (control point B4248B)

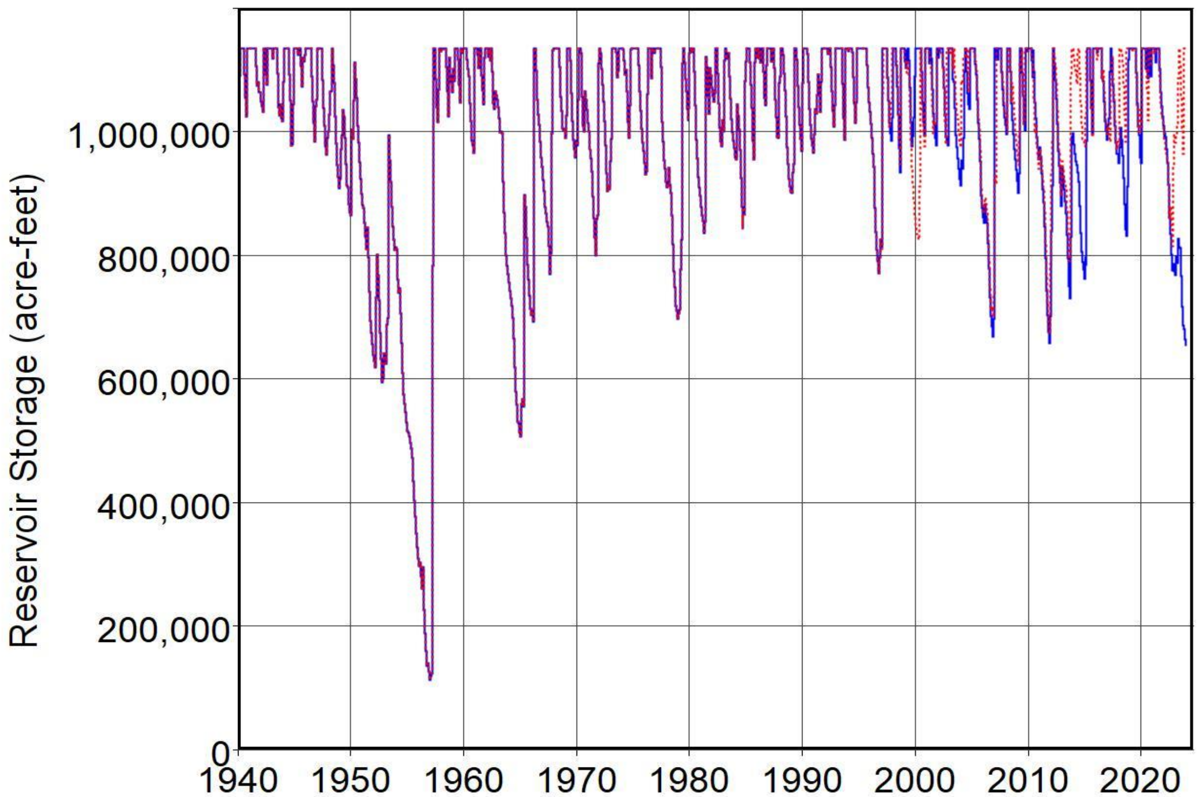


Figure 8.8 Simulated Storage in Richland-Chambers Reservoir (control point B5035A)

Simulated Storage in Reservoirs with Authorized Capacities Exceeding 50,000 acre-feet

The simulated end-of-month reservoir storage volumes in Figures 8.6-8.21 were generated with *SIM* using the previously described WAM comprised of the following files: Trinity3.DAT, Trinity3.DIS, and TrinityHYD.DSS. This WAM has updated 1940-2023 hydrology but no other changes. Figures 8.6-8.8 include plots from two alternative versions of the WAM with different 1997-2023 hydrology extensions. Figures 8.9-8.21 include only the simulation with the TWDB version of the 1997-2023 hydrology extension. Figure 8.6 is a plot of the summation of the storage contents of all reservoirs in the WAM. Figures 8.7 and 8.8 are for Lakes Livingston and Richland-Chambers which have the largest authorized storage capacities in the Trinity River Basin (Table 8.1). Simulated storage contents for the other thirteen reservoirs with authorized capacities exceeding 50,000 acre-feet are plotted in Figures 8.9-8.21. Locations of the reservoirs are shown in Figure 8.2 and their authorized storage capacities are tabulated in Table 8.1.

The storage plots show dramatic differences in the severity of drawdowns at these fifteen different largest reservoirs. In the *SIM* simulation, Lake Livingston, the largest reservoir in the river basin, empties only in 1957 at the end of the 1950-57 drought. Joe Pool empties and Lavon almost empties just before the March-April 1957 flood ends the 1950-1957 drought. Cedar Creek, Benbrook, Navarro Mills, and Bardwell Reservoirs experience their most severe simulated drawdowns during the 1950-1957 drought but are never completely empty. Lewisville, Ray Hubbard, Eagle Mountain, and Grapevine experience drawdowns that completely empty the reservoir multiple times throughout the 1940-2023 hydrologic period-of-analysis. Storage depletions in Lakes Ray Roberts, Bridgeport, and Fairfield are continuous and dramatically severe.

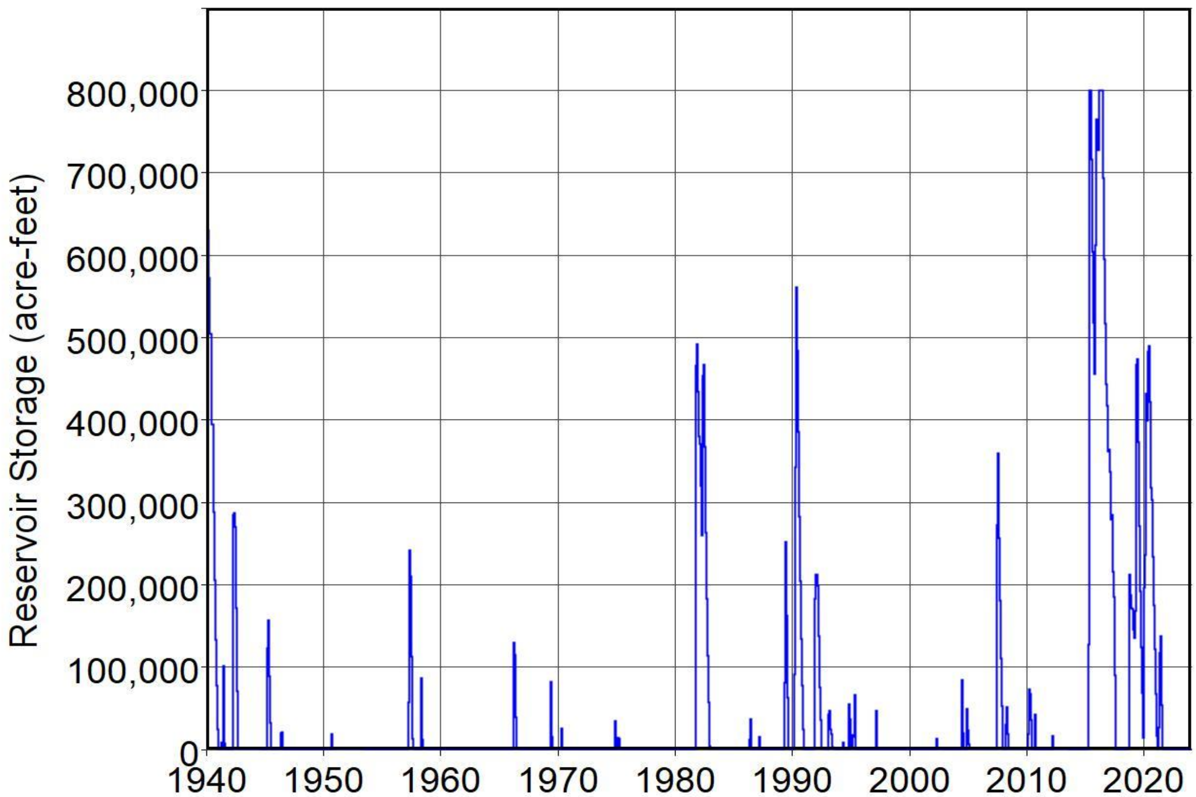


Figure 8.9 Simulated Storage in Ray Roberts Reservoir (control point B2335A)

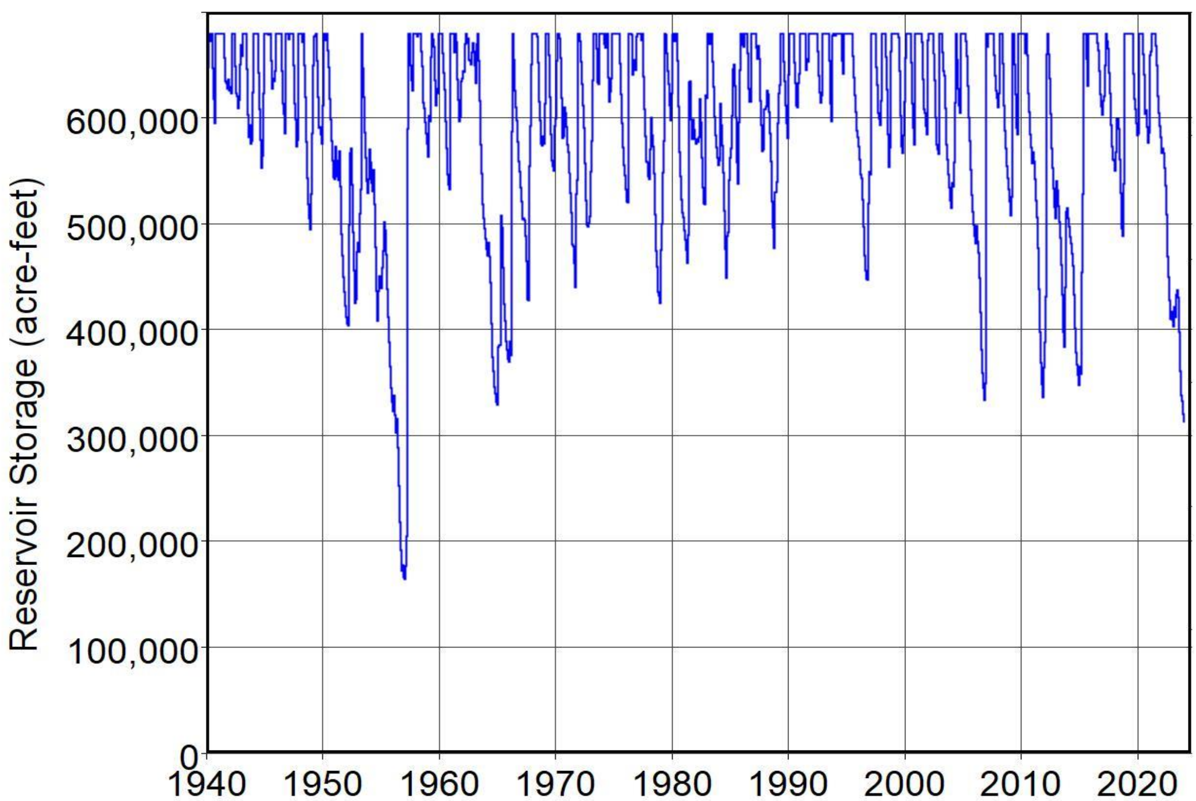


Figure 8.10 Simulated Storage in Cedar Creek Reservoir (control point B4976A)

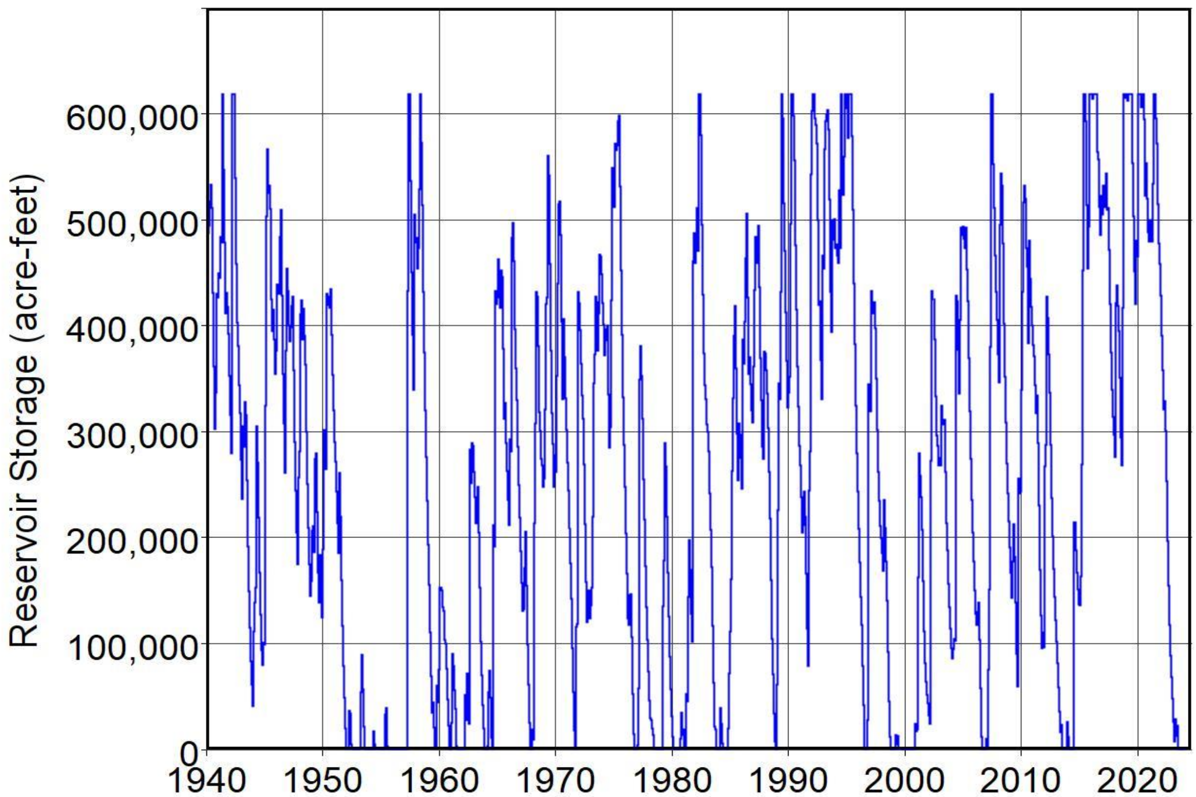

Figure 8.11 Simulated Storage in Lewisville Reservoir (control point B2456A)

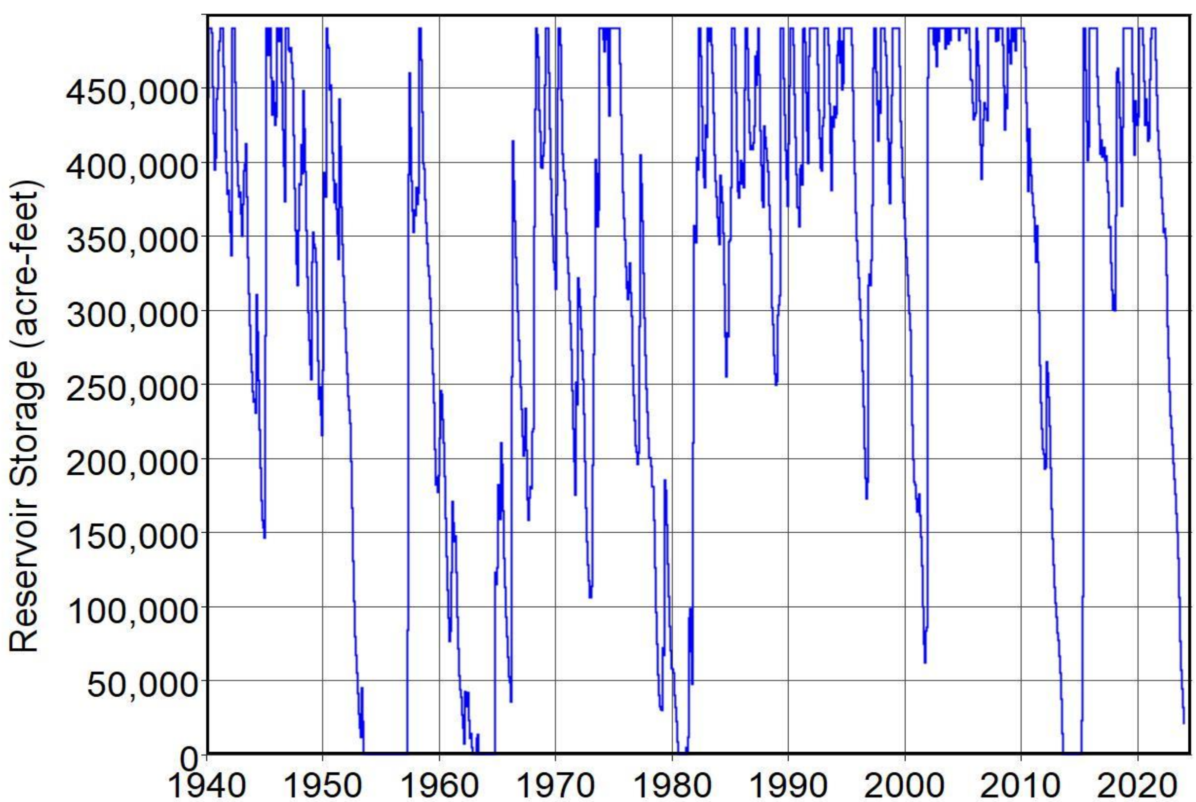

Figure 8.12 Simulated Storage in Ray Hubbard Reservoir (control point B2462A)

