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Water Rights Analysis Package Modeling System

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Abstract: The water rights analysis package (WRAP) simulates surface water development, allocation, management, and use and performs reliability and frequency analyses of simulation results. The computer modeling system facilitates assessments of hydrologic and institutional water availability and reliability in satisfying requirements for reservoir storage, water supply diversions, environmental instream flows, hydroelectric energy generation, and flood control. Salinity concentrations can also be modeled. Capabilities are provided for analyzing basin-wide impacts of water resources development projects and management practices. The modeling system is generalized for application anywhere, with input datasets being developed for particular river systems of concern. The water availability modeling system maintained by the Texas Commission on Environmental Quality and routinely applied by the professional water management community consists of WRAP and simulation input datasets for all Texas river basins. Model-users modify the input datasets as appropriate to evaluate alternative water use scenarios, development projects, and management strategies of interest. This paper explores concepts and methodologies incorporated in WRAP and other comparable modeling systems, as well as exploring implementation of water availability modeling in Texas and contributions to effective water management.

Keywords: rivers, reservoirs, water availability, reliability, simulation

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Terms used in paper

Acronym/Initialism	Descriptive Name
BRA	Brazos River Authority
cfs	cubic feet per second
CWMS	Corps Water Management System
DAY	WRAP daily flow parameter calibration program
DSS	Data storage system
DSSVue	DSS visual utility engine
EFS	Environmental flow standards
FIA	Flood impact analysis
GIS	Geographic information system
HEC	USACE Hydrologic Engineering Center
HEC-5	HEC model for simulation of reservoir systems
HEC-HMS	HEC Hydrologic Modeling System
HEC-PRM	HEC Prescriptive Reservoir Model
HEC-RAS	HEC River Analysis
HYD	WRAP hydrology data compilation program
IBWC	International Boundary and Water Commission
LP	Linear programming
ResSim	HEC reservoir simulation model
SALT	WRAP salinity simulation model
SB	Senate bill
SIM	WRAP monthly simulation model
SIMD	WRAP daily simulation model
SWAT	Soil and water analysis tool
TABLES	WRAP data organization and analysis program
TAMU	Texas A&M University
TCEQ	Texas Commission on Environmental Quality
TRA	Trinity River Authority
TWDB	Texas Water Development Board
TWRI	Texas Water Resources Institute
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
WAM	Water availability model or modeling
WinWRAP	WRAP Microsoft Windows user interface
WRAP	Water rights analysis package

INTRODUCTION

Effective management of the water resources of river basins requires an understanding of the amount of water available at alternative levels of reliability under various conditions. Water availability depends on hydrology, constructed facilities, institutional water allocation systems, water management practices, and basinwide water demands. Water resources are shared by numerous water users for various types of use. Streamflow is highly variable, reflecting the extremes of severe droughts and floods as well as more normal seasonal and continuous instant-to-instant fluctuations. Future streamflow, reservoir storage availability, and associated water supply capabilities must be expressed in terms of probability, frequency, percent of time, risk of shortage, and/or supply reliability.

The modeling and analysis strategy implemented in the water rights analysis package (WRAP) consists of simulating a specified scenario of water resources development, management, allocation, and use during a postulated repetition of past natural river basin hydrology. Supply reliability and storage and flow frequency metrics are developed from the results of the simulation. The river/reservoir/use system being simulated may range in complexity from a single water user being supplied by a single reservoir to complex systems with numerous water users being supplied by many multipurpose reservoirs.

The water availability modeling (WAM) system maintained by the Texas Commission on Environmental Quality (TCEQ) consists of the generalized WRAP modeling system and simulation input datasets for all the river basins of Texas. A WRAP simulation input dataset from the TCEQ WAM system for a particular river basin is combined with the generic WRAP software that performs the simulation computations. Twenty WAM datasets simulate river system hydrology for all river basins of Texas, operation of 3,460 reservoirs/dams and other constructed facilities, 6,200 water right permits, various water supply contracts, and the effects of several interstate river basin compacts and treaties between the United States and Mexico.

The latest editions of the WRAP software and documentation are available on the WRAP website maintained at Texas A&M University. WRAP is documented by a set of manuals (Wurbs 2009, 2019a, b, 2021a, b; Wurbs and Hoffpauir 2021) published as Texas Water Resources Institute (TWRI) technical reports available on both the WRAP and TWRI publications websites. The TCEQ WAM website links with the WRAP website and provides simulation input datasets and an array of WAM information.

Water right permit applicants or their consultants apply the WAMs to assess reliabilities associated with proposed actions. TCEQ staff use the WRAP/WAM modeling system to evaluate water right permit applications. The Texas Water Development Board (TWDB), regional planning groups, and their consultants employ the modeling system in statewide and regional planning. River authorities and other water management agencies apply the models in operational planning studies. The WRAP/WAM system is also used in research studies and various other types of water management endeavors.

The routinely applied WRAP/WAM modeling system is based on a monthly computational time step. The latest expanded WRAP software and manuals include daily modeling capabilities with monthly-to-daily flow disaggregation, routing, forecasting, flood control reservoir operations, and instream flow standards with subsistence, base, and pulse flow components. The primary motivation for adding the daily modeling features is to enhance the capability to model environmental flow standards established by the TCEQ in the WAMs.

MODELING OF RESERVOIR/RIVER SYSTEM OPERATIONS

Pioneering efforts in computer simulation of reservoir systems include U.S. Army Corps of Engineers (USACE) studies of six reservoirs on the Missouri River initiated in 1953 and International Boundary and Water Commission (IBWC) simulations of the Rio Grande in 1954 (Maass et al. 1966). TWDB began developing models in support of water planning in Texas in the late 1950s and 1960s, which resulted in several generalized river/reservoir system models (TWDB 1974; Martin 1983, 1987).

The massive literature on modeling and analysis of reservoir systems is dominated by thousands of university research papers published in journals and conference proceedings. Most of the published papers present mathematical programming methods for modeling reservoir system operations developed in academic research that have been applied only by the model developers and only for research case studies. Labadie (2004) reviews the extensive and complex research literature on reservoir system optimization models. Wurbs (1993, 1996, 2005a, 2012) presents state-of-the-art reviews of reservoir and river system analysis from a practical applications perspective.

Generalized modeling systems

Although the research literature is extensive, most actual practical applications of reservoir/river system management models in the United States have been performed with a relatively small number of generalized modeling systems developed by federal or state agencies or university research entities under the sponsorship of federal or state agencies. These generalized modeling systems have evolved through various versions over the past several decades (Wurbs 1993, 1996, 2012).

An online hydrologic modeling inventory maintained by TWRI and TAMU, organizes models under the categories of hydrology, hydraulics, water quality, and management and planning. Descriptive information for the following generalized modeling systems is provided under the category of management and planning: MIKE BASIN, developed by the Danish Hydraulic Institute; Water Resource Integrated Modeling System (WRIMS), formerly called CALSIM, developed by the California Department of Water Resources; MODSIM, developed at Colorado State University and applied by the U.S. Bureau of Reclamation (USBR) and others; RiverWare, developed by the Center for Advanced Decision Support at the University of Colorado and sponsored by the USBR and others; and WRAP, described in this paper. The hydrologic modeling inventory website provides model descriptions and website links to software and relevant documents.

Most large federal reservoirs in the United States were constructed and are operated by the USBR or USACE. These agencies developed many models for specific reservoir systems during the 1950s–1970s (Wurbs 1993, 1996). Many of the system-specific models have since been replaced with generalized models. The USBR currently employs MODSIM, RiverWare, and several system-specific models. The USACE Hydrologic Engineering Center (HEC) maintains a suite of generalized models that are widely applied by USACE offices, other agencies, consulting firms, and universities nationwide and abroad.

The HEC's Corps Water Management System (CWMS) has been deployed at 35 USACE district offices, including the Fort Worth and Galveston offices, to support real-time operations of flood control and multipurpose reservoir systems (McPherson 2019). The first non-USACE application of the CWMS was the Lower Colorado River Authority's modeling of real-time flood operations of the Highland Lakes in Texas. The CWMS combines data acquisition and management tools with simulation models that include the HEC Hydrologic Modeling System (HEC-HMS), HEC Reservoir Simulation (ResSim), HEC River Analysis System (RAS), and HEC Flood Impact Analysis (FIA). HEC-HMS and HEC-RAS are employed extensively, independently of the CWMS, by engineering consulting firms, city engineering staff, and university faculty and students in delineating floodplains and designing hydraulic structures and storm-water management facilities.