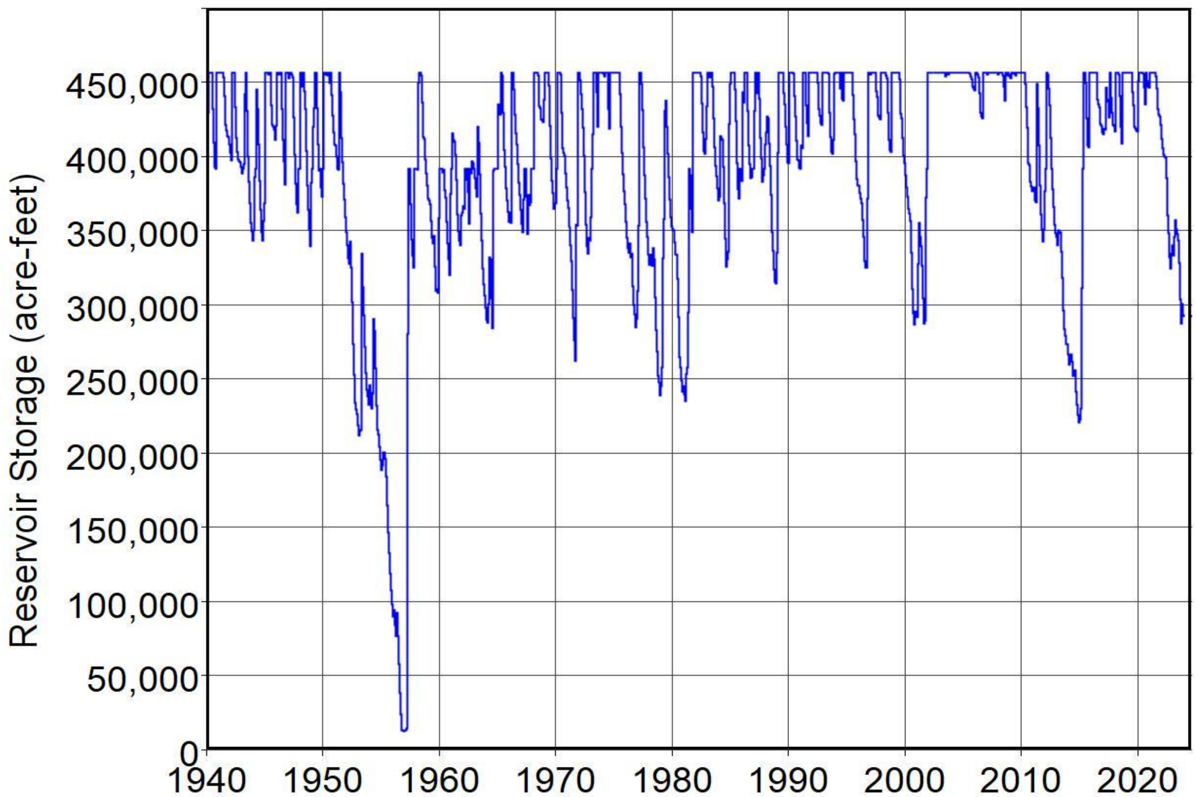

Figure 8.13 Simulated Storage in Lavon Reservoir (control point B2410A)

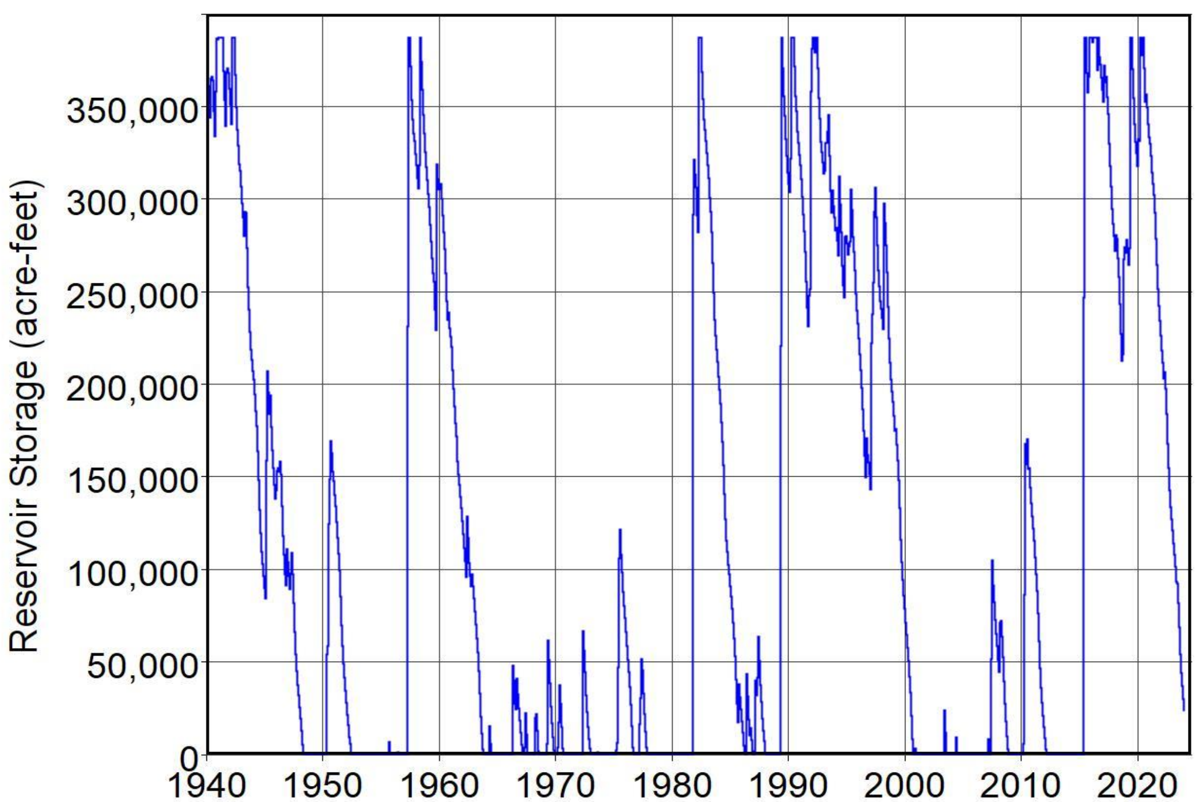

Figure 8.14 Simulated Storage in Lake Bridgeport (control point B3808A)

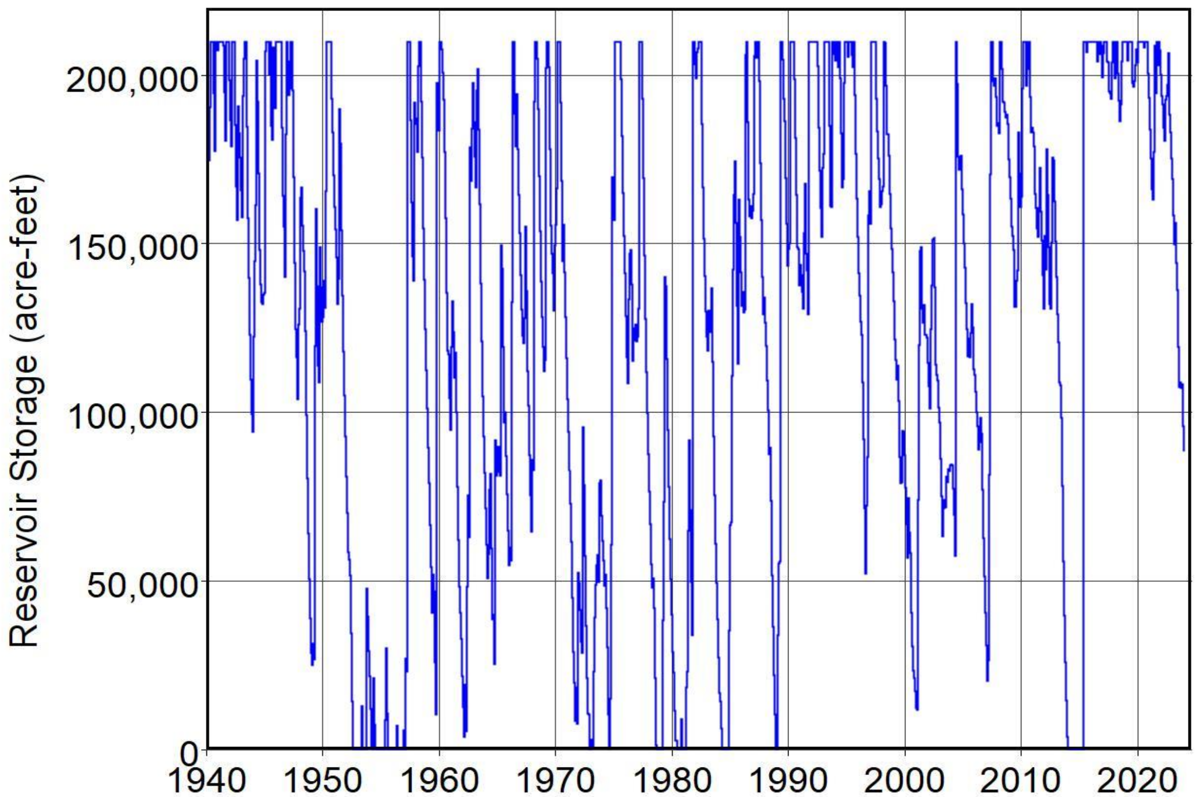

Figure 8.15 Simulated Storage in Eagle Mountain Lake (control point B3809A)

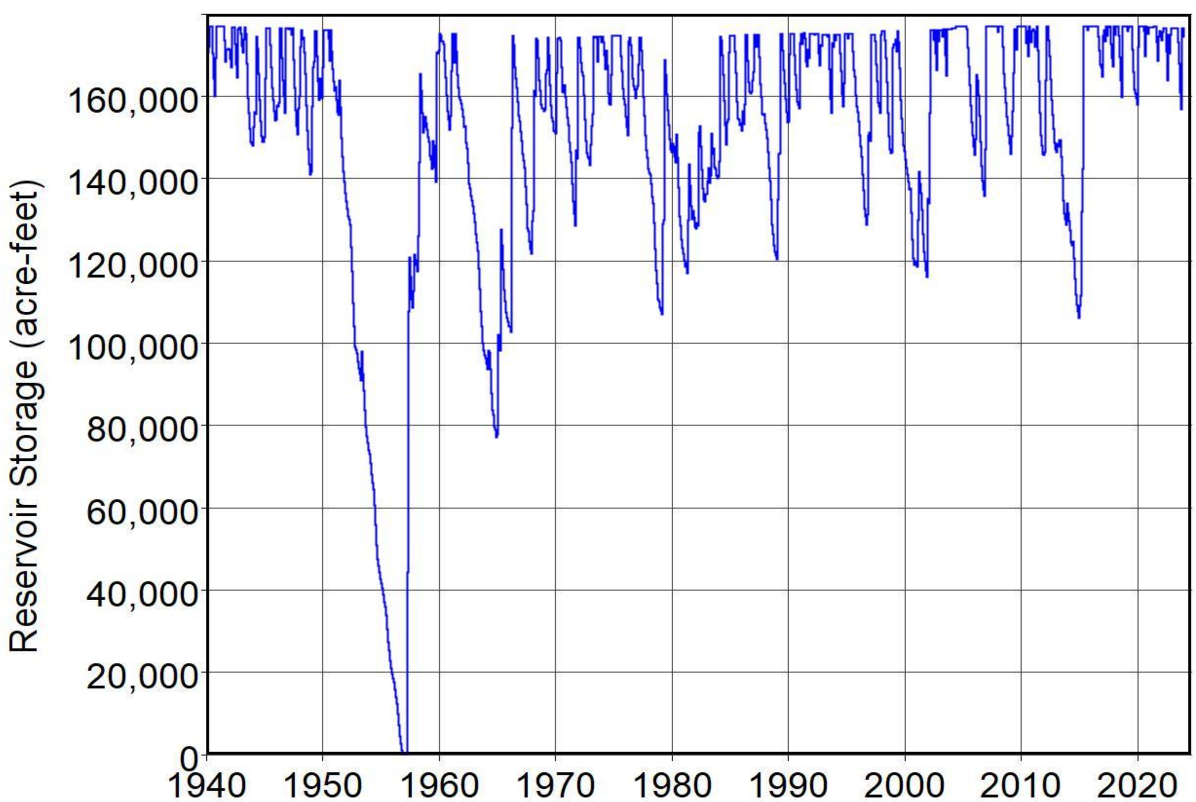

Figure 8.16 Simulated Storage in Joe Pool Reservoir (control point B3404A)

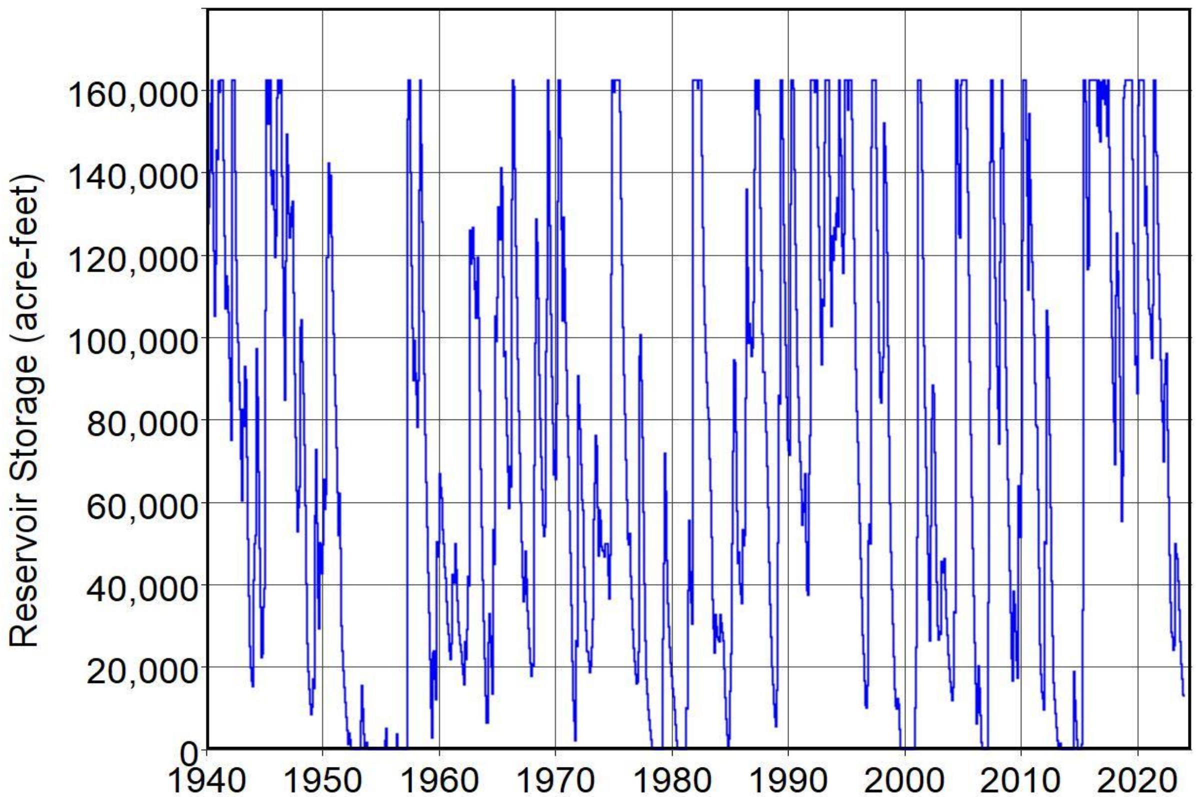


Figure 8.17 Simulated Storage in Grapevine Reservoir (control point B2362A)

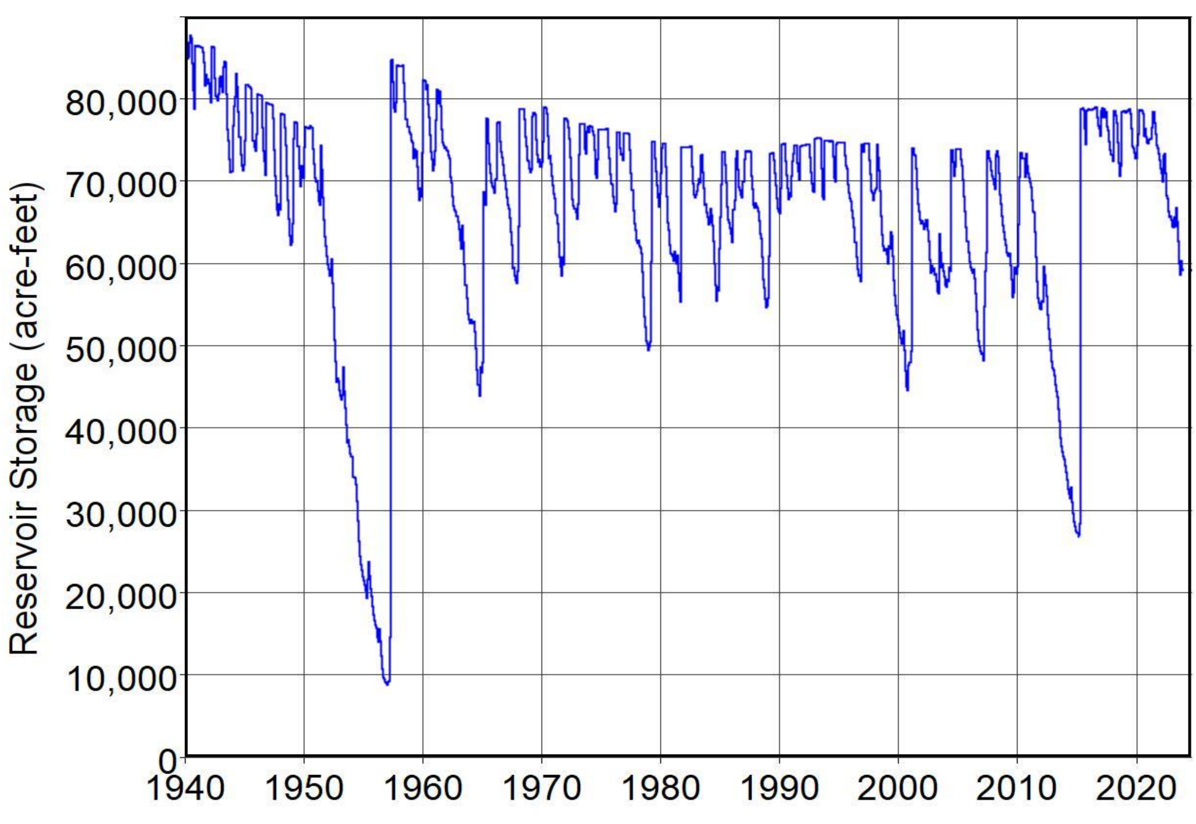


Figure 8.18 Simulated Storage in Benbrook Reservoir (control point B5157P)

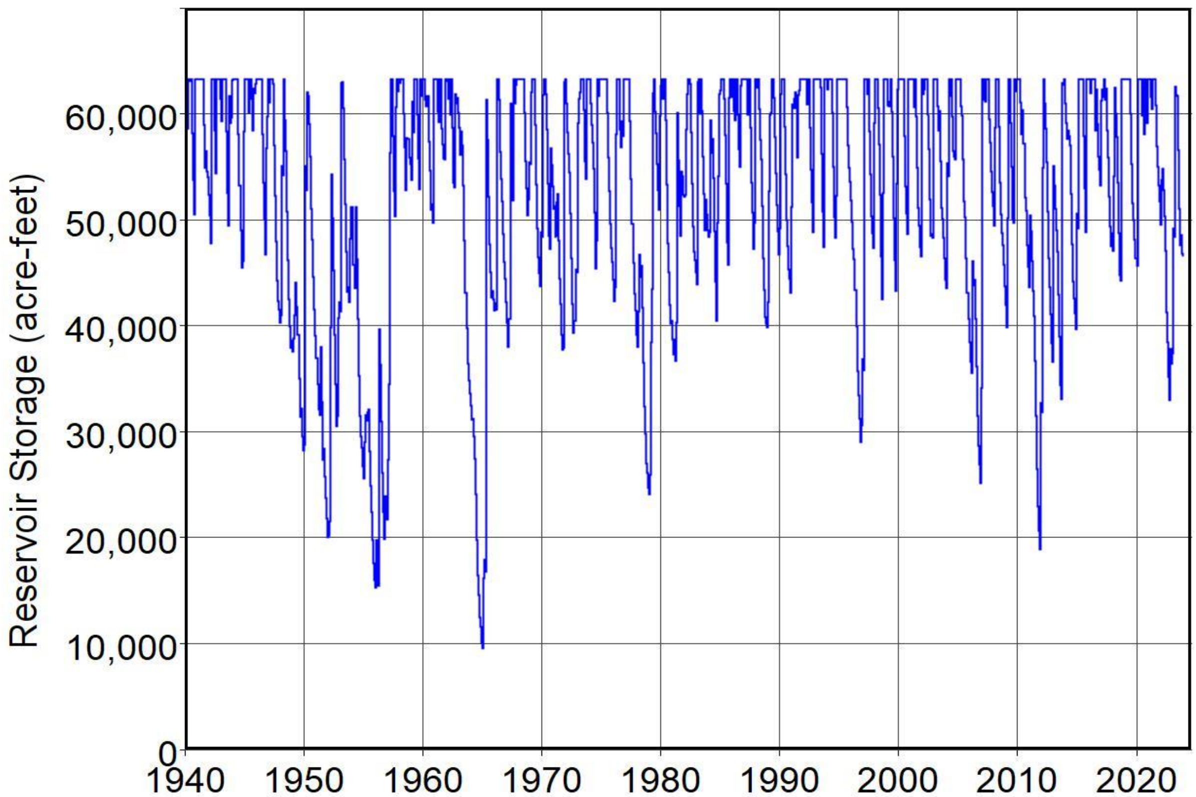


Figure 8.19 Simulated Storage in Navarro Mills Reservoir (control point B4992A)

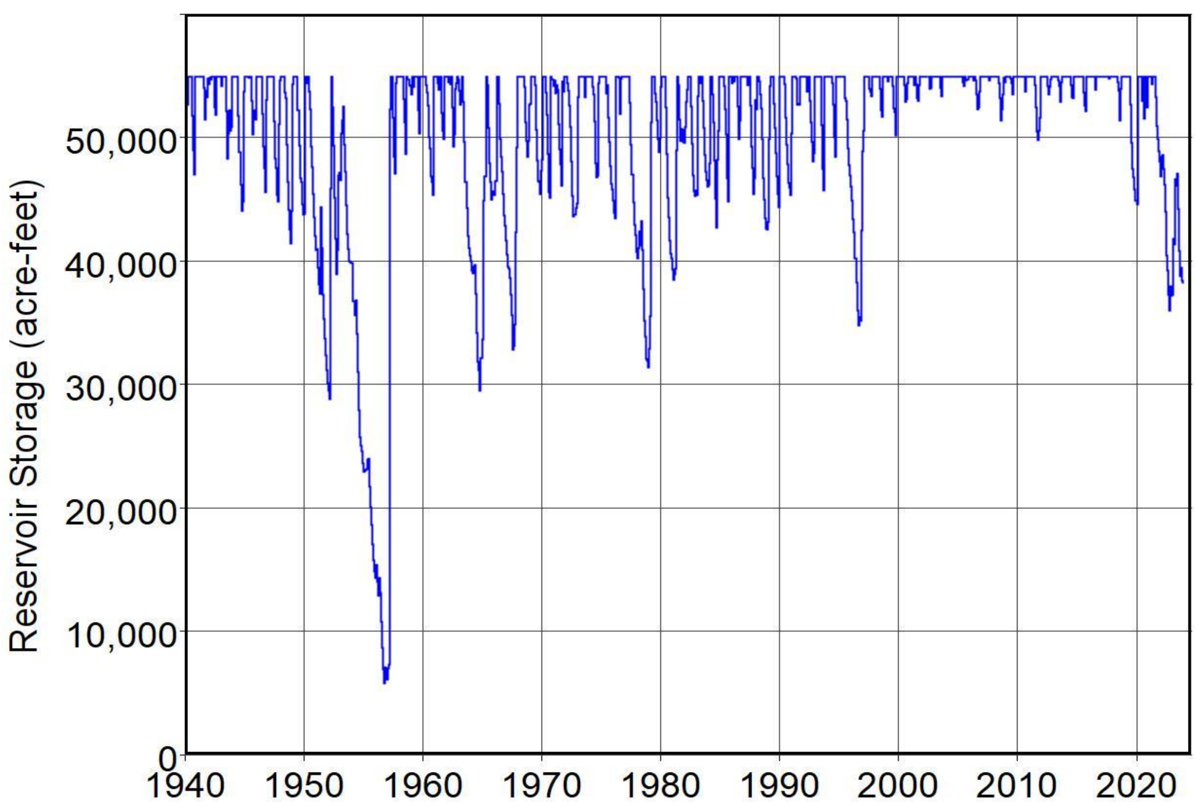


Figure 8.20 Simulated Storage in Bardwell Reservoir (control point B5021A)

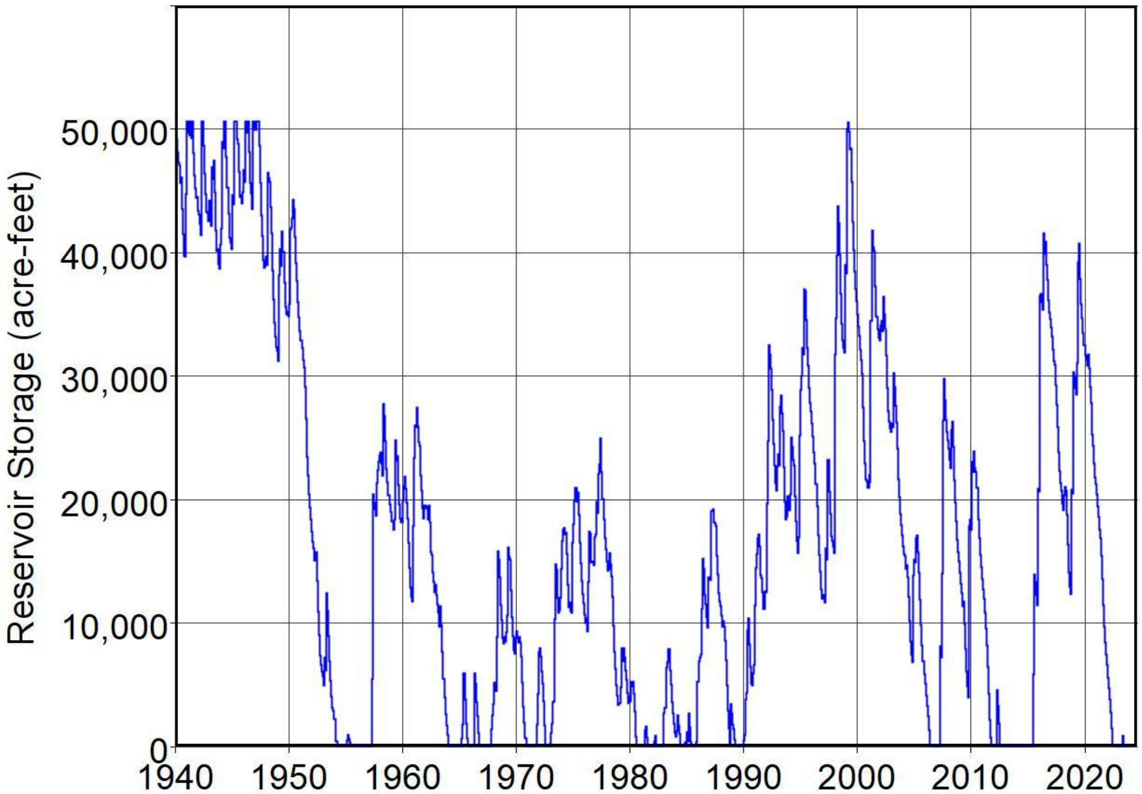


Figure 8.21 Simulated Storage in Fairfield Lake (control point B5040A)

Observed Reservoir Storage Contents

Summations of historical actually observed daily storage contents of 24 large reservoirs in the Trinity River Basin are plotted in Figures A2 and C30 of Appendixes A and C for 1934-2023 and 1994-2023, respectively. Essentially all of the storage capacity of the major reservoirs in the Trinity River Basin had been developed by 1994. Storage capacity increased dramatically between 1934 and about 1990. The similarities and differences in the general pattern and severity of drawdowns reflected in the summation of the full authorization WRAP/WAM simulated storage in all reservoirs in Figure 8.6 during 1994-2023 and the observed storage in 24 large reservoirs in Figures A2 and A30 are reasonably consistent with what would be expected.

Daily observed storage contents for Lakes Livingston and Ray Roberts from initial impoundment through 2023 are plotted as Figures A14 and A13 of Appendix A. Simulated 1940-2023 end-of-month storage contents for Lakes Livingston and Ray Roberts are plotted in Figures 8.7 and 8.9. The observed versus full authorization WRAP/WAM simulated storage in these two reservoirs differ greatly.

Flood control and surcharge storage are evident in the observed reservoir storage plots. Monthly WAMs do not include flood control and surcharge storage. Flood control storage in eight USACE reservoirs is added with the daily Trinity WAM discussed in the next section. The full authorization WAM simulated storage drawdowns are generally significantly greater than the observed drawdowns. Refilling of drawn down conservation pools in the WAM simulations significantly decrease encroachment into the flood control pools modeled in the daily WAM.

## Daily Trinity WAM

As discussed in earlier in this report, the primary reason for developing daily WRAP/WAM modeling capabilities is to improve capabilities for incorporating in the WAMs the environmental flow standards (EFS) established through the process created pursuant to the 1997 Senate Bill 3 (SB3). Daily *SIMD* capabilities also allow simulation of reservoir flood control operations. A daily WAM includes essentially all monthly *SIM* simulation input data plus additional "daily-only" *SIMD* input records. The components of a daily WAM are summarized in Chapter 2 of this report and explained in detail in the *Daily Manual* [5] and Chapter 4 of the *Users Manual* [2].

The 2019 daily Trinity WAM report [8] documents development of the full authorization and current use scenario daily and modified monthly versions of the WAM and associated research studies exploring various modeling issues. The 2019 daily full authorization WAM was developed from the TCEQ full authorization monthly WAM with DAT file last updated 10/7/2014, DIS file last updated 9/12/2014, FLO file last updated 4/2/2013, and EVA file last updated 2/25/2011. A 2019 daily current use Trinity WAM was developed from the TCEQ current use monthly WAM with DAT, DIS, FLO, and EVA files dated 10/26/2012, 8/21/2012, 10/25/2011, and 10/24/2007.

The updated 2024 version of the daily WAM discussed in this chapter was created from the official TCEQ monthly WAM last updated by TCEQ on 10/1/2023. Development of the daily WAM presented in this section includes the following major tasks described in Chapter 2.

1. Conversion to daily of the monthly full authorization WAM last updated by TCEQ on October 1, 2023.
2. Removal of the older types of input records approximating the SB3 EFS in the October 2023 monthly model along with addition of new environmental standard *ES*, hydrologic condition *HC*, pulse flow *PF*, and other related input records to model SB3 EFS that have been established at four USGS gage sites.
3. Addition of *FR*, *WS*, *FF*, and other records to model reservoir flood control operations in the daily model. Monthly WAMs have no flood control operations.

### Conversion of Monthly WAM to Daily

The 1940-1996 hydrology is from the TCEQ full authorization WAM last updated by TCEQ on 10/1/2023. The 1940-2016 period-of-analysis has been extended through 2023 in the present study by adopting the 1997-2023 *IN* and *EV* record extension developed by the TWDB. The daily and modified monthly WAMs presented later in this chapter were created by modifying the TCEQ full authorization WAM last updated by TCEQ on 10/1/2023.

*SIMD* input parameters controlling simulation options activated in the conversion of the monthly WAM to daily are described on pages 28-29 of Chapter 2 and page 155 of Chapter 7 of this report as well as in Chapter 4 of the *Users Manual* and in the 2019 daily Trinity WAM report [8]. The *SIMD* input records in the daily Trinity WAM DAT file containing parameters for controlling daily simulation options are replicated as Table 8.4. The *JT*, *JU*, and *OF* records control simulation input, output, and computation options. The *DF* records in the portion of the DAT file included in Table 8.4 reference *DF* record time daily pattern flow hydrographs read by *SIMD* from the hydrology input DSS file for use in disaggregating naturalized flows from monthly to daily.