A HEC model called HEC-5 Simulation of Flood Control and Conservation Systems (HEC 1998) was employed during the 1970s–2000s in many USACE and non-USACE applications. HEC-ResSim (HEC 2013) succeeded HEC-5 during the 2000s. The HEC Prescriptive Reservoir Model (HEC-PRM) was developed in conjunction with USACE studies of reservoir systems in the Missouri and Columbia river basins and later applied to systems in California, Florida, and Panama. HEC-PRM is a linear programming model that minimizes a cost based objective function.

The HEC has developed a data storage system (DSS) for time series data that is used routinely with HEC models and also with other non-HEC modeling systems including WRAP, RiverWare, and WRIMS. Multiple models share the same data management and graphics software. Time series data are stored in DSS files in a direct access binary format. The HEC-DSS Visual Utility Engine (HEC-DSSVue) is a graphical user interface program for viewing, editing, manipulating, and graphing data in DSS files and performing statistical analyses and mathematical operations (HEC 2009). HEC-DSSVue has been adopted as an integral component of WRAP.

Linear programming models

Of the many mathematical optimization methods available, linear programming (LP) has been most often adopted in water management applications. LP is a mathematical formulation with standard solution algorithms based on maximizing a linear objective function subject to a set of linear constraints. The TWDB pioneered early applications of LP in modeling river/reservoir system water management. Yield simulation, water allocation, and river/reservoir system simulation models called SIMYLD-II, AL-V, and SIM-V developed by the TWDB during the 1960s–1980s, employed variations of the same capacitated network flow LP solver as the basic computational engine of the models (TWDB 1974; Martin 1983). These early TWDB models, the original CALSIM, and the original versions of HEC-PRM and MODSIM were all based on the same Fortran subroutine implementing the LP algorithm originally developed for the TWDB models. HEC-PRM and MODSIM were later updated with more computationally efficient LP algorithms.

HEC-PRM, the RiverWare LP option, and many other LP models reported in the literature recently, as well as over the past 50 years, are formulated to compute quantities for all time intervals simultaneously, which means operating decisions are based on perfect knowledge of future streamflows. Simulations with MODSIM, WRAP, HEC-ResSim, and non-LP options in RiverWare step through time with operation decisions reflecting no knowledge of future streamflows. The daily WRAP simulation model and HEC-ResSim include options that base operations on flow forecasts a specified number of days into the future.

An early version of a WRAP simulation model called WRAP-NET was created using the network flow LP solver developed for the TWDB models (Yerramreddy and Wurbs 1996). However, rather than adopting a LP formulation employing a generic solution algorithm, all later versions of the WRAP simulation model are based on computational methods developed specifically for WRAP. LP provides the advantage of incorporating in the same generic LP computational solver as a subroutine in multiple different computer programs, reducing programming time. However, the WRAP-specific computer routines provide greater flexibility in incorporating a variety of modeling features and are very efficient in minimizing computer runtime.

Comparison of alternative modeling systems

Wurbs (2005a, 2012) reviewed the literature and available generalized reservoir/river system operations models in general followed by a focused comparison of WRAP and the following three modeling systems:

ResSim (HEC 2013)
MODSIM (Labadie and Larsen 2007)
RiverWare (Zagona et al. 2001)

These simulation models compute reservoir storage and releases and streamflows for each sequential time step of a hydrologic period-of-analysis for a particular scenario of water resources development, management, allocation, and use. Although fundamentally similar, ResSim, MODSIM, WRAP, and RiverWare differ significantly in their organizational structure, computational algorithms, and user interfaces. The alternative modeling systems provide general frameworks for constructing and applying models for systems of reservoirs and river reaches. Each is based on its own set of modeling strategies and methods and has its own terminology or modeling language.

ResSim, MODSIM, and WRAP software and documentation can be downloaded free-of-charge at their websites. RiverWare is a proprietary software product marketed by the Center for Advanced Decision Support at the University of Colorado for a licensing fee. The software packages all run on personal computers operating under Microsoft Windows. The four alternative modeling systems and their predecessors have evolved through multiple versions over more than 20 years of research and development, with new versions being released periodically.

The modeling systems simulate flood control, hydropower, water supply, environmental flows, and other reservoir/river system management purposes. Whereas development of the other three models was motivated primarily by conservation storage purposes, ResSim is motivated largely by flood control, is limited to daily or shorter time steps, and provides greater flexibility for flood routing and simulating flood control operations. The other models were originally monthly but now include options for daily or other computational time steps. RiverWare and WRAP now have optional features for modeling flood control reservoir operations.

ResSim and WRAP have model-specific computational frameworks. MODSIM is built on an LP framework. RiverWare has alternative options based on both model-specific algorithms and LP. The LP-based models have additional model-specific computations along with their LP solver. All of the models have iterative algorithms for evaporation and hydropower computations.

Each of the alternative modeling systems provides certain advantages. The remainder of this paper focuses on WRAP, which provides comprehensive features for modeling the prior appropriation water rights permit system and other institutional water allocation mechanisms and priority-based operating rules. Although equally applicable to simple systems, WRAP is designed for efficient modeling and analysis of large complex datasets with many hundreds of reservoirs and water users. The TCEQ and its contractors and stakeholders have created and continue to update and maintain the large, detailed datasets required to simulate water management in Texas. Comprehensive, flexible modeling capabilities have resulted from evolution of WRAP within Texas with its diverse and challenging climate, hydrology, and water management practices.

TEXAS WATER AVAILABILITY MODELING SYSTEM

The creation of the TWDB and the inaugural 1968 Texas Water Plan were motivated largely by the 1950–1957 drought. The Texas share of the waters of the Lower Rio Grande was allocated by judicial action during the two decades following the 1950s drought. Diverse surface water rights for the remainder of the state were consolidated during the 1970s–1980s pursuant to the Water Rights Adjudication Act of 1967, establishing the foundation for the present water rights permit system administered by the TCEQ (Wurbs 1995). A drought during the 1990s resulted in omnibus water management legislation in 1997. That legislation, Senate Bill 1 (SB1), implemented a "bottom-up" approach to regional planning in the statewide cyclic planning process and creation of a WAM system (Wurbs 2015).

The TCEQ, as lead agency, in partnership with the TWDB and Texas Parks and Wildlife Department developed the WAM system during 1997–2003 to support water rights regulatory, regional planning, and statewide planning activities (Alexander and Henderson 2020; Wurbs 2005b). Consulting firms and university research entities working under contract with the TCEQ provided technical support. Reports documenting development of the original WAM datasets are archived in the Texas Water Digital Library.

WRAP was adopted for the WAM system based on recommendations of a committee representing the three agencies and the professional water management community. The committee developed a list of additional improvements and expansions to WRAP required for the WAM system. About 10 consulting engineering firms serving as primary contractors, with assistance from other subcontractors, developed WAM datasets and performed simulations for the individual river basins with