Table 8.4
*SIMD* DAT File Input Records Controlling Simulation Options

```
**       1         2         3         4         5         6         7         8
**34567890123456789012345678901234567890123456789012345678901234567890123456789O
**      |       |       |       |       |       |       |       |       |       |
JD    84    1940       1       0       0       0       4       0       0      13
JO     6                                                                       3
JT
JU     1   1
OF     1   0   3   7   0   0                                  Trinity
OFV    1   2   3  15  27  28  29
CO         8WTGP   8TRDA   8TROA   8TRRO
DF         8WTJA   8BSBR   8WTBO   8CTAL   8CTFW   8WTFW   8WTGP   8MCGP   8ELSA
DF         8IDPP   8CLSA   8DNJU   8TRDA   8WRDA   8ETMK
DF         8SGPR   8ETCR   8TRRS   8TRTR   8CEKE   8KGKA   8CEMA   8RIRI   8CHCO
DF         8TEST   8TROA   8TRMI   8BEMA   8TRRI   8TRRO
DF        B3808A  B3809A  B3349A  B5157P  B3404A  B5136A  B2335A  B2456A    B304
DF        B2362A  B2457C  B2462A  B2410A  B4976A  B4992A
DF        B5021A  B5035A  B4248A  B4248B
```

Disaggregation of Monthly Naturalized Stream Flows to Daily

Disaggregation of monthly naturalized flow volumes to daily volumes is the basic key component of converting from a monthly WAM to a daily WAM. Other variables are also disaggregated from monthly to daily in a *SIMD* simulation by default uniformly.

With the standard default DFMETH option 4 activated, *SIMD* disaggregates monthly naturalized flow volumes to daily volumes in proportion to daily pattern hydrographs while preserving the monthly volumes. Daily flows on *DF* records are initially compiled in units of cfs for the daily WAMs. A *SIMD* simulation is performed with *DF* records for flows in cfs stored in the *SIMD* hydrology input DSS file. *SIMD* simulation results including daily naturalized flows in acre-feet are recorded by *SIMD* in its simulation results DSS output file. The daily naturalized flows in acre-feet in the *SIMD* simulation results DSS file are converted to *DF* records which are copied within *HEC-DSSVue* to the *SIMD* hydrology input DSS file.

Disaggregation of monthly naturalized flow volumes in acre-feet/month to daily volumes in acre-feet/day at the 1,407 control points in the Trinity WAM is controlled by parameters on the *JO* and *JU* records found in the DAT file and a *DC* record in the DIF file along with the 49 daily flow pattern hydrographs stored on *DF* records in the DSS file. Parameter REPEAT option 2 on the following *DC* record in the DIF file repeats the DSS file *DF* record flow pattern hydrographs at 49 control points for disaggregating monthly naturalized flows at about 1,400 control points.

```
DC  8TRGB    2    4    8TRRO
```

Flows at computational accounting control points not encompassed within the actual stream system are disaggregated uniformly by the default DFMETH option 1 in *JU* record field 2.

Monthly naturalized flows at about 1,400 control points are disaggregated to daily using 1940-2023 daily flows at 49 control points stored as *DF* records in the hydrology input DSS file. The *SIMD* automated procedure for repeating daily flows at multiple control points is described in Chapter 2 of the *Daily Manual* [4]. The *SIMD* pattern hydrograph selection 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.

Development of *DF* record daily flows for 1940-2017 at 49 control points is described in detail in Chapter 6 of the 2019 daily Trinity WAM report [8]. The 1940-2017 daily flows in the 2019 daily WAM are adopted without change in the 2024 update. The daily flows are extended from January 2018 through December 2023 employing the methods outlined in Tables 6.4, 6.5, and 6.6 of the 2019 report [8]. Daily 2018-2023 daily observed flows at 36 gage sites listed in Table 6.4 [8] represented by WAM control points were downloaded from the USGS National Water Information System (NWIS) website. Daily 2018-2023 flows at the other 22 control points were synthesized as outlined in Tables 6.5 and 6.6 of the 2019 report [8].

Routing and Forecasting

*SIMD* includes optional features for lag and attenuation of stream flow changes and forecasting in support of assessing stream flow availability and availability of stream channel flood flow capacities. The Trinity WAM includes calibrated routing parameters for 39 river reaches stored in the *SIMD* input DIF file as discussed in detail in the 2019 daily WAM Report [8]. Forecast periods are set by two input parameters on the *JU* record in the DAT file [5]. With the calibrated routing parameters already compiled, routing and/or forecasting can be easily activated or deactivated in alternative executions of *SIMD*.

As discussed in Chapter 2, daily WAMs are valid simulation models without activation of the routing and forecasting features of *SIMD*. Forecasting is problematic and is relevant only if routing is employed. The accuracy of a simulation perhaps may be improved by activating routing with or without forecasting for appropriate stream reaches such as very long reaches [5, 8].

## Simulation of Reservoir Flood Control Operations

Operation of reservoirs for flood control is explained in a recently published book [19]. Simulation of reservoir operations during floods in *SIMD* is explained in Chapter 5 of the *Daily Manual* [5]. Flood control operations of eight USACE reservoirs listed in Table 8.5 are incorporated in the Trinity WAM as described in Chapter 4 of the 2019 daily Trinity WAM report [8]. The *FR*, *WS*, and *FF* records used for modeling reservoir flood control operations are replicated on the next page as Table 8.6. Metrics specified in the flood control operating rules are found at a USACE website: http://www.swf-wc.usace.army.mil/pertdata/TRINITY.htm

Flood control operations are not activated in the simulation as long as the storage contents is at or below the conservation pool storage capacity. If storage exceeds the top of conservation pool (bottom of flood control pool), the flood control pool is emptied as quickly as possible subject to the constraints that (1) reservoir release rates cannot exceed the outlet release rates specified on the *FR* records and (2) releases cannot be allowed that would contribute to flows at downstream control points exceeding the maximum allowable flow rates specified on *FF* records. As discussed further later in this chapter on pages 223-226, FCDEP option 2 in *FR* record column 32 removes the flood flow release constraint of considering flows at downstream gage sites. FCDEP option 2 deactivates the *FF* record limits for specified reservoirs. Parameter FFNUM on the *FR* record limits the number of downstream gages considered in limiting releases for specified reservoirs.

Table 8.5
USACE FWD Flood Control Reservoirs

| Reservoir | Stream Location of Dam | Drainage Area (sq miles) | Pool Elevation (feet) Conser vation | Pool Elevation (feet) Flood Control | Storage Capacity (acre-feet) Top of Conservation | Storage Capacity (acre-feet) Top of Flood Control | Storage Capacity (acre-feet) Flood Control |
|---|---|---|---|---|---|---|---|
| Benbrook | Clear Fork | 429 | 694.0 | 710.0 | 88,250 | 164,800 | 76,550 |
| Joe Pool | Mountain Creek | 232 | 522.0 | 536.0 | 176,900 | 304,000 | 127,100 |
| Ray Roberts | Elm Fork | 692 | 632.5 | 640.0 | 799,600 | 1,064,600 | 265,000 |
| Lewisville | Elm Fork | 1,660 | 522.0 | 532.0 | 618,400 | 959,170 | 340,770 |
| Grapevine | Denton Creek | 695 | 535.0 | 560.0 | 162,500 | 406,900 | 244,400 |
| Lavon | East Fork | 770 | 492.0 | 503.5 | 456,500 | 748,100 | 291,600 |
| Navarro Mills | Richland Creek | 320 | 424.5 | 443.0 | 63,300 | 212,200 | 148,900 |
| Bardwell | Waxahachie Ck | 178 | 421.0 | 439.0 | 54,900 | 140,000 | 85,100 |

Table 8.6
SIMD DAT File Records Modeling Flood Control Operations of Eight USACE Reservoirs

```
**       1         2         3         4         5         6         7         8         9        10
**3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234
**     !       !       !       !       !       !       !       !       !       !       !       !       !
FRB5157P9100000092000000       2  3310.  125340          48790                BENBR4-FRSTOR   BENBR4-FRREL
WSBENBR4
FRB3404A9100000092000000       2  3880.  304000         176900                JOPOOL-FRSTOR   JOPOOL-FRREL
WSJOPOOL
FRB2335A9100000092000000       2  6000.  856704         591704                ROBDAL-FRSTOR   ROBDAL-FRREL
WSROBDAL
FRB2456A9100000092000000       2  7000.  554770         214000                LEWDA1-FRSTOR   LEWDA1-FRREL
WSLEWDA1
FRB2362A9100000092000000       2  7000.  329400          85000                GPVDAL-STOR     GPVDAL-FRREL
WSGPVDAL
FRB2410A9100000092000000       2  8000   748100         456500                LAVON2-FRSTOR   LAVON2-FRREL
WSLAVON
FRB4992A9100000092000000       2  2000   212200          63300                NAVARO-FRSTOR   NAVARO-FRREL
WSNAVARO
FRB5021A9100000092000000       2  2000.  140000          54900                BARDWL-FRSTOR   BARDWL-FRREL
WSBARDWL
**  FCDEP option 2 on the FR record for each reservoir specifies that the FF record limits not be employed.
FF 8WTGP   6000.                FFLIM- 8WTGP
FF 8MCGP   4000.                FFLIM- 8MCGP
FF 8DNGR   2000.                FFLIM- 8DNGR
FF   839   6000.                FFLIM-   839
FFB2457C   7000.                FFLIM-B2457C
FF 8TRDA  13000.                FFLIM- 8TRDA
FF 8ETCR   8000.                FFLIM- 8ETCR
FF 8TRRS  15000.                FFLIM- 8TRRS
FF 8RIDA   2000.                FFLIM- 8RIDA
FF 8WABA   2000.                FFLIM- 8WABA
FFB5023A   5000.                FFLIM-B5023A
FF 8TROA  24000.                FFLIM- 8TROA
```

The Trinity WAM sets outflows equal to inflows in a *SIMD* simulation whenever storage exceeds flood control capacity. However, *FV* and *FQ* records can be added to set outflow as a function of storage volume in reservoirs with or without flood control pools. A varying outlet capacity as a function of storage level can be applied to model surcharge above the flood control pool or above conservation storage for reservoirs with no flood control storage.

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

Environmental flow standards (EFS) established pursuant to the process mandated by the 2007 Senate Bill 3 (SB3) are discussed in Chapter 3. The geographic area covered by "*Subchapter B: Trinity and San Jacinto Rivers and Galveston Bay* " of Chapter 298 of Title 30 of the Texas Administrative Code consists of the Trinity and San Jacinto Rivers, their associated tributaries, Galveston Bay, and associated estuaries [98]. Environmental instream flow recommendations are developed for freshwater inflows to Galveston Bay, instream flows at four stream gaging stations on the Trinity River and its tributaries, and instream flows at two gage sites in the San Jacinto River Basin. However, only the EFS for the four gage sites on the Trinity River and its tributaries are incorporated in the daily Trinity WAM by the work documented by this 2024 report and the preceding 2019 report [8]. Both the Trinity and San Jacinto Basins contribute freshwater inflows into Galveston Bay but are modeled as separate WAMs. Combining the two WAMs or allocating instream flow requirements between them is not addressed in this report or the preceding report.

SB3 EFS have been established at the four USGS gage sites in the Trinity River Basin listed in Table 8.7 with locations shown in Figure 8.9. Metrics for the SB3 EFS are tabulated in Tables 8.8 and 8.9. Seasons are defined as follows for the EFS for the Trinity River system: Winter (December, January, February), Spring (March, April, May), Summer (June, July, August), Fall (September, October, November). Unlike the EFS established for other river basins, hydrologic conditions are not specified for the Trinity EFS.

Table 8.7
Trinity WAM Control Point Locations for SB3 Environmental Flow Standards

| Control Point | River | Nearest City | Watershed Area | USGS Gage Period-of-Record | 1940-2023 Mean Naturalized Flow |
|---|---|---|---|---|---|
| | | | (mile$^2$) | | (cfs) |
| 8WTGP | West Fork | Grand Prairie | 3,065 | April 1925 to present | 781 |
| 8TRDA | Trinity | Dallas | 6,106 | October 1903 to present | 2,139 |
| 8TROA | Trinity | Oakwood | 12,833 | October 1923 to present | 6,217 |
| 8TRRO | Trinity | Romayor | 17,186 | May 1924 to present | 8,952 |

The four SB3 EFS are included in the official TCEQ Trinity WAM last updated by TCEQ on 10/1/2023 using several hundred *IF*, *WR*, *TO*, *PX*, and *FS* records and about 150 *UC*, *CP*, and *CI* records. These initial records modeling the four SB3 EFS in the monthly WAM were removed and replaced in the daily WAM with the *IF*, *ES*, and *PF* records replicated as Table 8.10. This set of input records shown in Table 8.10 modeling eight *IF* record water rights representing the four SB3 EFS can be inserted anyplace in the water rights section of the DAT file. Pulse flow and subsidence/base flow components of an EFS can also be combined within the same *IF* record right.

The SB3 EFS in the Trinity River Basin and Trinity WAM are described in the 2019 daily Trinity WAM report [8]. These records from the 2019 daily WAM are adopted without revision in the 2024 version of the daily WAM. The set of four *IF* record instream flow rights are replicated as Table 8.10. The modified monthly WAM contains the eight records shown later in Table 8.12.

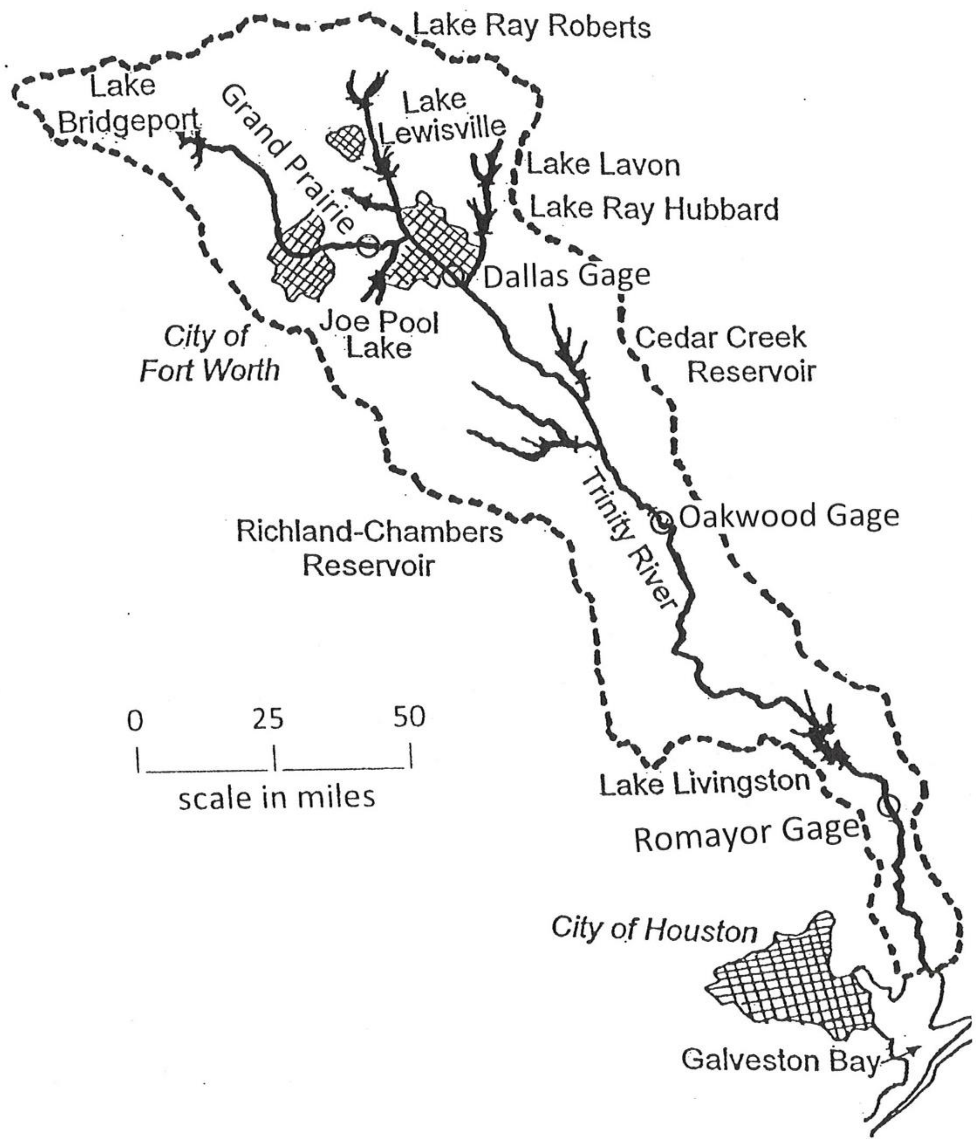


Figure 8.22 Four USGS Gage Locations with SB3 EFS

The daily minimum instream flow target is the greater of the subsistence and base flow target and high pulse target. The applicable subsistence flow standard varies with seasons of the year as shown in Table 8.8. For a water right holder to which an EFS applies, the water right holder may not store or divert water unless the stream flow at the gage is above the subsistence flow limit shown in Table 8.8. If the flow at the gage is above the subsistence flow limit but below the base flow limit, the water right holder may divert or store water as long as the flow at the gage does not fall below the subsistence flow limit. If the flow is above the base flow limit, the water right holder may store or divert stream flow as long as the flow does not fall below the base flow standard.

The quantities used to set high flow pulse targets are tabulated in Table 8.9. A qualifying pulse event is initiated when the flow exceeds the prescribed peak trigger flow tabulated in Table 8.9. A pulse flow event is terminated when either the volume limit (in acre-feet in Table 8.9) or the duration limit in days is reached. Pulse flow events initiated in a particular season or year continue into the following season or year if and as necessary to meet the volume and/or duration termination criteria. Pulse flow events are tracked in the WRAP/WAM modeling system to set minimum instream flow targets for each day of the tracked flow event. The daily pulse flow target in acre-feet/day is computed as the lesser of the (1) daily regulated flow, (2) peak trigger flow rate shown in Tables 8.9 and 8.10 in cfs converted within *SIMD* to acre-feet/day, or (3) remaining volume that will satisfy the volume criterion.

Table 8.8
Subsistence and Base Flow Limits for SB3 Environmental Flow Standards

| Control Point | Gage Site Nearest City | Subsidence Flow Limits (cfs) | | | | Base Flow Limits (cfs) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Winter | Spring | Summer | Fall | Winter | Spring | Summer | Fall |
| 8WTGP | Grand Prairie | 19 | 25 | 23 | 21 | 45 | 45 | 35 | 35 |
| 8TRDA | Dallas | 26 | 37 | 22 | 15 | 50 | 70 | 40 | 50 |
| 8TROA | Oakwood | 120 | 160 | 75 | 100 | 340 | 450 | 250 | 260 |
| 8TRRO | Romayor | 495 | 700 | 200 | 230 | 875 | 1,150 | 575 | 625 |

Table 8.9
Metrics for High Flow Pulse Components of SB3 Environmental Flow Standards

| CP | Site | Criteria | Winter | Spring | Summer/Fall |
|---|---|---|---|---|---|
| 8WTGP | West Fork of Trinity River at Grand Prairie | Trigger (cfs) | 300 | 1,200 | 300 |
| | | Volume (acre-feet) | 3,500 | 8,000 | 1,800 |
| | | Duration (days) | 4 | 8 | 3 |
| 8TRDA | Trinity River at Dallas | Trigger (cfs) | 700 | 4,000 | 1,000 |
| | | Volume (acre-feet) | 3,500 | 40,000 | 8,500 |
| | | Duration (days) | 3 | 9 | 5 |
| 8TROA | Trinity River at Oakwood | Trigger (cfs) | 3,000 | 7,000 | 2,500 |
| | | Volume (acre-feet) | 18,000 | 130,000 | 23,000 |
| | | Duration (days) | 5 | 11 | 5 |
| 8TRRO | Trinity River at Romayor | Trigger (cfs) | 8,000 | 10,000 | 4,000 |
| | | Volume (acre-feet) | 80,000 | 150,000 | 60,000 |
| | | Duration (days) | 7 | 9 | 5 |

## Instream Flow Targets in the Daily and Modified Monthly WAMs

The simulation procedure described as follows was performed with 1940-2018 hydrology as reported in the 2019 daily Trinity WAM report [8] and repeated with 1940-2023 hydrology in conjunction with the present 2024 report. A daily *SIMD* simulation was performed with the *IF*, *ES*, and *PF* records of Table 8.10 in the DAT file controlling computation of daily instream flow targets for the SB3 EFS at the four USGS gage sites (WAM control points). Daily instream flow targets in acre-feet/day were summed within *SIMD* to monthly quantities in acre-feet/month, which are included in the simulation results DSS file. The DSS records of monthly targets were copied from the daily *SIMD* simulation results DSS output file to the *SIM/SIM* hydrology input DSS file and the pathnames were revised using *HEC-DSSVue*. The *TS* records in the monthly *SIM* DAT file reference the DSS file target series employed by the *IF* record water rights.

Table 8.10
Instream Flow Rights that Model the SB3 EFS in the Daily Trinity WAM DAT File

```
**        1         2         3         4         5         6         7         8         9        10
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234
       !       !       !       !       !       !       !       !       !       !       !       !       !
IF 8WTGP     -9.        20091201   2            IF-WTGP-ES
ES SUBS      19.     19.     25.     25.     25.     23.     23.     23.     21.     21.     21.     19.
ES BASE      45.     45.     45.     45.     45.     35.     35.     35.     35.     35.     35.     45.
IF 8WTGP     -9.        20091201   2            IF-WTGP-PF
ES PFES
PF   1 0    300.   3500.   4   2      12   2           2
PF   1 0   1200.   8000.   8   2       3   5           2
PF   1 0    300    1800.   3   2       6   8           2
PF   1 0    300    1800.   3   2       9  11           2
IF 8TRDA     -9.        20091201   2            IF-TRDA-ES
ES SUBS      26.     26.     37.     37.     37.     22.     22.     22.     15.     15.     15.     26.
ES BASE      50.     50.     70.     70.     70.     40.     40.     40.     50.     50.     50.     50.
IF 8TRDA     -9.        20091201   2            IF-TRDA-PF
ES PFES
PF   1 0    700.   3500.   3   2      12   2           2
PF   1 0   4000.  40000.   9   2       3   5           2
PF   1 0   1000    8500.   5   2       6   8           2
PF   1 0   1000    8500.   5   2       9  11           2
IF 8TROA     -9.        20091201   2            IF-TROA-ES
ES SUBS     120.    120.    160.    160.    160.     75.     75.     75.    100.    100.    100.    120.
ES BASE     340.    340.    450.    450.    450.    250.    250.    250.    260.    260.    260.    340.
IF 8TROA     -9.        20091201   2            IF-TROA-PF
ES PFES
PF   1 0   3000.  18000.   5   2      12   2           2
PF   1 0   7000. 130000.  11   2       3   5           2
PF   1 0   2500   23000.   5   2       6   8           2
PF   1 0   2500   23000.   5   2       9  11           2
IF 8TRRO     -9.        20091201   2            IF-TRRO-ES
ES SUBS     495.    495.    700.    700.    700.    200.    200.    200.    230.    230.    230.    495.
ES BASE     875.    875.   1150.   1150.   1150.    575.    575.    575.    625.    625.    625.    875.
IF 8TRRO     -9.        20091201   2            IF-TRRO-PF
ES PFES
PF   1 0   8000.  80000.   7   2      12   2           2
PF   1 0  10000. 150000.   9   2       3   5           2
PF   1 0   4000   60000.   5   2       6   8           2
PF   1 0   4000   60000.   5   2       9  11           2
```

The strategy for incorporating monthly instream flow targets computed in a daily *SIMD* simulation into the *SIM* input dataset for a monthly WAM is outlined in Chapter 6 of the *Daily Manual* [5] and also briefly described in Chapter 2 of this report. The methodology is illustrated in an example in Chapter 8 of the *Daily Manual* [5]. The method has been applied for each of the case study WAMs as discussed in Chapters 7 through 12 of this report. Daily targets computed by *SIMD* are aggregated within *SIMD* to monthly targets which are included in the *SIMD* simulation results. These time series of monthly targets are converted in *HEC-DSSVue* to target series *TS* records incorporated in the *SIM/SIMD* hydrology input DSS file. The process is illustrated by the DSS input file pathnames of *TS* records and DAT file input records of Tables 8.11 and 8.12.

The 1940-2023 sequences of monthly instream flow targets in acre-feet/month stored as DSS records labeled by the pathnames listed in Table 8.11 model the SB3 EFS at the four sites. The *TS* records in the DSS input file with the pathname identifiers of Table 8.11 are referenced by the *TS* records in the DAT file of Table 8.12. The four DSS records are stored along with the other time series records (*IN*, *EV*, *HI* records) in a DSS file with filename TrinityHYD.DSS that can be read by *SIM*, *SIMD*, *HEC-DSSVue*, or any other computer program with DSS capabilities.

Table 8.11
Pathnames for Target Series *TS* Records in Hydrology Input DSS File

| Part A | Part B | Part C | Part D | Part E |
|---|---|---|---|---|
| Trinity | 8WTGP | TS | 31Jan1940-31Dec2023 | 1MON |
| Trinity | 8TRDA | TS | 31Jan1940-31Dec2023 | 1MON |
| Trinity | 8TROA | TS | 31Jan1940-31Dec2023 | 1MON |
| Trinity | 8TRRO | TS | 31Jan1940-31Dec2023 | 1MON |

Table 8.12
Instream Flow Rights that Model the EFS in the Monthly Trinity WAM DAT File

```
IF 8WTGP                20091201                EFS-SFAS06
TS      DSS
IF 8TRDA                20091201                EFS-DMAS09
TS      DSS
IF 8TROA                20091201                EFS-BRSE11
TS      DSS
IF 8TRRO                20091201                EFS-CFNU16
TS      DSS
```

The group of four *IF* and four *TS* records replicated in Table 8.12 are inserted in the DAT file read by *SIM* in the same manner as all *IF* and *WR* record water rights. These are the only input records included in the *SIM* input DAT file to model the SB3 EFS. The 1940-2023 time series of monthly targets are read by *SIM* from the *TS* records in the DSS input file labeled with the pathnames listed in Table 8.11 as specified by the *IF* and *TS* records in Table 8.12. Model users can apply the monthly WAM without being concerned with the daily WAM.

Computing monthly SB3 EFS targets by aggregating *SIMD* daily targets allows the improved accuracy of a daily *SIMD* simulation to be incorporated in a monthly WAM. Daily target volumes are precisely replicated in the monthly targets. The accuracy of the *SIM* simulation of constraints of SB3 EFS on junior water rights is significantly improved. This improvement is a key fundamental consideration in WAM support of the water right application evaluation process.

Shortages in meeting the SB3 EFS are computed within the monthly *SIM* simulation based upon monthly regulated flows computed in the simulation. Thus, the benefits of the daily WAM are reduced significantly in monthly *SIM* based assessments of capabilities for meeting SB3 EFS.

This report focuses largely on applications in which the daily WAM is applied occasionally to develop or update monthly SB3 EFS instream flow targets for incorporation in a monthly WAM used frequently in routine applications with the *SIM* simulation model. However, daily WAMs can be applied directly, instead of using monthly versions of the WAMs, in various applications involving assessments of capabilities for meeting SB3 EFS requirements, flood control operating considerations, or integration of multiple water management purposes and objectives.

## Comparison of Simulated Reservoir Storage for Alternative Modeling Premises

Reservoir storage capacities and contents provide insightful water availability metrics for assessing hydrologic conditions and water management capabilities. Summations of the total *SIM* simulated end-of-month storage contents of all reservoirs in the WAM are compared earlier in this chapter in Figure 8.6 for two alternative hydrology extensions. Similar storage comparisons for Lakes Livingston and Richland-Chambers are presented in Figures 8.7 and 8.8. Storage contents of each of the fifteen largest reservoirs in the WAM generated in a monthly *SIM* simulation are plotted in Figures 8.9-8.21.

Simulated 1940-2023 sequences of end-of-day storage contents generated with *SIMD* with alternative modeling premises are compared in this section. Daily *SIMD* simulation results are also compared with monthly *SIM* simulation results. The first subsection of this section presents summations of storage volumes of all 677 reservoirs in the Trinity WAM. The second subsection focuses on the eight multipurpose reservoirs operated by the Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE) for both flood control and water supply.

### Summation of Storage Contents of All Reservoirs in the WAM

The following discussion explores 1940-2023 reservoir storage volumes computed in *SIM* and *SIMD* simulations with the WAM datasets described earlier on page 141 of this chapter. The simulations are listed below.

1. Simulation 1 uses the monthly *SIM* version of the latest TCEQ WAM comprised of files with filenames Trinity3.DAT, Trinity3.DIS, and TrinityHYD.DSS.
2. Simulation 2 uses the daily WAM comprised of *SIMD* input files with filenames TrinityD.DAT, Trinity.DIS, Trinity.DIF, and TrinityHYD.DSS without activation of the routing parameters on the *RT* records in the DIF file.
3. *S*imulation 3 is identical to *SIMD* simulation 2 except routing is performed by activating the routing parameters on the *RT* records. Effects of routing on simulated storage volumes are examined by comparing the results of simulations 2 and 3.
4. Simulation 4 uses the monthly WAM with SB3 EFS instream flow targets computed in the *SIMD* daily simulation 3 (Tables 8.11 and 8.12). Monthly *SIM* input files used in simulation 3 have filenames TrinityM.DAT, Trinity.DIS, and TrinityHYD.DSS.

Summations of 1940-2023 simulated end-of-day or end-of-month storage contents of all reservoirs in the Trinity WAM from the alternative *SIM* and *SIMD* simulations defined above are compared in Table 8.13 and Figures 8.23 and 8.24.

The full authorization WAM simulates about 677 storage facilities that are represented by 699 "model reservoirs" located at 677 control points. Several of the actual reservoirs are modeled as sets of component reservoirs or otherwise as multiple reservoirs. The authorized storage capacities of all reservoirs in the WAM sum to 7,602,146 acre-feet. Flood control storage capacity is not included in the water right authorizations and monthly WAM. Flood control storage capacities totaling 1,579,520 acre-feet in eight USACE multipurpose reservoirs are included in the daily Trinity WAM. Thus, the total flood control storage capacity plus authorized conservation storage capacity of all reservoirs in the daily WAM is 9,181,666 acre-feet. The 32 largest reservoirs in the Trinity River Basin listed in Table 8.1 contain 97.94% of the total authorized conservation storage capacity and all of the flood control capacity included in the daily WAM.

Statistics for the summation of storage volumes of all reservoirs at the end of each of the 1,008 months or 30,681 days of the 1940-2023 hydrologic period-of-analysis are tabulated in Table 8.13. Both end-of-day and end-of-month storage volumes are recorded for *SIMD* daily simulations 2 and 3. Simulations 1 and 4 with *SIM* are performed with monthly versions of the WAM.

Table 8.13
Statistics for Simulated 1940-2023 Storage Contents of All Reservoirs

| | | Summation of Storage in All Reservoirs (acre-feet) | | | |
|---|---|---|---|---|---|
| Simulation | Time Step | Mean | Median | Minimum | Maximum |
| 1 | month | 5,070,387 | 5,285,030 | 453,378 | 7,552,833 |
| 2 | day | 4,632,644 | 4,745,824 | 398,421 | 7,878,311 |
| 2 | month | 4,632,255 | 4,761,953 | 398,421 | 7,870,860 |
| 3 | day | 4,143,050 | 4,177,123 | 233,969 | 7,552,528 |
| 3 | month | 4,142,046 | 4,178,986 | 236,731 | 7,356,395 |
| 4 | month | 5,067,344 | 5,296,576 | 453,600 | 7,552,833 |

Referring to Table 8.13, the mean 1940-2023 simulated end-of-day reservoir storage without and with routing is 4,632,255 and 4,143,050 acre-feet, respectively. The median reservoir storage without and with routing is 4,745,824 and 4,177,123 acre-feet, respectively. Without routing, storage ranges from 398,421 to 7,878,311 acre-feet. With routing, storage ranges from 233,969 to 7,552,528 acre-feet. Concluding whether simulation results are more accurate with or without routing is difficult.

Summations of storage volumes in all reservoirs in the WAM for simulations 1 and 2 are plotted in Figure 8.23 with the following legend.

- *SIM* 1,008 end-of-month storage volumes from simulation 1 (**green dashed line**)
- *SIMD* 30,681 end-of-day storage volumes from simulation 2 (**blue solid line**)
- *SIMD* 1,008 end-of-month storage volumes from simulation 2 (**red dotted line**)

The 1940-2023 sequences of the summations of end-of-day and end-of-month storage contents of the 677 reservoirs generated in the daily *SIMD* simulation (labeled simulation 2) are compared in Figure 8.23 with the corresponding storage volumes from the monthly SIM simulation. The storage volumes from *SIMD* simulation 2 are generally a little smaller than those from *SIM* simulation 1. The 1,008 end-of-month storage volumes from daily *SIMD* simulation 2, which include only the end-of-day storage at the end of the last day of each month, are an exact subset of the 30,681 end-of-day storage volumes. These two plots are almost the same. Peak storage levels during floods that occur within the month may be higher than the end-of-month storage levels. Minimum daily flows during dry periods may also occur within the month but tend to be less noticeable than the flood peaks.