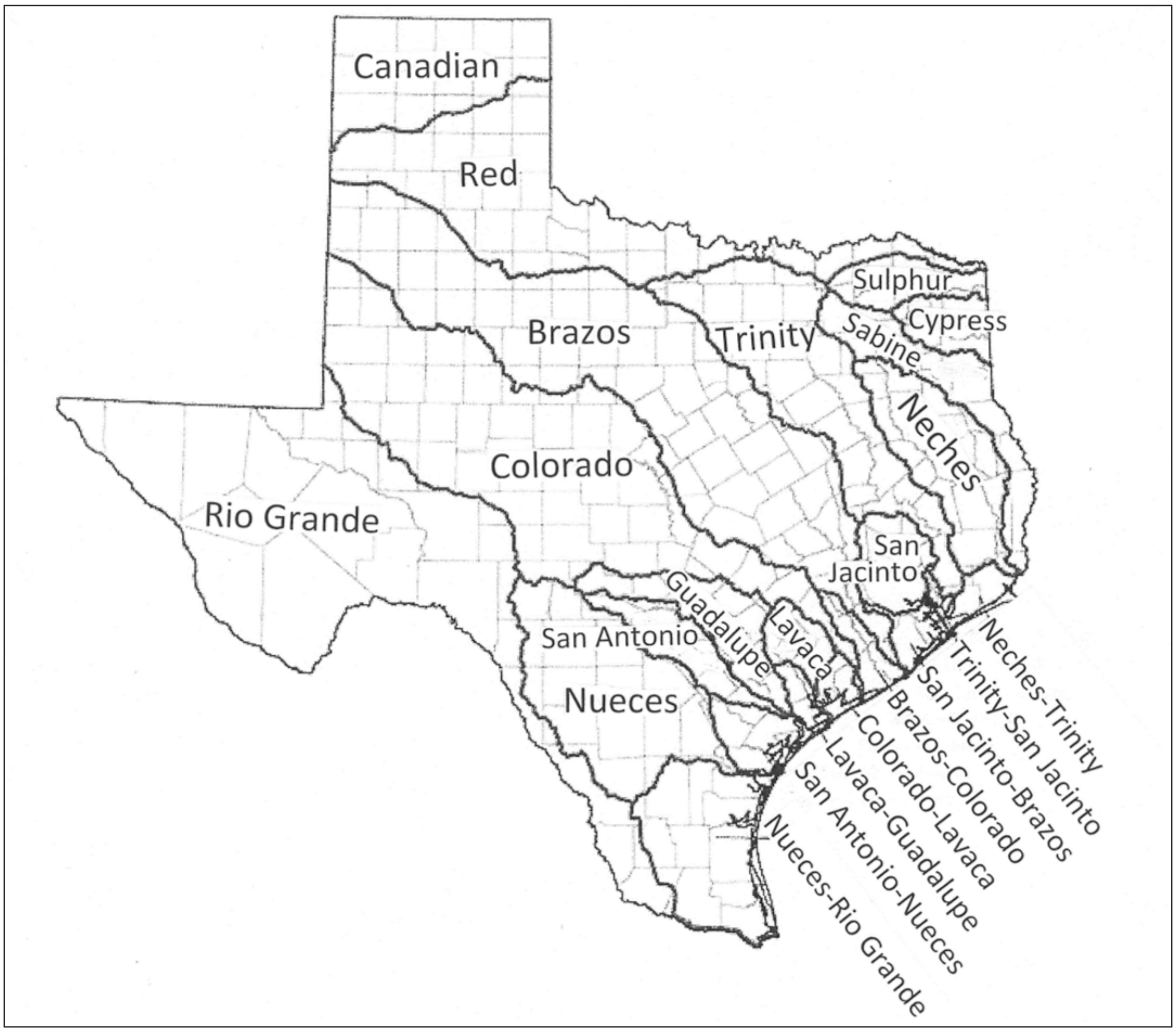

Figure 1. Texas river basins delineated by the TWDB.

alternative water use scenarios. The Center for Research in Water Resources at the University of Texas provided geographic information system (GIS) support in developing the WAM datasets.

The 15 major river basins and eight coastal basins of Texas delineated in Figure 1 are modeled as 20 WAMs. The Brazos River Basin and Brazos-San Jacinto Coastal Basin are combined as a single WAM. The Brazos-Colorado Coastal Basin is included in the Colorado River Basin WAM. The San Antonio River flows into the Guadalupe River and is included in the Guadalupe-San Antonio WAM. For the interstate and international river basins, hydrology and water management in neighboring states and Mexico along with interstate river basin compacts and treaties are considered to the extent necessary to assess water availability in Texas. Data for the full authorization scenario version of the WAMs as of 2014 are tabulated in Table 1, with six coastal basin WAMs combined as a single line for brevity (Wurbs and Zhang 2014).

Full authorization and current conditions scenario datasets, as well as supporting GIS data, are available from the TCEQ for each of the 20 WAMs. The full authorization scenario is based on the premise that all water right permit holders use the full amount of water to which they are legally entitled, subject to water availability. Return flows are not included in the full authorization scenario WAMs because return flows are not required by the water right permits. Permitted but not yet constructed projects are included. The current conditions scenario represents actual maximum annual use for each water right during a recent 10-year period and includes return flows and reservoir storage capacities reflecting updated estimates of sedimentation. The current use water supply demands are often smaller than the authorized use, which may include projected future use.

Model users modify the WAM datasets to reflect projected water needs, proposed projects, and management strategies of interest. The TWDB has developed WRAP simulation input

Table 1. Control points, water rights, and reservoirs in full authorization WAMs.

WAM	Number of Control Points		Model Water Rights		Number of Reservoirs	Capacity (acre-feet)
	Total	Primary	Number	(acre-feet/year)		
Rio Grande	957	55	2,584	2,228,870	113	3,499,070
Nueces	543	41	374	637,040	121	959,827
Guadalupe-San Antonio	1,338	46	848	420,780	238	756.527
Lavaca	185	8	70	61,620	22	167,718
Colorado	2,422	45	2,006	2,235420	518	4,709,829
Brazos	3,842	77	1,643	1,519,140	678	4,015,865
San Jacinto	412	17	150	520,360	114	587,529
Trinity	1,398	40	1,061	6,617,850	697	7,356,200
Neches	378	20	399	621,610	180	3,656,259
Sabine	387	27	321	550,280	212	6,262,314
Cypress	147	10	163	496,230	91	877,938
Sulphur	84	8	83	242,070	57	718,699
Red	448	47	507	860,600	247	3,780,342
Canadian	85	12	56	94,160	47	879,824
Six Coastal	775	47	316	267,900	125	184,660
Total	13,401	500	10,581	17,373,930	3,460	37,656,830

datasets representing projections of future water needs for use in planning studies.

In WRAP terminology, a water right is a set of water management capabilities and requirements for reservoir storage, water supply, instream flow needs, and/or hydroelectric energy generation. The simulation model provides considerable flexibility for defining water management and use requirements and capabilities. An actual water right permit may be represented by any number of model water rights representing various aspects of the permit. Model water rights are not necessarily required to be associated with a water right permit. The counts in Table 1 of model water rights with reservoir storage and/or water supply diversions total 10,581, which exceeds the total number of actual water right permits of about 6,200. The authorized annual water supply diversions for all of the water rights in the 20 WAMs as of 2014 totaled 17,373,930 acre-feet/year.

The TCEQ WAM datasets include all reservoirs associated with water right permits that authorize impoundment of state water inflows. A dam with storage capacity of up to 200 acre-feet can be constructed for domestic and livestock purposes without a permit. Water right permits are not required for flood control storage. The 80 reservoirs with conservation storage capacities exceeding 50,000 acre-feet account for about 92% of the permitted conservation capacity of the 3,460 reservoirs in the 20 WAMs of 37,656,830 acre-feet.

The spatial configuration of a river system is defined in the model by a set of control points, with the next downstream control point being specified for each control point. All reservoirs, diversions, return flows, hydropower plants, instream flow requirements, and other system components are assigned control point locations. Table 1 indicates that the 20 WAMs have a total of 13,401 control points, of which 500 are classified as primary. Primary control points are sites, usually U.S. Geological Survey (USGS) gaging stations, for which hydrologic period-of-analysis sequences of monthly naturalized streamflows are included in the simulation input datasets. Naturalized flows at all other control points are computed within the simulation from the naturalized flows at primary control points and watershed parameters included in the datasets.

The WAMs combine the authorized or current use scenario (or some modification thereof) for water management with historical natural river system hydrology. The TCEQ updates the water rights data in the WAMs as individual applications for new permits or revisions to existing permits are approved. The original hydrologic periods-of-analysis for naturalized streamflows and net reservoir evaporation-precipitation depths for most of the WAMs extend from 1940 or before through 1996, 1997, 1998, or 2000. Some of the hydrology datasets have been extended one or more times by the TCEQ or other agencies. The Sulphur and Colorado WAMs were recently updated by water management entities in those basins in cooperation with the TCEQ. In House Bill 723 in 2019, the Texas Legislature authorized the TCEQ to update the hydrology input datasets for the Rio Grande, Red, Neches, and Brazos WAMs. The TCEQ has contracted with consulting firms to perform these WAM hydrology updates, and the work is anticipated to be complete by August 2021. WRAP includes features for approximate preliminary hydrology updates between more detailed but less frequent updates.

The 2007 Senate Bill 3 (SB3) created a process for establishing environmental flow standards (EFS) and incorporating the standards in the WAMs. SB3 EFS are defined with subsistence, base, and high pulse flow components that vary seasonally and in some cases with hydrologic conditions. The EFS are inserted in the WAM datasets with a priority based on the date that the designated science team submits recommended EFS to the TCEQ for review and approval. Existing senior water right permit holders are not affected. SB3 EFS have been established for all river basins draining to the Gulf of Mexico within Texas. Periodic future updates to the EFS are anticipated with advances in instream flow science and management.

The routinely applied WRAP/WAM modeling system is based on a monthly computational time step. The latest expanded WRAP software and manuals include daily modeling capabilities with monthly-to-daily naturalized flow disaggregation, routing, forecasting, flood control reservoir operations, and instream flow standards with subsistence, base, and pulse flow components. The primary motivation for adding the daily modeling features is to support modeling water rights permit applications and regional planning studies that require a more refined approach to incorporating SB3 EFS in the WAMs. A strategy has been proposed for computing daily instream flow targets for SB3 EFS in daily WRAP simulations that are aggregated to monthly instream flow targets for incorporation in the input datasets for the routinely applied monthly WAMs (Wurbs and Hoffpauir 2016, 2021; Wurbs 2019c).

EVOLUTION AND APPLICATION OF THE WRAP MODELING SYSTEM

Development, improvement, and expansion of the WRAP modeling system has progressed continuously over many years and is still underway. Research to develop and improve modeling capabilities has been integrally intertwined with application of the resulting modeling system.