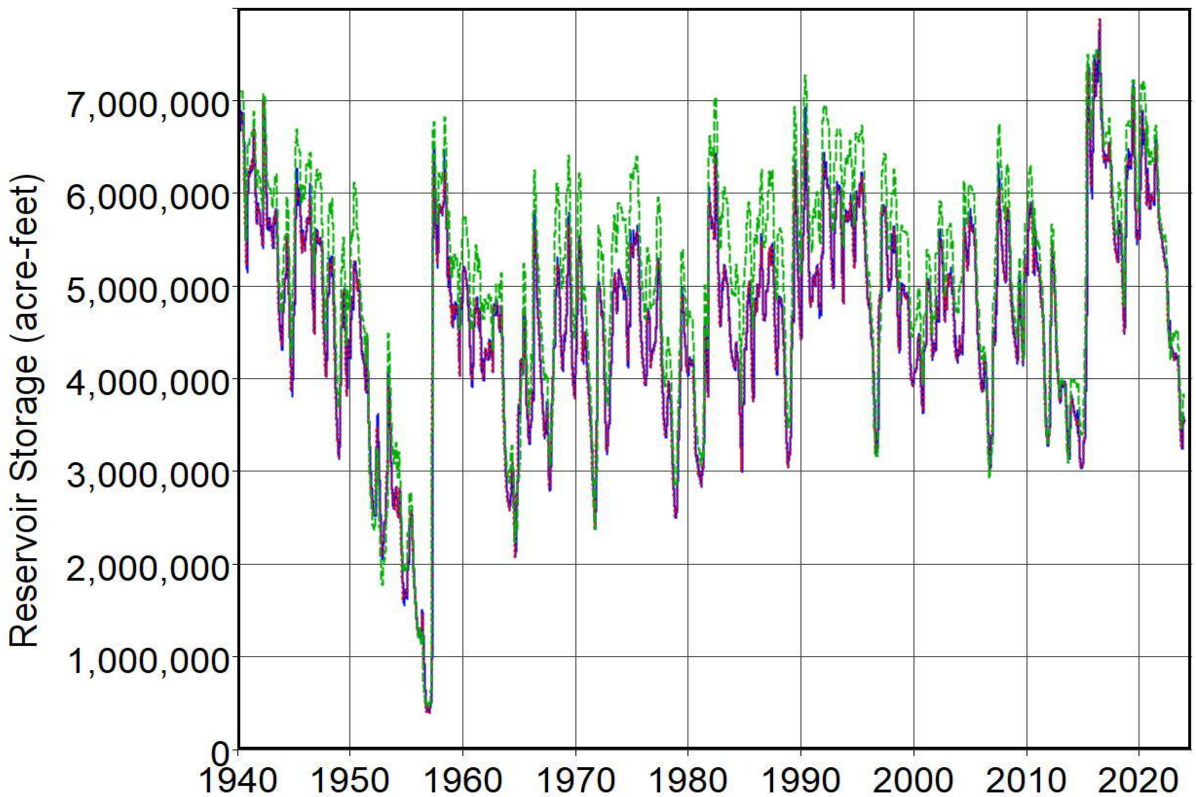


Figure 8.23 Summation of Storage Contents of All Reservoirs from Simulations 1 and 2

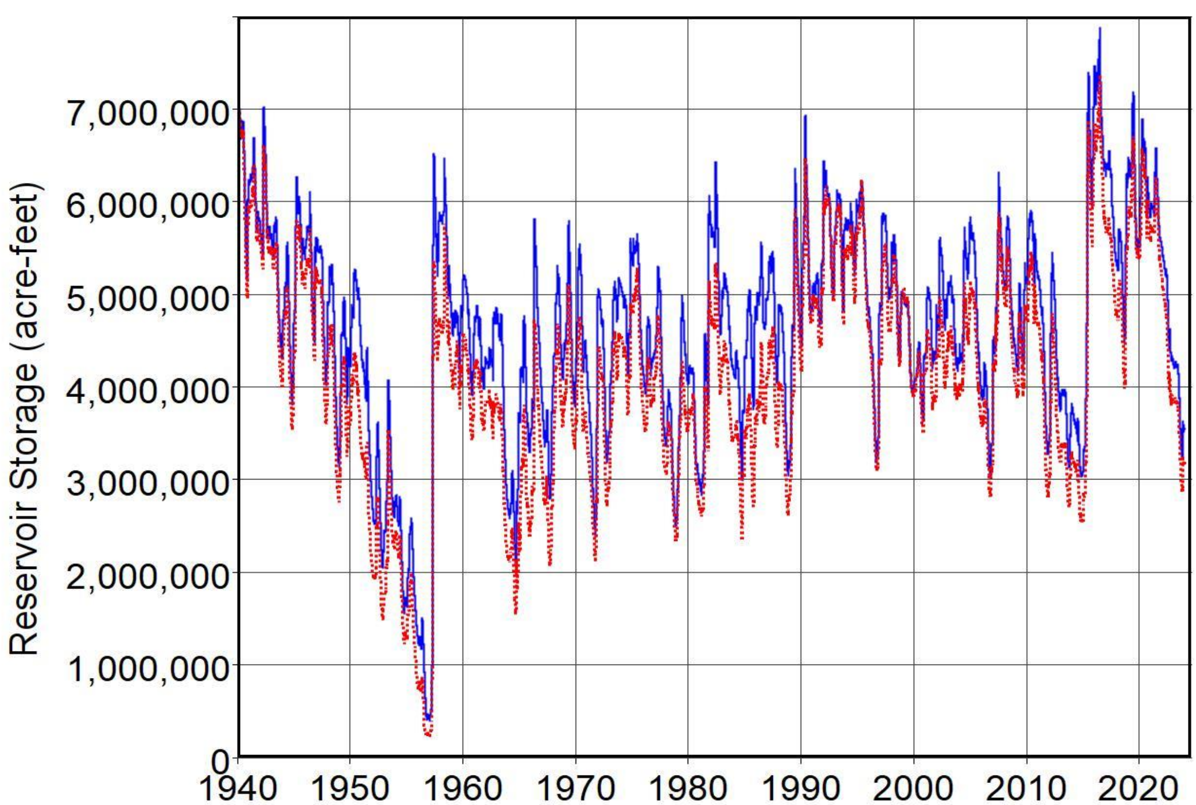


Figure 8.24 Total Storage Without (**blue solid line**) and With (**red dotted line**) Routing

Daily storage in all reservoirs in the WAM generated in simulations 2 and 3 are plotted in Figure 8.24 to illustrate the effects of the optional routing computations to model lag and attenuation. Routing is not activated in simulation 2 but is activated in simulation 3. Forecasting is not activated in any of the four simulations discussed here.

The lag and attenuation routing methodology and parameter calibration methodology are explained in detail in the *Daily Manual* [5]. Routing and forecasting complexities and issues are discussed in Chapter 2 of the present report. The 2019 daily Trinity WAM report [8] presents simulation results exploring the effects and accuracy of routing and forecasting. Routing and forecasting complexities and issues are discussed in detail in the 2019 report [8]. The calibrated routing parameters presented in the 2019 report are incorporated in the 2024 updated daily WAM.

With the calibrated routing parameters available from the earlier studies, routing and forecasting are easily activated or deactivated. Simulation results appear generally to not be overly sensitive to routing strategies and values of routing parameters [8]. Forecasting can unreasonably constrain stream flow availability. Reasonable results can be obtained with or without routing. With routing, results vary only minimally with significant changes to routing parameter values [8].

Based on research results, both routing and forecasting were deactivated in the 2019 studies in simulations to develop SB3 EFS instream flow targets [8]. Likewise, routing and forecasting are not applied in the final daily *SIMD* simulation presented in the last section of this chapter employed to determine daily and monthly instream flow targets for the SBS EFS.

Simulation 4 in Table 8.13 is generated with the monthly WAM with SB3 EFS instream flow targets computed in the *SIMD* daily simulation 3 as outlined in Tables 8.11 and 8.12. Monthly *SIM* input files used in simulation 3 have filenames TrinityM.DAT, Trinity.DIS, and TrinityHYD.DSS. The daily and monthly flow targets representing the SB3 EFS at four USGS gage sites are discussed later in the last section of this chapter.

Summations of Storage Contents of the Eight USACE Reservoirs

The eight multipurpose reservoirs listed in Table 8.5 are owned and operated by the USACE FWD for flood control, water supply, and recreation. These reservoirs are included in Table 8.1 and Figure 8.2. The authorized storage capacity in these eight reservoirs total 2,420,350 acre-feet. Storage capacities of the eight flood control pools total 1,579,420 acre-feet. The total storage capacity below the top of flood control pool of the eight USACE reservoirs sum to 3,999,770 acre-feet. Summations of 1940-2023 storage contents of the eight reservoirs generated with WRAP/WAM simulations reflecting alternative modeling premises are plotted in Figures 8.25, 8.26, and 8.27 to support exploration of issues in modeling flood control operations.

Summations of 1940-2023 sequences of total storage contents of the eight USACE reservoirs (Table 8.5) from a monthly *SIM* simulation and daily *SIMD* simulation without flood control are compared in Figure 8.25. This monthly simulation is labeled Simulation 1 in Figure 8.23. The daily simulation in Figure 8.25 uses the same WAM dataset as simulation 2 in Figure 8.23 with the exception that flood control operations have been totally deactivated. Simulated storage contents are plotted in Figure 8.25 as a green dotted line (monthly *SIM*) and black solid line (daily *SIMD*). *SIMD* daily storage tends to be a little lower than *SIM* monthly storage.

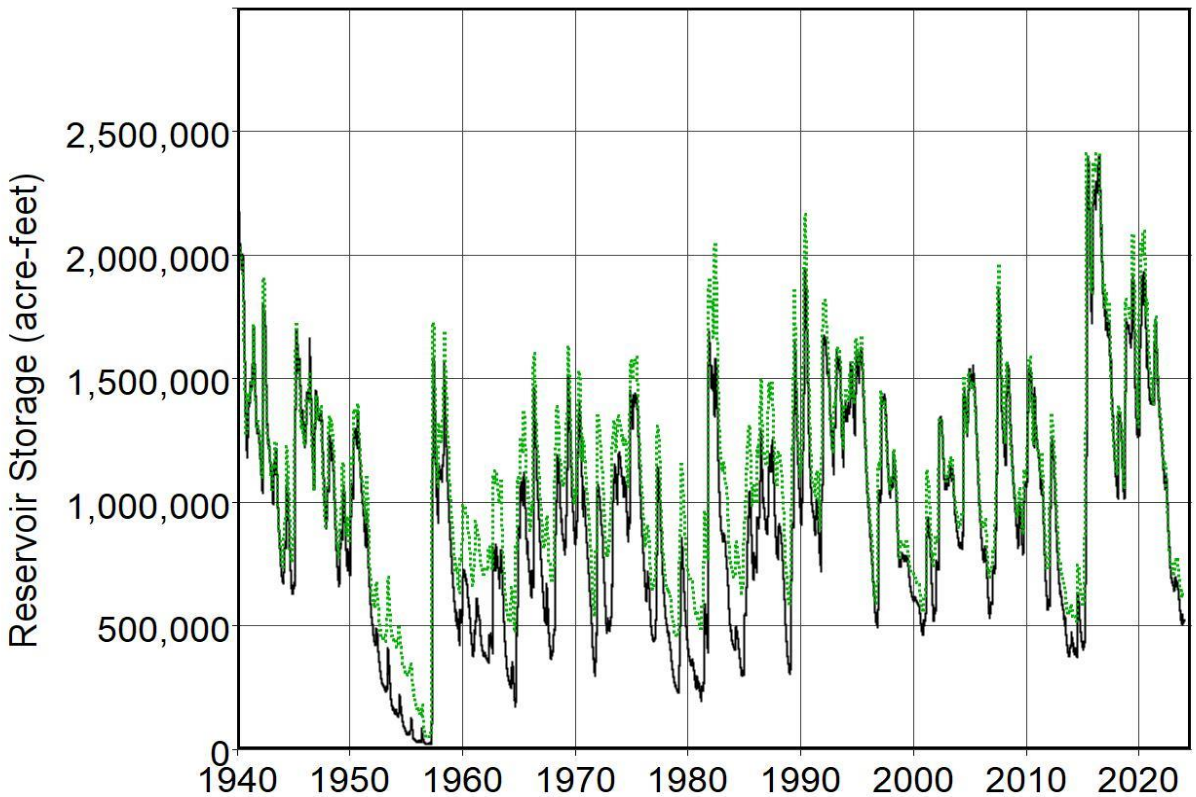


Figure 8.25 Total Storage in USACE Reservoirs in Monthly (**green dotted line**) and Daily Without Flood Control (**black solid line**) Simulations

Both the lag and attenuation routing computations and reservoir flood control operations are deactivated in the daily *SIMD* simulation with storage results included in Figure 8.25. The monthly *SIM* has no features for either routing or flood control operations.

Daily simulations without and with routing are compared in Figures 8.24 and 8.26. Summations of storage in all 677 reservoirs in the WAM are plotted in Figure 8.24. Summations of storage in the eight USACE reservoirs are plotted in Figure 8.26. Results from the same two simulations are plotted in each of these figures. As discussed in the following paragraphs, FCDEP option 2 is activated on the *FR* records to simplify flood control operations in these simulations.

Effects of flood control operations on storage volumes are demonstrated in Figure 8.27. The three plots of 1940-2023 end-of-day storage in Figure 8.27 are almost the same with only minimal differences. The green dashed line is daily *SIMD* storage from a simulation with no flood control storage. The other two plots, which are essentially indistinguishable from each other, represent two levels of flood control operations: full consideration of allowable flows at all control points on the flood flow *FF* records in Table 8.6 and alternatively operations based only on the release limits at the dams specified on the flood reservoir *FR* records in Table 8.6. FCDEP option 2 selected on all the *FR* records automatically constrains flood releases based only on the flows at the dam specified on the *FR* records, which is equivalent to removing the *FF* records. Comparison of the plots in Figure 8.27 indicates that the *FF* record downstream flow limits have essentially no effect on the storage levels and the *FR* record release limits at the dams have only minimal effect.