Texas A&M University Water Rights Analysis Program (TAMUWRAP)

The original version of WRAP, then called TAMUWRAP, was conceived in a 1986–1988 research project called Optimizing Reservoir Operations in Texas, sponsored by the cooperative federal/state cost-shared university research program of the USGS and TWRI, with the Brazos River Authority (BRA) serving as non-federal sponsor (Wurbs and Walls 1989). A simulation study of a 12-reservoir system operated by the USACE and BRA using HEC-5 (Hydrologic Engineering Center 1998) investigated multipurpose, multiple-reservoir system operations for improving water supply capabilities by sharing risk between reservoirs, combining regulated and unregulated flows and firm and secondary yields, and reallocation of storage capacity between purposes (Wurbs et al. 1988). The need for expanded capabilities for modeling basinwide interactions of numerous water rights became evident, leading to the creation of the TAMUWRAP model (Wurbs and Walls 1989).

Expanded versions of TAMUWRAP, since renamed WRAP, were developed in conjunction with research projects sponsored by the TWRI, TWDB, USACE, and Texas Advanced Technology Program. The expanded versions included improved system operations, optional salinity tracking (Wurbs et al. 1994, Wurbs and Sanchez-Torres 1996) and an alternative version based on network flow LP called WRAPNET (Yerramreddy and Wurbs 1996). The TCEQ, TWDB, TWRI, USACE, National Institute for Global Environmental Change, and other entities have since sponsored improvements to the modeling system and/or research studies addressing particular water management issues using WRAP as a modeling and analysis tool (Wurbs 2020b, 2021a).

Application of WRAP and the WAM modeling system in Texas

WRAP has been greatly improved and expanded since 1997 under the auspices of the TCEQ in conjunction with the TCEQ-led creation and improvement of the WAM system. A WRAP additions and revisions report maintained at the WRAP website describes the modifications that have occurred between the evolving editions of the software and manuals. Current TCEQ-sponsored research and development at TAMU is focused largely on improving capabilities for incorporating SB3 environmental flow standards in the WAMs and refining daily simulations.

The TCEQ maintains the WAM system in conjunction with administrating the water rights permit system to assess reliabilities of proposed actions. Reliabilities of existing water right permit holders are protected from additional new water use because the WAMs incorporate the priority system. TCEQ staff apply the modeling system during the process of reviewing applications for new water right permits or amendments to existing permits. Permit applicants and their consultants apply the WAMs during preparation of water right applications. The list of pending applications maintained at the TCEQ water rights permit website included 152 applications as of early June 2021. Permit applications are often relatively simple but can be very complex, as illustrated by the BRA system operations permit approved in November 2016.

A BRA system operations permit with an accompanying water management plan approved by the TCEQ in November 2016 significantly increased water supply capabilities based on a better understanding of reliability provided by the WAM. The amount of water supplied by BRA under contracts with customers is limited to the total amount allowed by its water right permits. Previous BRA water right permits were issued for individual reservoir projects near the time of their construction. Much of the total water use is from diversions in the lower basin that are significant distances below the dams and can be supplied by releases from multiple reservoirs, which facilitates managing risk of shortages by balancing storage drawdowns. The new permit allows the BRA to use unregulated flow entering the river system below the dams along with releases from 11 reservoirs to supply its customers. Contracts can commit different levels of reliability called firm and interruptible for different types of water use and available alternative backup sources of supply and demand management plans. For example, municipal water supply commitments may be based on the conventional concept of firm yield while agricultural irrigation commitments may be based on lower levels of reliability with greater likelihood of interruption during droughts.

The TWDB and regional planning groups or their consultants apply the WAMs in the regional water planning process established by the 1997 SB1. Sixteen regional plans developed by planning groups and a consolidated statewide plan developed by the TWDB in collaboration with the water management community are updated in a 5-year planning cycle with a 50-year future planning horizon (TWDB 2017). The 2002, 2007, 2012, and 2017 water plan reports are available at the TWDB website, and work on the 16 updated 2021 regional plans and 2022 statewide plan is underway.

River authorities and other entities apply the WAMs in operational planning, project feasibility studies, and other endeavors. The modeling system also supports environmental flow studies, research investigations, and other water management activities. The National Wildlife Federation applied the WAMs to study freshwater inflows to the estuaries of Texas (Johns et al. 2004). The USACE has explored use of the modeling system in the federal Section 404 regulatory program (CDM Smith 2016). The USGS combined the Guadalupe WAM with the Soil and Water Assessment Tool (SWAT) watershed model to assess increases in water supply in Canyon Lake resulting from different brush management strategies (Asquith and Bumgarner 2014).

The Texas Water Conservation Association Surface Water Committee WRAP/WAM Subcommittee and other stakeholders provide feedback to the TCEQ and its TAMU contractor regarding water management issues and needs for expanded modeling and analysis capabilities and review research and development products. Eleven WRAP user group conferences held since 2006 have been attended by water professionals from the TCEQ, TWDB, river authorities, other agencies, engineering firms, and universities.

University research investigations of water management issues

Appendix A of the WRAP Reference Manual (Wurbs 2021a) is a *Bibliography of WRAP Related Publications* that includes 10 Ph.D. dissertations, 19 M.S. theses, and many technical reports, journal papers, and conference papers derived from research at TAMU. Several of the research studies performed at TAMU are noted as follows.

The effects of long-term future climate change associated with global warming on water availability in the San Jacinto and Brazos River Basins and adjoining coastal basin were modeled by combining WRAP with the SWAT watershed rainfall-runoff modeling system and output from a global circulation model maintained by the Canadian Center for Climate Modeling and Analysis (Muttiah and Wurbs 2005, Wurbs et al. 2005). The potential for incorporating indices of the El Niño Southern Oscillation or other multiple-year climatic cycles in forecasting short-term future water availability was investigated by Bista (2015) using WRAP short-term conditional reliability modeling features.

The SWAT modeling system was investigated but not adopted for use in transferring WAM monthly naturalized flows from gaged to ungaged sites (Wurbs 2006). Ryu (2015) investigated the use of SWAT to develop daily streamflow input data for the daily WRAP.

The salinity simulation component of WRAP was applied to investigate the impacts on water supply capabilities of natural salt pollution from geologic formations in the upper Brazos River Basin (Wurbs and Lee 2009, 2011). Natural salt pollution in the upper watersheds of several Texas river basins significantly constrain the use of water from many large reservoirs.

The 20 WAMs were used in a statewide investigation of reservoir evaporation, which was found to be a very large component of reservoir water budgets (Wurbs and Ayala 2014). Wurbs and Zhang (2014) employed WRAP and the WAMs in a statewide investigation of hydrologic characteristics of Texas river basins. Wurbs (2021c) explored statewide reservoir operations.

Hoffpauir (2010) researched and developed daily modeling methods for incorporation into WRAP. Wurbs and Hoffpauir (2013, 2016) and Pauls and Wurbs (2016) modeled SB3 environmental flow standards with the daily WRAP. Demirel and Wurbs (2017) modeled reservoir storage reallocations between flood control and water supply using the daily WRAP.

WRAP has been applied by researchers and practitioners, mainly in university research studies, in other countries and other states in the United States but not nearly to the extent as in Texas. The following publications report academic research in other countries. Koch and Grunewald (2009) present simulation results comparing WRAP and the WBalMo modeling system developed by the Danish Hydraulic Institute from the perspective of the European Water Framework Directive without concluding which of the two modeling systems is advantageous. Chen and Chan (2007), Zhang et al. (2010), and others have applied WRAP to river systems in China. Kim and Kim (2016) employed WRAP to establish operating plans for the Soyang Reservoir in Korea.

The author of this paper presented 5-day WRAP workshops for groups of professionals from multiple water management agencies in Armenia and Peru in conjunction with consulting projects sponsored by the U.S. Agency for International Development and National Institute of Development of Peru with the objective of implementing WRAP in those two countries. Limitations in institutional capabilities were found to be a key constraint to implementation of computer modeling systems in support of actual water management endeavors.

WRAP CAPABILITIES AND ORGANIZATION

WRAP simulation studies combine a specified scenario of river/reservoir system management and water use with hydrology represented by sequences of naturalized streamflows and reservoir evaporation, minus precipitation rates at pertinent locations, for each monthly or daily interval of a hydrologic period-of-analysis. Model application includes the following:

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

Simulation input datasets for alternative scenarios have been developed 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 management strategies. WRAP applications outside of Texas require compilation of input datasets.

Applications range from simple to very complex. For example, the Lavaca-Guadalupe coastal basin WAM has only 10 water rights and no reservoirs. Wurbs (2019c) presents a simulation study comparing WRAP monthly simulation model (SIM) and WRAP daily simulation model (SIMD) results from the Brazos WAM with 680 reservoirs and over 2,400 model water rights.

WRAP software and manuals

The modeling system consists of a set of executable programs developed primarily in Fortran and documented in detail by a set of manuals. The latest versions of the WRAP executable programs, manuals, and other supporting materials can be downloaded free-of-charge from the WRAP website.

WinWRAP is a user interface for managing programs and data files in Microsoft Windows®. The other executable programs perform the four functions outlined below.

1. Development of hydrology input data for the simulation model
   - The WRAP hydrology data compilation program (HYD) develops and updates SIM input files containing monthly naturalized streamflows and reservoir evaporation minus precipitation rates.
   - The WRAP daily flow parameter calibration program (DAY) is used to calibrate routing parameters and otherwise compile daily hydrology input data for SIMD.
   - HEC-DSSVue reads, creates, and manages DSS files of time series data, plots the data, and performs frequency analyses and mathematical operations.
2. Simulation of the river/reservoir/water use system
   - SIM performs simulations using a monthly computational time step.
   - SIMD performs simulations using a daily computational time step.
3. Tracking salinity loads and concentrations through the river/reservoir system
   - The WRAP salinity simulation model (SALT) performs a salinity simulation by combining SIM simulation results with salinity input.
4. Organization and analyses of simulation results
   - The WRAP data organization and analysis program (TABLES) reads SIM, SIMD, and SALT simulation results, performs frequency and reliability analyses, and creates a variety of tables in user-selected formats to organize, summarize, and display simulation results.
   - HEC-DSSVue reads DSS files of simulation results or any other time series data, organizes the data, prepares plots, and performs statistical analysis.

The WRAP executable programs are documented by Reference, Users, Fundamentals, Hydrology, Salinity, and Daily Manuals (Wurbs 2021a, b, Wurbs 2019a, b, 2009; Wurbs and Hoffpauir 2021). The Reference Manual provides an overview of the modeling system and describes modeling and analysis concepts and methods. Logistics of applying SIM, SIMD, and TABLES are explained in the User's Manual. Additional daily features are covered in the Daily Manual. HYD and SALT are documented in the Hydrology and Salinity Manuals. Input datasets for the many examples in all of the manuals are available at the WRAP website along with the software and manuals.

The Fundamentals Manual provides a condensed tutorial of basics from the Reference and User's Manuals, employing a hypothetical but realistic example WAM with 11 control points, six reservoirs, 30 water rights, and a 1940–2018 hydrologic period-of-analysis. Several of the examples in the other manuals build upon and expand the example in the Fundamentals Manual. The Fundamentals Manual also describes the WinWRAP user interface.

HEC-DSS and its HEC-DSSVue interface are integral components of WRAP. The HEC-DSSVue software and user's manual (HEC 2009) are available at the HEC website. WRAP use of DSS and HEC-DSSVue to manage and analyze time series input and simulation results is explained in the WRAP User's Manual.

Conventional, firm yield, salinity, and short-term CRM modes

In the conventional long-term simulation mode applied in planning studies and evaluation of water right permit applications, a specified water management/use scenario is combined with naturalized flows and net reservoir evaporation rates covering the entire hydrologic period-of-analysis in a single or dual simulation. A dual simulation option in SIM/SIMD is useful in modeling multiple rights with different priorities associated with the same reservoir. Program SIM simulation results consist of hydrologic period-of-record sequences of monthly streamflows, reservoir storage, diversions, diversion shortages, and other quantities. The programs TABLES and HEC-DSSVue are used to perform reliability and frequency analysis, prepare time series plots, and otherwise organize, analyze, and summarize the SIM or SIMD time series results.

Program SIM has a feature that automatically repeats the complete hydrologic period-of-analysis simulation many times in a search for a firm yield. With the SIM yield-reliability option, one or more selected diversion rights start with a specified target that is iteratively incremented until the firm yield is reached. Options are also provided for computing safe yield versions of firm yield based on defined water supply reserves.

The WRAP program SALT reads a SIM simulation results file and salinity input file and tracks salinity loads and concentrations through the river/reservoir system. Frequency analysis and time series plots of simulated concentrations support assessments of the impacts of salinity on supply capabilities for alternative water management plans. The program SALT is documented by the Salinity Manual (Wurbs 2009). Wurbs and Lee (2009, 2011) demonstrate the salinity simulation features of WRAP in an investigation of natural salt pollution in the Brazos River Basin.

Conditional reliability modeling (CRM) is an alternative to the conventional long-term simulation mode. CRM supports short-term drought management and operational planning activities in which consideration of preceding reservoir storage levels is important. An array of options are provided for organizing CRM simulations and analyzing the simulation results. A CRM version of the example in the Fundamentals Manual is presented in the Reference Manual. Wurbs et al. (2012) demonstrate and explore various CRM options using the Brazos WAM.

In the short-term CRM mode, water availability over the next several months or one or more years is probabilistically conditioned on preceding reservoir storage. The hydrologic period-of-analysis is divided into many sequences within SIM, and the simulation is automatically repeated with each hydrologic sequence starting with the same specified initial reservoir storage contents. TABLES develops frequency tables from the SIM results showing the likelihood of reservoir storage contents exceeding various levels any number of months in the future given preceding storage levels. Flow frequency and water supply reliability metrics are also computed.

SIMULATION OF RESERVOIR/RIVER SYSTEM WATER MANAGEMENT

Hydrology input for the simulation model SIM consists of sequences of naturalized streamflows at primary control points and reservoir evaporation minus precipitation rates. The daily SIMD input dataset also includes daily flow pattern hydrographs used by SIMD to disaggregate monthly naturalized flows to daily while preserving the monthly volumes.

Watershed parameters for delineating incremental sub-watersheds and applying alternative flow distribution options are used in synthesizing naturalized monthly or daily flows at secondary control points. Total and/or incremental watershed areas are used in all the WRAP SIM/SIMD flow distribution options. Channel loss factors, curve numbers, and/or mean annual precipitation are also included as input parameters for some of the options. Although curve numbers and mean annual precipitation depths were compiled in the original development of the TCEQ WAMs, none of the WAMs currently adopt the SIM/SIMD flow distribution options requiring curve numbers and mean annual precipitation depths.

In WRAP terminology, sets of simulation model input information describing reservoirs and other constructed facilities, water use, management practices, and permit requirements are collectively called "water rights." Water right data and specifications input to the model include the following:

- locations of system components by control point;
- priority specifications;
- water supply diversion, instream flow, and hydroelectric energy targets for each of the 12 months of the year and optional specifications for varying the water use targets as a function of reservoir storage contents or streamflow;
- seasonal or annual limits on diversions, reservoir releases, or flow depletions;
- return flow specifications in various optional formats;
- conveyance of flow through pipelines and canals;
- reservoir operating rules including multiple-reservoir system operations, multipurpose operations, multiple-owner reservoirs, and off-channel storage;
- reservoir storage volume, surface area, and elevation relationships as tables or coefficients; and
- specifications for recording time series simulation results for control points, reservoirs, water rights, or specified groups of related water rights.

Simulation results include quantities for many variables computed in the simulation for each month or day of the hydrologic period-of-analysis. The model-user selects the control points, water rights, reservoirs, and the variables for which simulation results are recorded. Output variables include but are not limited to:

- naturalized, regulated, and unappropriated flows, streamflow depletions, return flows, and channel loss quantities for each selected control point;
- reservoir storage volume, net evaporation-precipitation, inflows, releases, diversions, and hydroelectric energy at each selected reservoir;
- diversion targets and shortages, return flows, available flows, flow depletions, and storage for each selected water supply right;
- hydropower targets, firm energy produced, secondary energy produced, energy shortages, and storage for each selected hydropower right; and
- instream flow target and shortage for each selected instream flow right.

Simulated naturalized, regulated, and unappropriated streamflow

A SIM or SIMD simulation generates period-of-analysis sequences of naturalized, regulated, and unappropriated streamflows at each control point. The program HYD facilitates developing naturalized flows by adjusting sequences of observed monthly flows at gaging stations to remove the historical effects of water resources development and management. SIMD disaggregates monthly naturalized flows to daily based on daily pattern flow hydrographs while preserving monthly volumes. SIM and SIMD include methods for transferring monthly or daily naturalized flows from gaged to ungaged control points (Wurbs 2006, 2021a).

A simulation begins with naturalized flows consisting of past streamflows adjusted to represent natural conditions with no human impact or some defined level of development. Adjusting observed streamflow to remove absolutely all effects of people is not feasible for developed river basins. For the WAM system, naturalized flows are ideally flows that would have occurred historically without the water management activities reflected in the water rights input data, but with all other aspects of the river basin reflecting constant defined conditions.