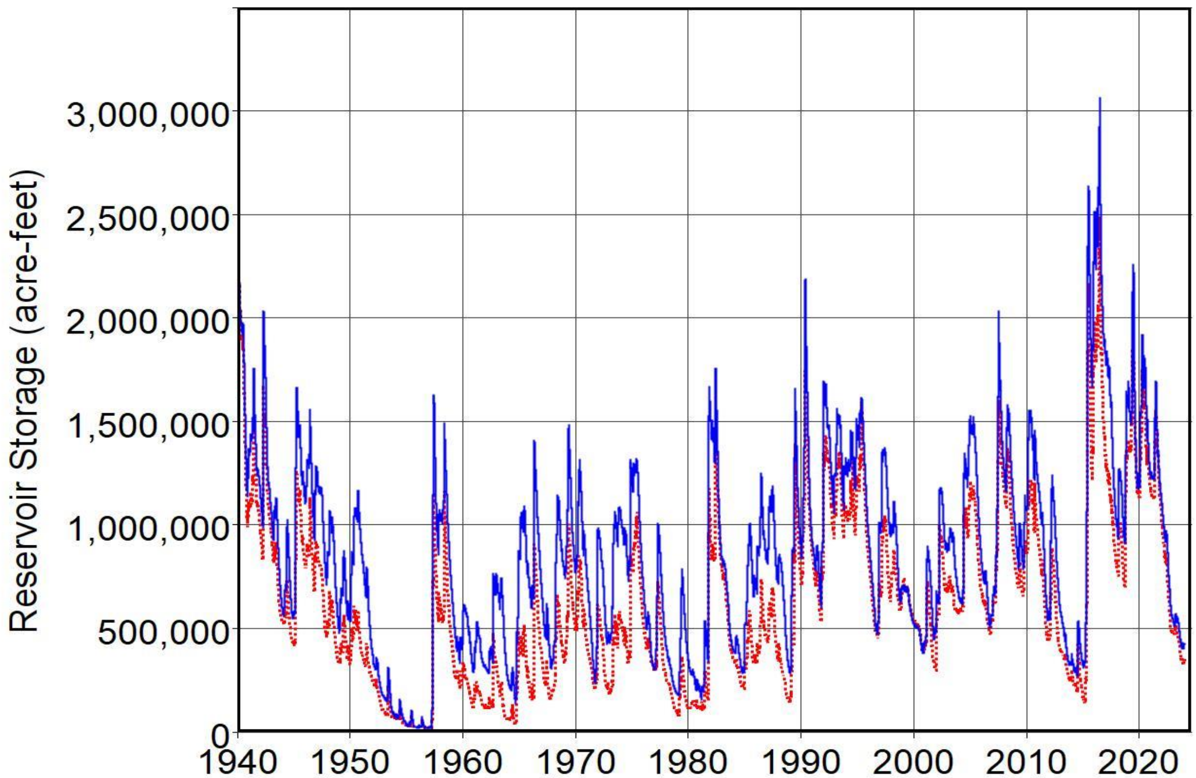


Figure 8.26 Daily Simulations Without (**blue solid**) and With (**red dots**) Routing

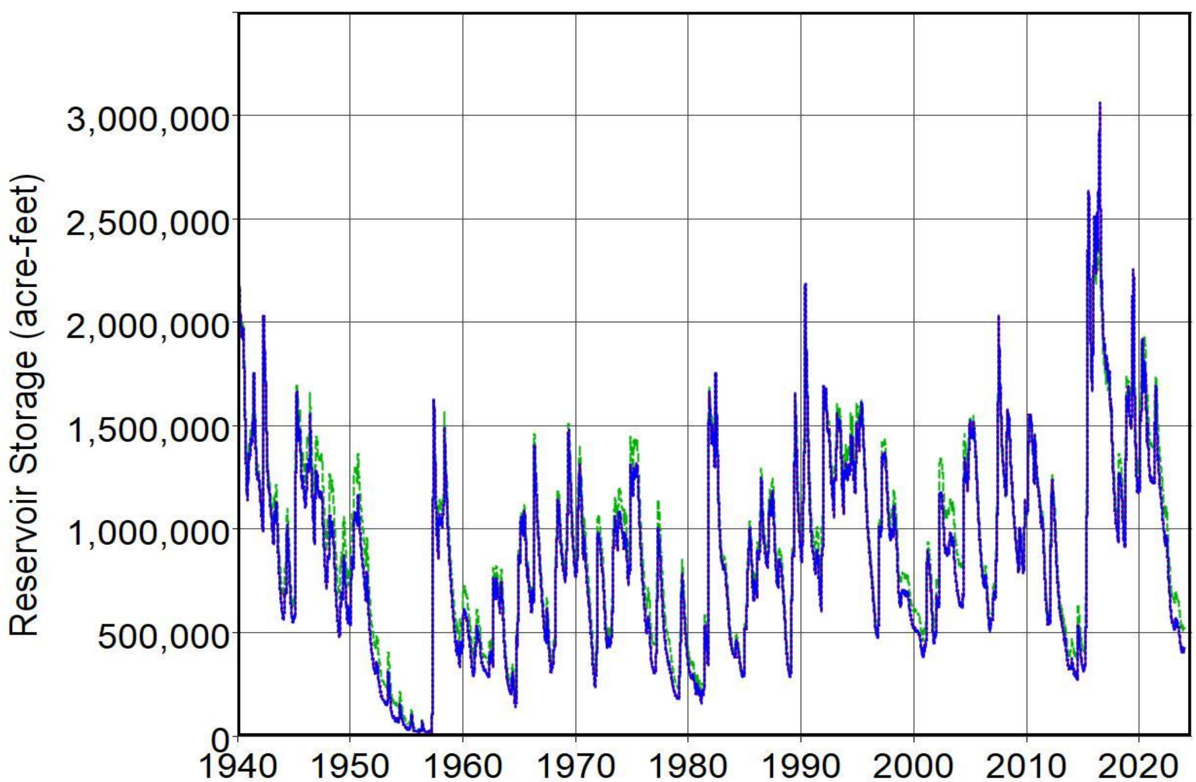


Figure 8.27 USACE Reservoirs in Daily Simulations with No Flood Control (**green dashes**), Full Flood Control (**red dots**), and Release Limits Only at Dams (**blue solid**)

The following summations of storage capacities of the eight multipurpose USACE reservoirs should be noted along with the storage plots in Figures 8.25, 8.26, and 8.27. Conservation and flood control pools are defined in Figure 3.1.

| | |
|---|---|
| Total storage capacity at top of flood control pool = | 3,999,770 acre-feet |
| Total storage capacity at top of conservation pool = | 2,420,250 acre-feet |
| Flood control pool storage capacity = | 1,579,420 acre-feet |
| Conservation storage capacity = authorized storage = | 3,999,770 acre-feet |

Storage plots for each of the 15 largest reservoirs in the Trinity River Basin from a monthly *SIM* simulation in Figures 8.7-8.21 illustrate the great differences in the extent to which storage is depleted in the different individual reservoirs during the 1940-2023 full authorization simulation. The eight USACE reservoirs are included in the largest 15 reservoirs (Table 8.1). The eight USACE reservoirs contain all of the controlled (gated) flood control storage capacity in the basin. Lakes Livingston and Richland-Chambers, the two largest reservoirs in the basin, contain no designated flood control storage capacity. These two largest reservoirs are located in the middle and lower basin far below the Dallas and Fort Worth metropolitan area. The conservation pool of Ray Roberts Reservoir, the third largest reservoir and the largest flood control reservoir, is dramatically depleted throughout most of the 1940-2024 full authorization monthly simulation, filling to authorized capacity only in May-June 2015 and March-June 2016 (Figure 8.9).

Although the extent of storage fluctuations differs greatly between the individual reservoirs, the total storage approaches or reaches the total conservation storage capacity in Figures 8.25-8.27 during a 1940-2023 daily full authorization WAM simulation during only during flood events in 2015 and 2016. The peak storage of 3,060,026 acre-feet in Figure 8.26 occurs on June 28, 2016. As illustrated by Figure 3.1, water does not encroach into the flood control pool of a reservoir until the conservation pool is full to capacity. Flood control operations are not activated unless water has risen into the flood control pool. Storage depletions in the full authorization Trinity WAM are so great that the conservation storage pools (authorized storage capacity) of the 677 reservoirs, including the eight USACE reservoirs, attenuate flood flows much more than the flood control pools of the eight USACE multipurpose reservoirs. Flood control operations have only minimal relevance in a full authorization Trinity WAM simulation.

Flood control operations are modeled in the daily Trinity WAM with the DAT file input records replicated in Table 8.6. The *SV* and *SA* records in the have been extended to include the flood control pools of the eight USACE reservoirs. The lag and attenuation routing parameters stored on *RT* records in the DIF file include separate quantities for routing flood flows versus normal flows. As previously noted, routing is easily activated or deactivated.

FCDEP option 2 is activated in *FR* record field 6 for each of the eight USACE reservoirs in Table 8.6. This option is adopted for the simulation presented in the next (last) section of this chapter These means that releases from the flood control pools are constrained only by maximum release limits specified on the *FR* records. FCDEP option 2 is equivalent to removing or deactivating the downstream limits specified on the flood flow *FF* records. *SIMD* includes capabilities for comprehensive modeling of flood control operations that includes constraining releases based on maximum allowable flows at downstream gages specified on *FF* records. However, the more complex features of the flood control modeling capabilities are not relevant for the full authorization Trinity WAM and add unnecessary and largely untested complexities.

## **SB3 EFS Instream Flow Targets**

This last section of Chapter 8 addresses instream flow targets for the environmental flow standards (EFS) established through the process created by the 1997 Senate Bill 3 (SB3). Daily and monthly SB3 EFS instream flow targets at the USGS gage sites (WAM control points) shown on the map of Figure 8.22 are determined employing the WAM. Descriptive information for the four sites is provided in Table 8.7. The sites are on the West Fork of the Trinity River at Grand Prairie (8WTGP) and the Trinity River at Dallas (8TRDA), Oakwood (8TROA), and Romayor (8TRRO). Observed daily, monthly, and annual flows at three of these four USGS gages are plotted in Figures B4, B5, and B6 of Appendix B. Naturalized monthly flows at control point 8TRRO are plotted in Figure 8.3. The 1940-2023 monthly SB3 EFS instream flow targets and shortages at the four control points are plotted as Figures C20, C21, C22, and C23 of Appendix C.

### *SIMD* and *SIM* Input Files

Results from one daily WAM simulation and one monthly WAM simulation are discussed in this last section of Chapter 8. The daily full authorization *SIMD* input dataset consists of a set of files with the following filenames.

TrinityD.DAT, Trinity.DIS, Trinity.DIF, TrinityHYD.DSS

The daily WAM was executed with *SIMD* to generate monthly instream flow targets stored as *TS* records in the file TrinityHYD.DSS that model the four sets of environmental flow standards (EFS) previously established through a process authorized by the 1997 Senate Bill 3 (SB3). This modified monthly WAM is comprised of a set of *SIM* input files with the following filenames.

TrinityM.DAT, Trinity.DIS, TrinityHYD.DSS

The same hydrology DSS file with filename TrinityHYD.DSS can be read by either *SIM* or *SIMD* in various versions of the WAM input dataset. *HEC-DSSVue* reads any DSS file including *SIM* or *SIMD* input files or simulation results output files.

The adopted daily WAM includes the DAT file records replicated as Tables 8.4, 8.6, and 8.10. Routing and forecasting are deactivated but can be easily activated since routing parameter quantities are included on *RT* records in the DIF file. The hydrology input DSS file read by both *SIMD* and *SIM* includes the original 1940-1996 *IN* and *EV* records extended through 2023 by TWDB and also includes *DF* records read by *SIMD* and *TS* records read by *SIM*.

The 1940-2023 monthly SB3 EFS instream flow targets and shortages in acre-feet/month at the four WAM control points are plotted as Figures C20 through C23 of Appendix C. The monthly instream flow targets plotted in Appendix C were computed by *SIMD* by summing the daily instream flow targets computed in the *SIMD* simulation (Tables 8.11 and 8.12). These instream flow targets stored on *TS* records in the hydrology DSS input file are read by *SIM*.

### Statistics for Daily Stream Flows and SB3 EFS Targets

Statistics for the 1940-2023 daily observed stream flows, naturalized stream flows, simulated regulated and unappropriated stream flows, and SB3 EFS instream flow targets and shortages at the four USGS gage sites are compared in Table 8.14. These statistics for the 1940-2023 time series of 30,681 daily quantities are the mean (average), median (50% exceedance frequency), minimum and maximum. The quantities in Table 8.14 are all in units of cubic feet per second (cfs). *SIMD* performs simulation computations in units of acre-feet/day. Data management, unit conversions, and statistical computations were performed within *HEC-DSSVue*.

Table 8.14
Statistics for Stream Flows and SB3 EFS Targets and Shortages

| USGS Gage Site Location (nearest city)<br>Control Point Identifier | Grand Prairie<br>8WTGP | Dallas<br>8TRDA | Oakwood<br>8TROA | Romayor<br>8TRRO |
|---|---|---|---|---|
| Mean of Daily Observed Flows (cfs) | 771.7 | 2,055 | 5,685 | 8,349 |
| Mean of Daily Naturalized Flows (cfs) | 780.7 | 2,139 | 6,217 | 8,952 |
| Mean of Daily Regulated Flows (cfs) | 368.5 | 811.9 | 4,031 | 6,003 |
| Mean of Daily Unappropriated Flows (cfs) | 139.3 | 259.9 | 2,202 | 4,535 |
| Mean of Daily SB3 EFS Targets (cfs) | 41.32 | 256.6 | 464.9 | 1,036 |
| Mean of Pulse Flow Targets (cfs) | 14.33 | 51.21 | 240.5 | 375.5 |
| Mean of Subsistence/Base Flow Targets (cfs) | 28.45 | 37.59 | 246.9 | 714.6 |
| Mean of Daily SB3 EFS Target Shortages (cfs) | 11.71 | 128.7 | 28.18 | 57.07 |
| Mean of Monthly *SIM* EFS Shortages (cfs) | 13.13 | 81.71 | 23.82 | 34.733 |
| Median of Daily Observed Flows (cfs) | 225.0 | 519.0 | 1,660 | 2,740 |
| Median of Daily Naturalized Flows (cfs) | 192.5 | 503.7 | 1,941 | 3,494 |
| Median of Daily Regulated Flows (cfs) | 4.013 | 29.56 | 644.1 | 1,749 |
| Median of Daily Unappropriated Flows (cfs) | 0.000 | 0.000 | 0.000 | 0.000 |
| Median of Daily SB3 EFS Targets (cfs) | 23.00 | 209.9 | 250.0 | 625.0 |
| Median of Pulse Flow Targets (cfs) | 0.000 | 0.000 | 0.000 | 0.000 |
| Median of Subsistence/Base Flow Targets (cfs) | 23.00 | 37.00 | 250.0 | 625.0 |
| Median of Daily SB3 EFS Shortages (cfs) | 17.38 | 184.0 | 0.000 | 0.000 |
| Median of Monthly *SIM* EFS Shortages (cfs) | 0.000 | 1,989 | 0.000 | 0.000 |
| Minimum Daily Observed Flow (cfs) | 12.00 | 10.00 | 85.00 | 104.0 |
| Minimum Daily Naturalized Flows (cfs) | 0.000 | 0.000 | 0.000 | 0.000 |
| Minimum Daily Regulated Flow (cfs) | 0.000 | 0.000 | 0.000 | 0.000 |
| Minimum Daily Unappropriated Flow (cfs) | 0.000 | 0.000 | 0.000 | 0.000 |
| Minimum Daily SB3 EFS Target (cfs) | 19.00 | 209.9 | 75.00 | 200.0 |
| Minimum Daily Pulse Flow Target (cfs) | 0.000 | 0.000 | 0.000 | 0.000 |
| Minimum Daily Subsistence/Base Target (cfs) | 19.00 | 15.00 | 75.00 | 200.0 |
| Minimum Daily SB3 EFS Shortage (cfs) | 0.000 | 0.000 | 0.000 | 0.000 |
| Minimum Monthly *SIM* EFS Shortage (cfs) | 0.000 | 0.000 | 0.000 | 0.000 |
| Maximum Daily Observed Flow (cfs) | 48,900 | 103,000 | 153,000 | 117,000 |
| Maximum Daily Naturalized Flows (cfs) | 61,525 | 159,494 | 254,947 | 175,475 |
| Maximum Daily Regulated Flow (cfs) | 52,179 | 128,008 | 144,639 | 168,351 |
| Maximum Daily Unappropriated Flow (cfs) | 32,934 | 55,852 | 132,440 | 167,726 |
| Maximum Daily SB3 EFS Target (cfs) | 1,200 | 4,000 | 7,000 | 10,000 |
| Maximum Daily Pulse Flow Target (cfs) | 1,200 | 4,000 | 7,000 | 10,000 |
| Maximum Daily Subsistence/Base Target (cfs) | 45.00 | 70.00 | 450.0 | 1,150 |
| Maximum Daily SB3 EFS Shortage (cfs) | 25.00 | 232.4 | 160.0 | 700.0 |
| Maximum Monthly *SIM* EFS Shortage (cfs) | 53.49 | 326.8 | 1,899 | 2,778 |

Observed, naturalized, and *SIMD* simulated regulated and unappropriated stream flows are extremely variable over time with a great range between minimum and maximum flows. The median of stream flows is much smaller than the mean for the quantities in Figure 8.14 since high flood flows increase the mean more than the median. Naturalized flows are generally higher than observed flows at these sites. Simulated regulated flows are generally but not always lower than naturalized flows. Simulated unappropriated flows are much lower than naturalized flows.

For example, the means of observed, naturalized, and *SIMD* simulated regulated and unappropriated stream daily flows at the Romayor gage on the lower Trinity River are 8,349 cfs, 8,952 cfs, 6,003 cfs, and 4,535 cfs. Observed, naturalized, and simulated regulated flows of 2,740 cfs, 3,494 cfs, and 1,749 cfs are exceeded during 50 percent of the 30,651 days of 1940-2023. Unappropriated flows are zero during more than 50 percent the of the 30,651 days. Minimum and maximum daily flows during 1940-2023 are also included in Table 8.14.

<u>*IF* Record Instream Flow Targets for the SB3 EFS</u>

A table accompanying the *OF* record description in the WRAP *Users Manual* [2] defines 43 time series variables that may be included in *SIM* and *SIMD* simulation results output files. The five variables that are forms of instream flow targets or shortages in meeting instream flow targets are listed below in Table 8.15. Labels defining the quantities in *SIM/SIMD OF* records, *TABLES* input files, and *DSS* simulation results files are shown in Table 8.15.