Regulated and unappropriated flows computed by SIM or SIMD reflect adjustments to naturalized flows for water right requirements representing a specified scenario of water resources development and use. Regulated flows are physical flows considering all water rights in the input dataset. Unappropriated flows are available for further appropriation after all the water rights receive their allocated share. Regulated flows may be greater than unappropriated flows due to instream flow requirements at the site or commitments to other rights at downstream control points.

Streamflow depletions are the quantities of water appropriated to meet water supply diversion requirements and refill reservoir storage. Diversion return flows, return flows from groundwater or other supply sources, and reservoir releases are added to streamflows. Channel losses are considered as flow adjustments are cascaded downstream. Daily flow adjustments are lagged and attenuated in an optional SIMD routing algorithm.

For example, naturalized flows at 40 primary control points stored in the Trinity WAM input dataset are distributed to 1,363 other secondary control points with each execution of SIM or SIMD. The simulated regulated and unappropriated flows computed in each of the 948 months or 28,855 days of the 1940–2018 simulation at each of the 1,403 control points reflect the effects of 1,057 model water rights with 697 reservoirs.

Observed and naturalized 1940–2018 monthly and annual flows of the Trinity River at the USGS gage near the Romayor, Texas, plotted in Figures 2 and 3, illustrate the tremendous variability that is characteristic of streamflow throughout Texas. This gage is located 20 miles below Livingston Dam and 50 miles above the Trinity River outlet at Galveston Bay. Annual summations of naturalized flows, regulated flows, unappropriated flows, and instream flow targets for SB3 EFS at this site from a monthly simulation are compared in Figure 4 (Wurbs 2019d). The targets for SB3 EFS include only flows in the river at the gage site. The freshwater inflow into Galveston Bay component of the SB3 EFS is not included in the model.

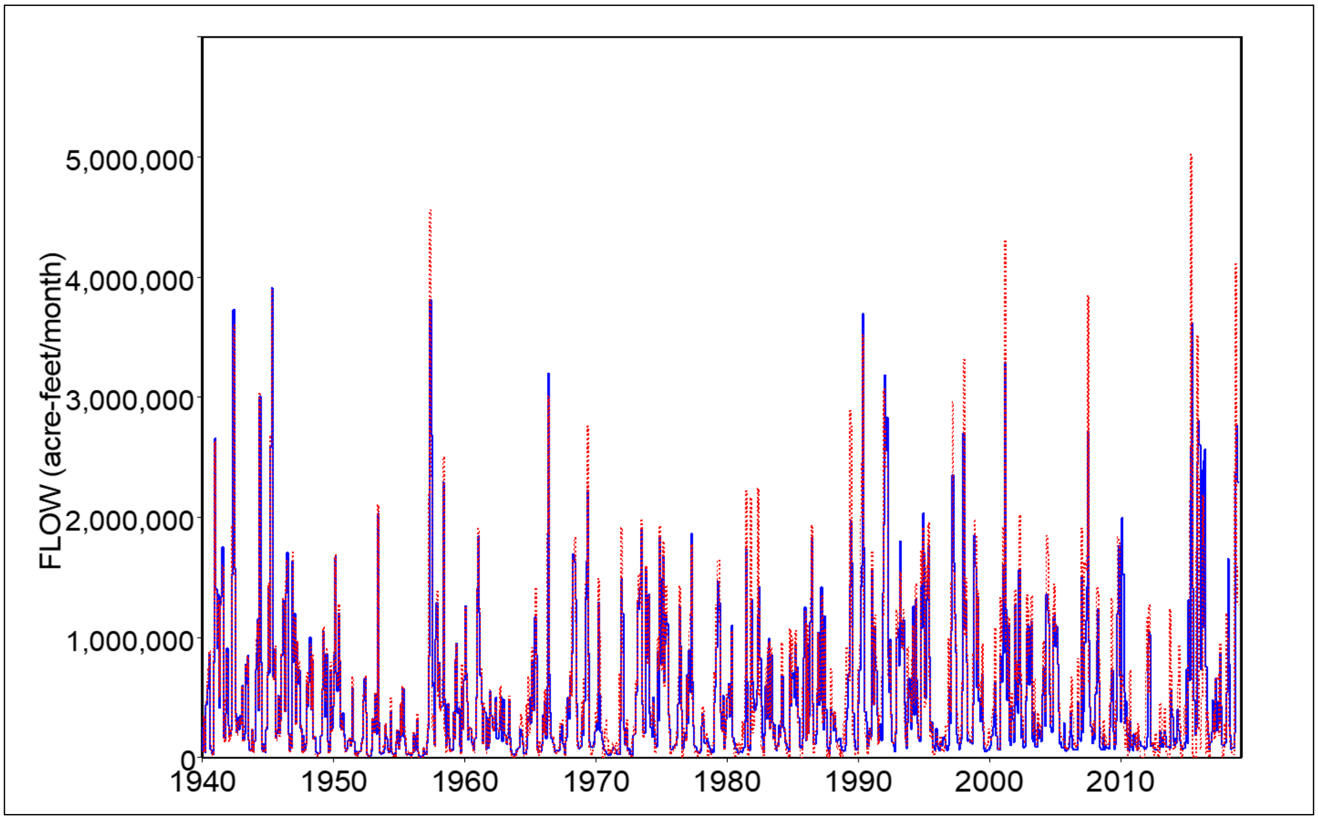

Figure 2. Monthly observed (blue solid line) and naturalized (red dotted line) flows of the Trinity River at Romayor.

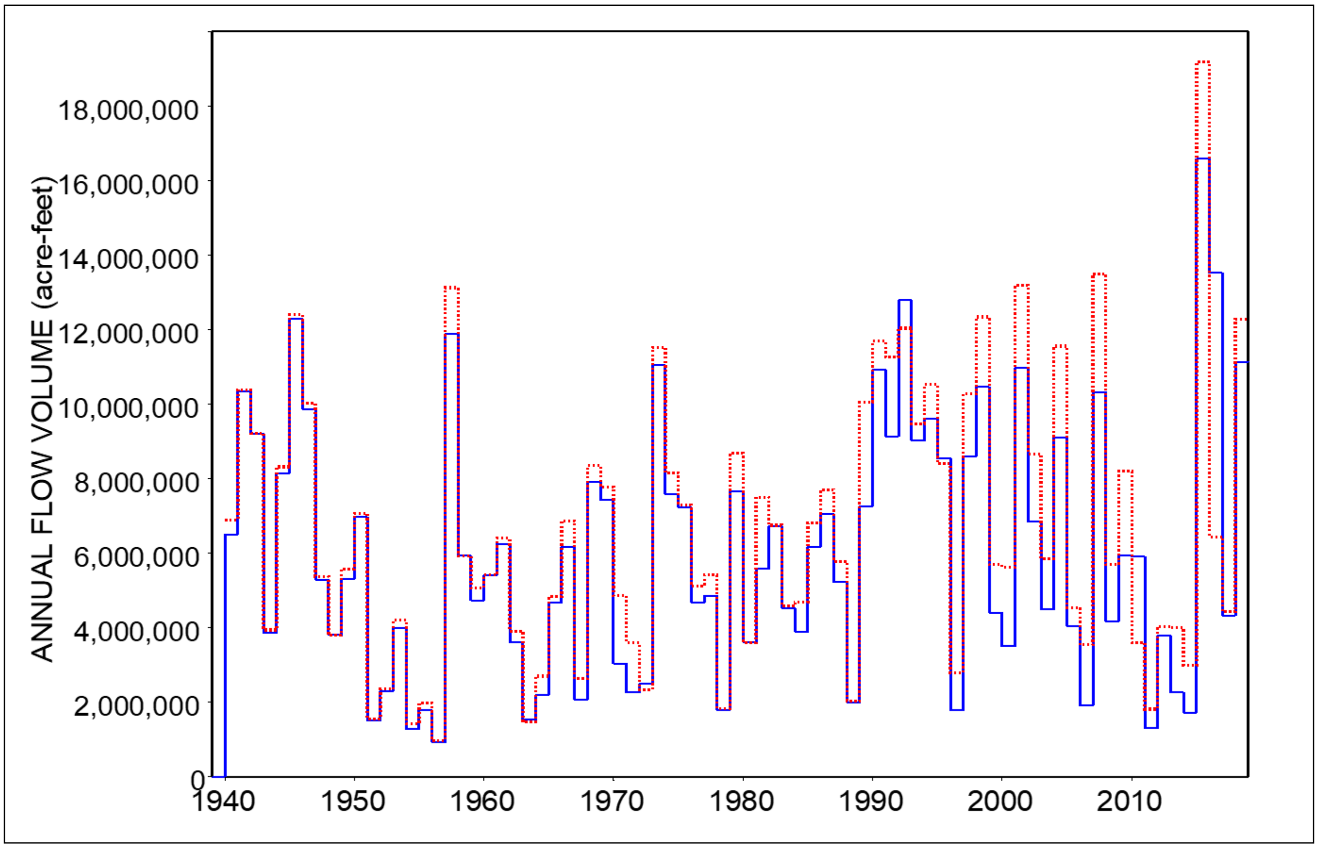

Figure 3. Annual observed (blue solid line) and naturalized (red dotted line) flows of the Trinity River at Romayor.