Table 8.15
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 |

Any number of instream flow *IF* record water rights can be located at the same control point. Combining instream flow targets for multiple *IF* record rights at the same control point is controlled with *IF* record parameter IFM(if,2) with the following options: (1) a junior target replaces a senior target; (2) the largest target is adopted; or (3) the smallest target is adopted.

SB3 EFS are modeled as a set of *IF*, *HC*, *ES*, and *PF* records as explained in the *Daily and Users Manuals* [2, 4] and earlier in this chapter. The set of records replicated in Table 8.10 separate the pulse flow and subsistence/base flow components of the EFS into two separate *IF* record water rights. Pulse flow *PF* and subsistence/base flow *ES* records can be combined into a single *IF* record instream flow water right at a control point by removing the extra *IF* records without affecting the final combined instream flow targets. The extra *IF* records in Table 8.10 allow the pulse flow component and combined subsistence and base flow components of the SB3 EFS to be examined separately in Table 8.14 and Figures 8.28, 8.29, 8.30, and 8.31.

The computation of a SB3 EFS target consists of computing a subsistence and base flow target as specified by *ES* records and a pulse flow target as specified by *PF* records. The larger of the two targets in each individual day is adopted as the final target applied in the simulation. However, both target components are recorded in the simulation results for information using labels listed in Table 8.15.

Statistics for the final daily targets (IFT-CP or IFT-WR), pulse flow component of the daily targets (TIF-WR), subsistence/base flow component of daily targets (TIF-WR), and final shortage in meeting total combined daily targets (IFS-WR) are tabulated in Table 8.14. The final total combined daily targets (blue line) and the subsistence/base flow component (red line) are plotted in Figures 8.28-8.31. The difference between the final total targets and the subsistence and base flow component of the targets in Figures 8.28-8.31 is the pulse flow component.

The non-zero daily quantities for the high pulse flow component of the EFS targets are much larger than the subsistence and base flow quantities but occur only during infrequent flood or high flow events. The subsistence and base flow component of the EFS targets are relatively small quantities in each day but occur continuously.

Monthly summations of *SIMD* simulated SB3 EFS instream flow targets and shortages in meeting the targets are compared for each of the SB3 EFS sites in the 1940-2023 monthly time series plots in Appendix C. The means of either the 30,681 daily or 1,008 monthly SB3 EFS instream flow targets at control points 8WTGP, 8TRDA, 8TROA, and 8TRRO are 11.2%, 31.6.%, 11.5%, and 17.3% of the means of the regulated flows (Table 8.14). The means of the daily *SIMD* simulated shortages in meeting the daily SB3 EFS targets are 28.3%, 50.2%, 6.06%, and 5.51% of the means of the SB3 EFS targets at control points 8WTGP, 8TRDA, 8TROA, and 8TRRO.

<u>SB3 EFS Instream Flow Targets and Shortages in the Modified Monthly WAM</u>

The monthly totals of the daily instream flow targets are incorporated in the monthly WAM as outlined in Tables 8.11 and 8.12. The monthly summations of daily target volumes generated in the daily *SIMD* simulation are precisely replicated in the monthly targets provided as input to *SIM* in the monthly WAM dataset. Shortages in meeting the SB3 EFS are computed within the monthly *SIM* simulation based on monthly regulated flows computed in the *SIM* simulation. Monthly summations of daily *SIMD* target shortages differ from monthly target shortages computed in the *SIM* simulation for the same targets. The monthly shortages in Appendix C are *SIMD* summations of daily shortages, which differ from shortages computed in a *SIM* simulation.

Each sequence of 30,681 daily quantities in cfs, corresponding 1,008 monthly means in cfs, and entire period 1940-2023 mean in cfs are the same. Means from Table 8.14 are as follows.

| 1940-2023 Means | 8WTGP | 8TRDA | 8TROA | 8TRRO |
|---|---|---|---|---|
| *SIMD* and *SIM* EFS Targets (cfs) | 28.45 | 37.59 | 246.9 | 714.6 |
| *SIMD* EFS Shortages (cfs) | 11.71 | 128.7 | 28.18 | 57.07 |
| Modified *SIM* EFS Shortages (cfs) | 13.13 | 81.71 | 23.82 | 34.73 |

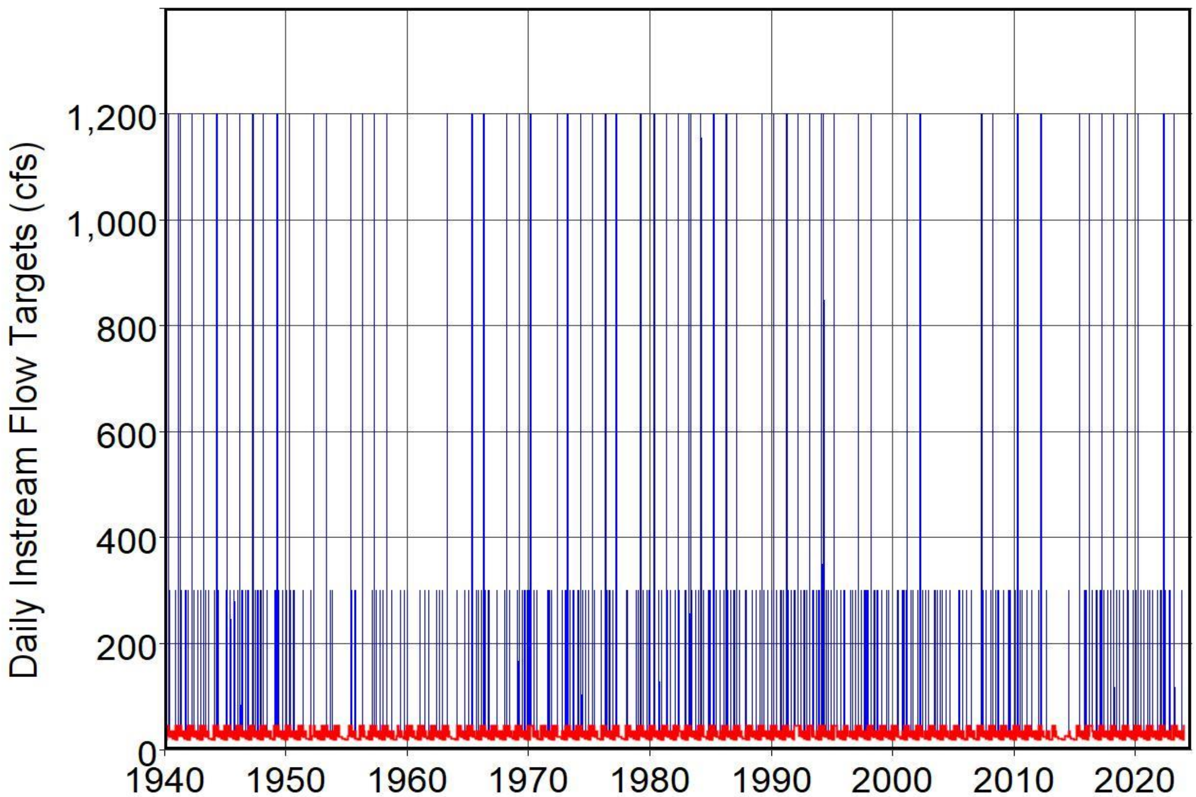

Figure 8.28 SB3 EFS Total (blue) and Subsistence/Base (red) Targets at Grand Prairie (8WTGP)

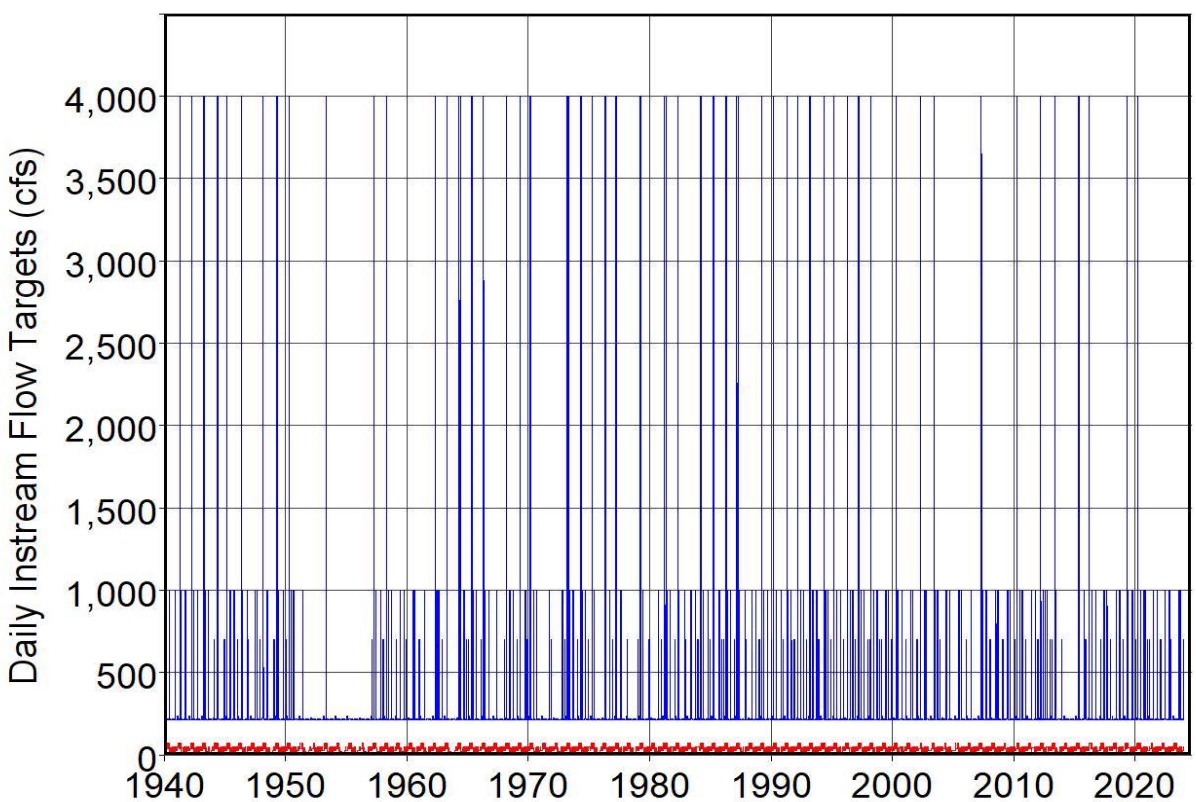

Figure 8.29 SB3 EFS Total (blue) and Subsistence/Base (red) Targets at Dallas (8TRDA)

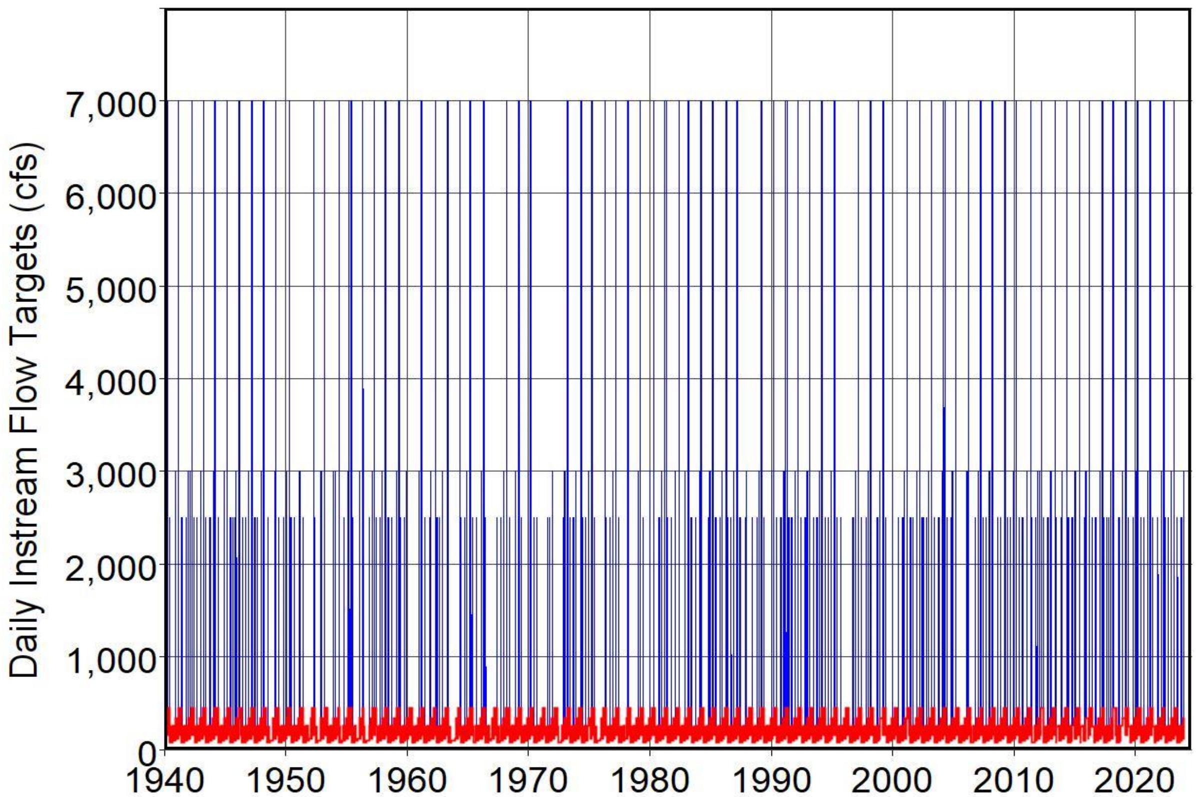

Figure 8.30 SB3 EFS Total (blue) and Subsistence/Base (red) Targets at Oakwood (8TROA)

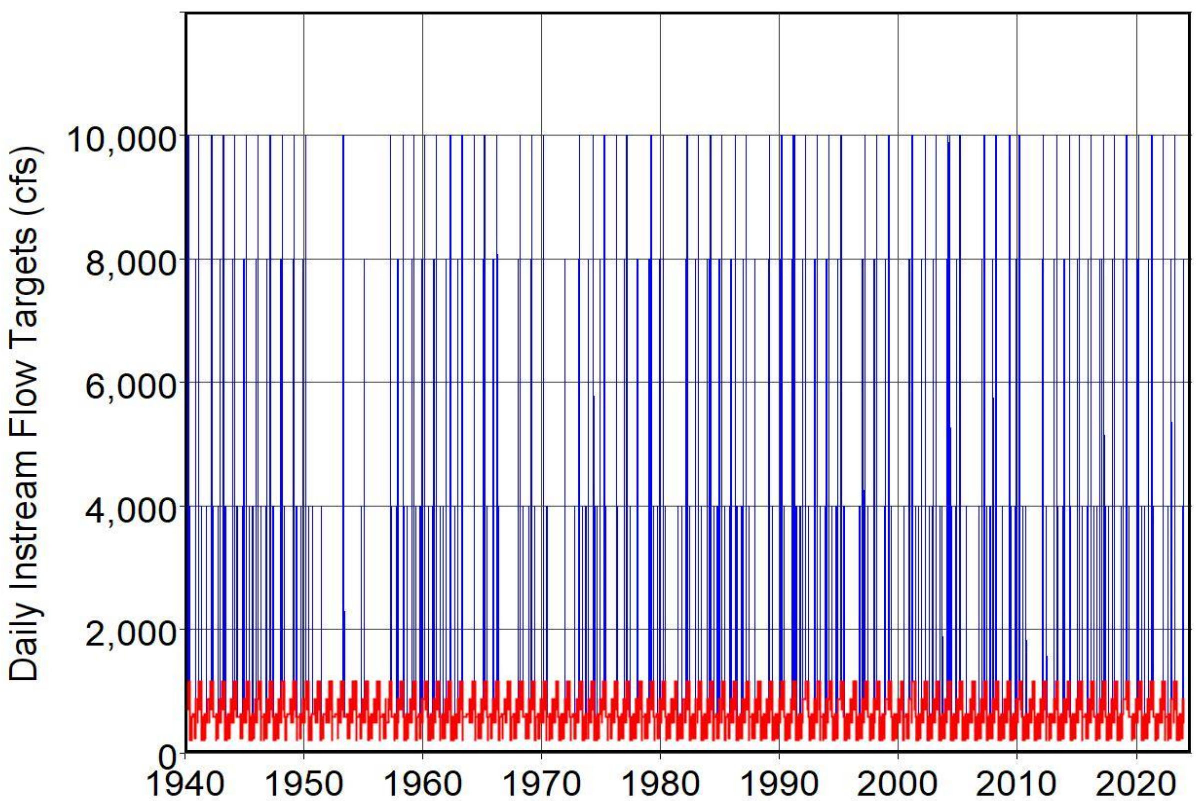

Figure 8.31 SB3 EFS Total (blue) and Subsistence/Base (red) Targets at Romayor (8TRRO)