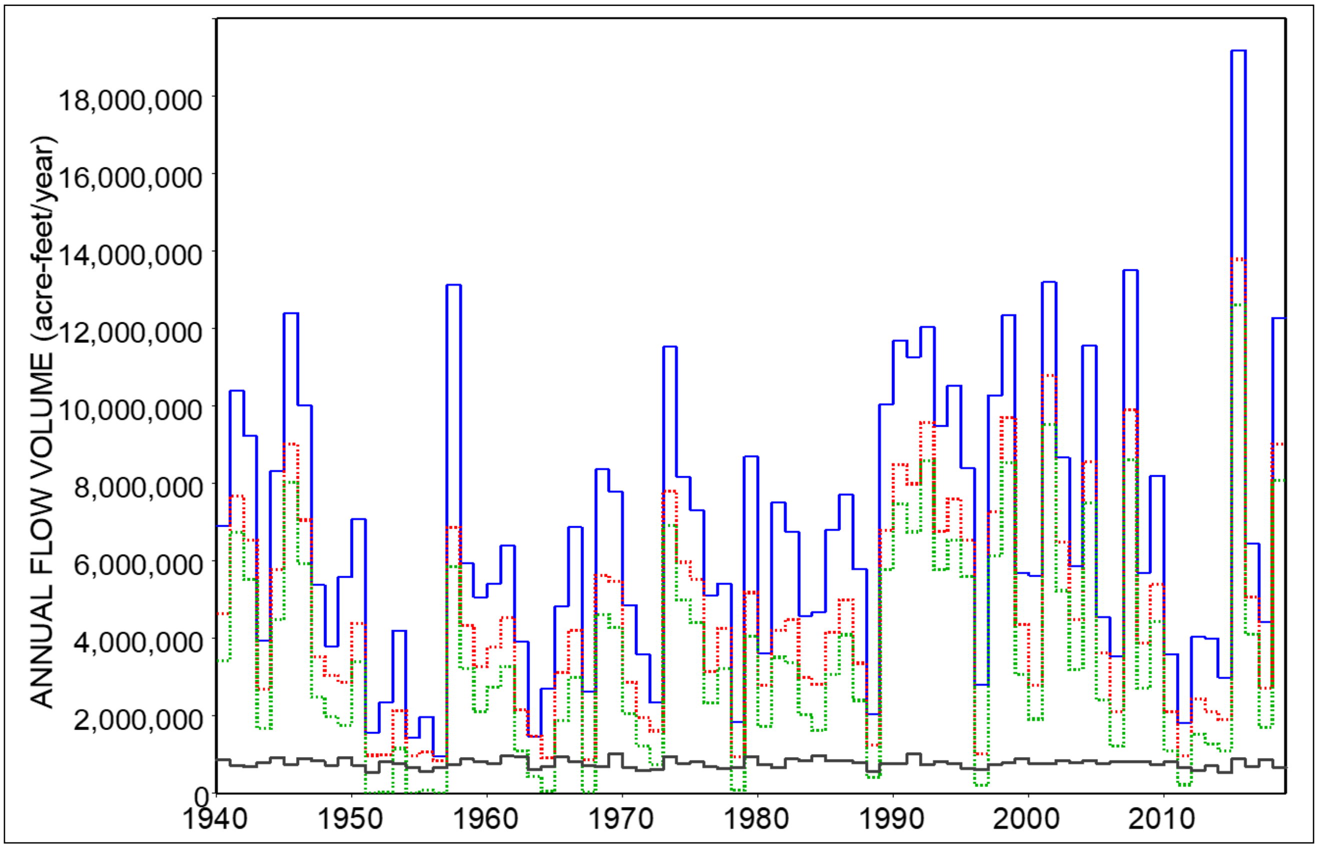

Figure 4. Annual naturalized flows (blue solid), regulated flows (red dotted), unappropriated flows (green dotted), and SB3 instream EFS Targets (black solid) for the Trinity River at Romayor.

Stepping through the time sequence and water rights priority sequence

SIM simulation computations are performed in a water rights priority loop embedded within either a monthly or daily time step loop. Model execution begins with reading and organizing input data. Water rights are sorted into priority order. The simulation steps through time. Naturalized flows for primary control points and net evaporation rates for reservoirs are read. Flows are distributed from primary control points to all other sites based on watershed parameters. Within each sequential month or day, water accounting computations are performed as each set of water use requirements (water right) is considered in priority order.

Priority numbers included in the SIM input datasets for each water right serve as the primary method for specifying priorities. A small priority number represents a more senior priority than a larger priority number. Only relative seniority is relevant. The Texas prior appropriation water rights system is based on including priority dates in the water right permits. A permit priority date of May 8, 1965, for example, is expressed as the priority number 19650508 in the SIM input dataset. This number is larger than the numbers for senior dates and smaller than the numbers for junior dates. However, other priority numbers may be assigned to water rights. For example, an assigned priority number of 9999999 makes a water right junior to all water rights with priorities based on dates. The SIM simulation model also includes an option for automatically assigning water right priorities in upstream-to-downstream order.

Water allocation and management are modeled by accounting procedures within the water rights priority loop. An array is maintained of streamflow available for appropriation at all control points. As each water right is considered in priority order, the following four tasks are performed:

1. The diversion, instream flow, or hydropower target is set starting with an annual amount and 12 monthly distribution factors provided as input. The target may be further modified as a function of the: storage content in any number of specified reservoirs; naturalized, regulated, or unappropriated flow at any control point; or other variables.
2. The amount of streamflow available to the water right is determined considering available flows at the control point of the water right and all downstream control points.
3. Water use requirements are met subject to water availability following specified system operating rules. Water

accounting computations are performed to determine the diversion, diversion shortage, end-of-month storage, and related quantities. Reservoir evaporation and hydroelectric power generation depend on both beginning-of-month and end-of-month storage and thus necessitate an iterative algorithm.

4. The available streamflow is adjusted for the control point of the water right and all downstream sites to reflect the effects of the water right. Channel loss factors are applied in translating adjustments for streamflow depletions and return flows to downstream sites.

Daily modeling system

The routinely applied WRAP and WAMs employ a monthly time interval. The daily simulation model SIMD has all capabilities of the monthly SIM plus the following additional features, used only in a daily simulation:

- disaggregation of monthly naturalized flows to daily using daily pattern hydrographs while preserving monthly volumes
- disaggregation of water use targets
- routing of streamflow adjustments to reflect lag and attenuation effects
- forecasting of future flows over a specified forecast period to protect senior downstream rights and support reservoir flood control operations
- simulation of flood control system operations of systems of any number of reservoirs
- simulation of high pulse flow environmental flow requirements

Wurbs (2019c, 2019d, 2020a) converted monthly Brazos, Trinity, and Neches WAMs to daily in research at TAMU sponsored by the TCEQ. The primary objective was to improve capabilities for modeling environmental flow standards (EFS) that have been developed pursuant to the TCEQ-managed process established by the 2007 SB3. The EFS include subsistence, base, and high flow pulse components that may vary seasonally and/or with hydrologic condition.

A modeling strategy was employed that is based on developing daily EFS instream flow targets in a SIMD simulation that are summed to monthly quantities within SIMD. The monthly instream flow targets from the daily SIMD simulation are incorporated in the SIM input dataset. This procedure works well from the perspective of modeling the appropriation of streamflow for the EFS and the impacts on other water rights that are junior to the EFS. However, EFS shortages as well as targets are important in studies assessing capabilities for meeting the EFS. Shortages in meeting the daily targets are normally assessed directly from the daily simulation results.

Various modeling issues were investigated in simulation studies performed in conjunction with creating the daily Brazos, Trinity, and Neches WAMs. The basic advantage of the daily computational time step is capturing the within-month variability of daily streamflow. Daily SIMD modeling is much more complex than monthly SIM modeling due primarily to SIMD routing, forecasting, and other options that may or may not be warranted for particular applications. Wurbs (2019c, 2019d, 2020a) outlines considerations in selecting an optimal set of SIMD options that achieve the objectives of a particular application while eliminating unnecessary complexity.

TWDB staff and consulting firms employed by the TWDB are applying modified versions of the Brazos, Trinity, and Neches daily WAMs during 2021 to assess capabilities for meeting SB3 EFS and the impacts of the EFS on water availability for supplying other growing water needs. Daily modeling studies are expected to extend to other river basins in the future.

Simulated reservoir storage as a measure of water supply capabilities

Many alternative simulations with the daily and monthly Brazos, Trinity, and Neches WAMs, with different options activated, are presented in three technical reports in a comparative exploration of alternative modeling methods (Wurbs 2019c, 2019d, 2020a). The selected final simulations described in the reports are adopted for Figures 2, 3, 4, 5, 6, and 7 and Table 2 of this paper. The Brazos, Trinity, and Neches WAMs employed in these simulation studies have hydrologic periods-of-analysis of 1940–2017, 1940–2018, and 1940–2019, respectively.

HEC-DSSVue plots of reservoir storage computed in monthly SIM and daily SIMD full authorization scenario simulations are presented in Figures 5, 6, and 7. A specific water right with a single reservoir or multiple-reservoir system is of interest in most applications of the modeling system. However, summations of end-of-month and end-of-day storage contents of all reservoirs in the WAMs are plotted in Figures 5, 6, and 7, reflecting a broader basinwide perspective for the brief discussion in this paper. Storage fluctuations in individual reservoirs tend to be greater than the basinwide totals. Timing differences in storage depletions result in summations of storage volumes in multiple reservoirs being averaged out to some extent.

Texas has thousands of dams/reservoirs, but most of the storage capacity is contained in a relatively small number of very large projects. The 210 major reservoirs in Texas with water right permits and storage capacities of 5,000 acre-feet or greater contain 98.0% of the total capacity of the 3,460 reservoirs in the 20 full authorization WAMs (Wurbs 2021c).

The full authorization Brazos, Trinity, and Neches WAMs referenced in this discussion have 680, 697, and 180 reservoirs, respectively, with authorized conservation storage capac-

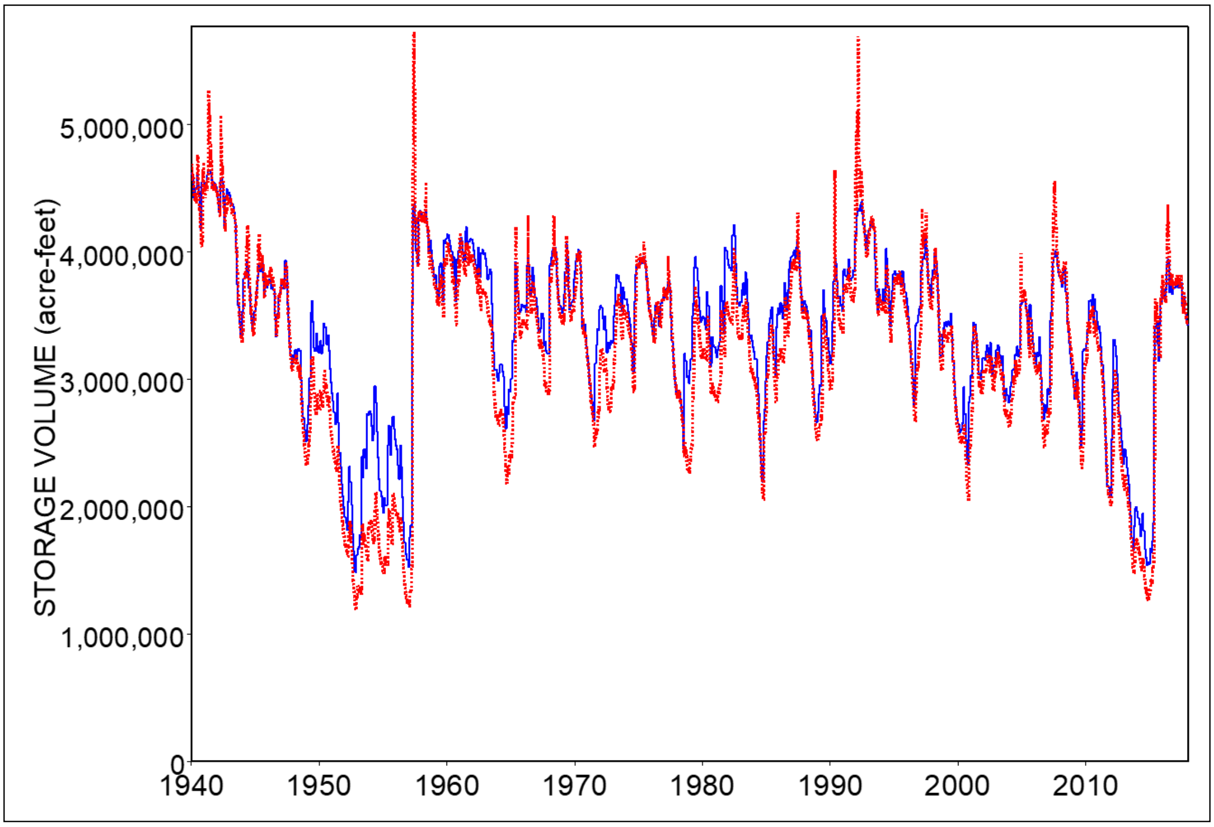

Figure 5. Storage contents of 680 reservoirs in the Brazos WAM from monthly SIM (blue solid) and daily SIMD (red dotted) simulations.

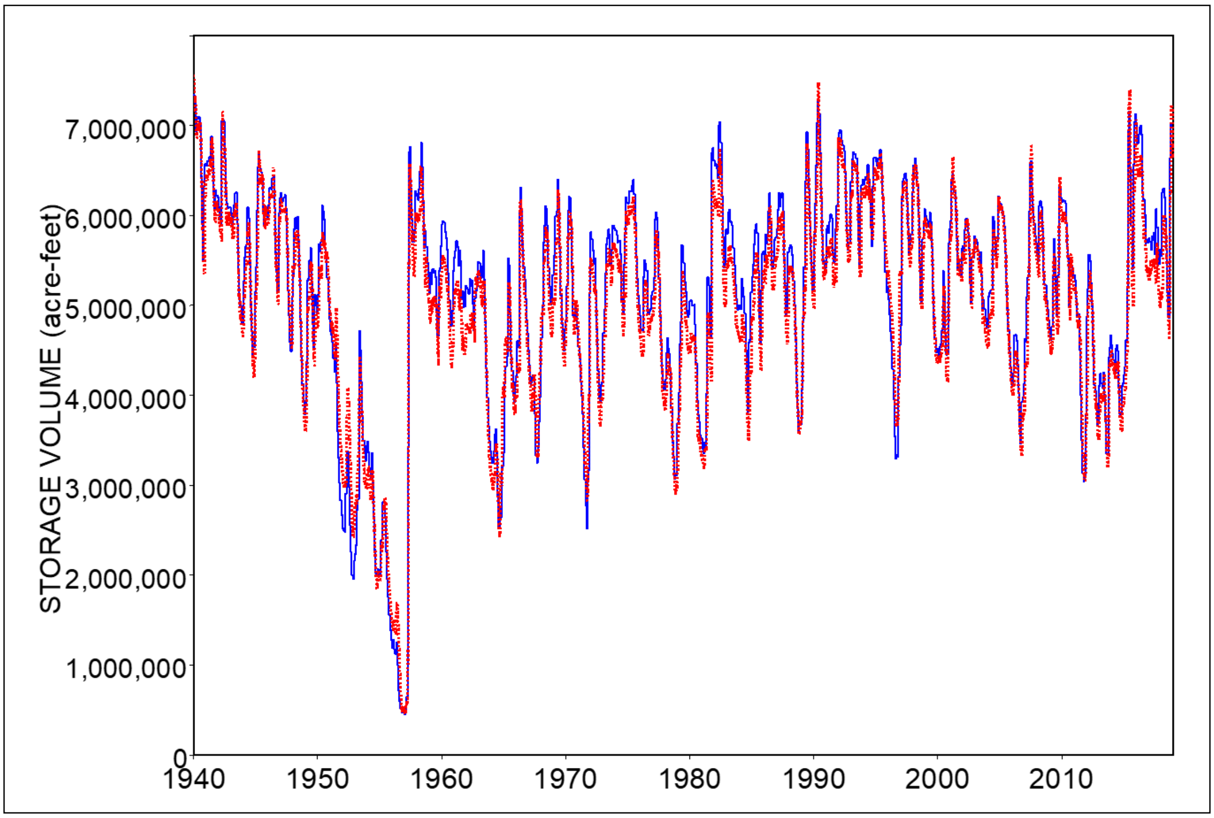

Figure 6. Storage contents of 697 reservoirs in the Trinity WAM from monthly SIM (blue solid) and daily SIMD (red dotted) simulations.

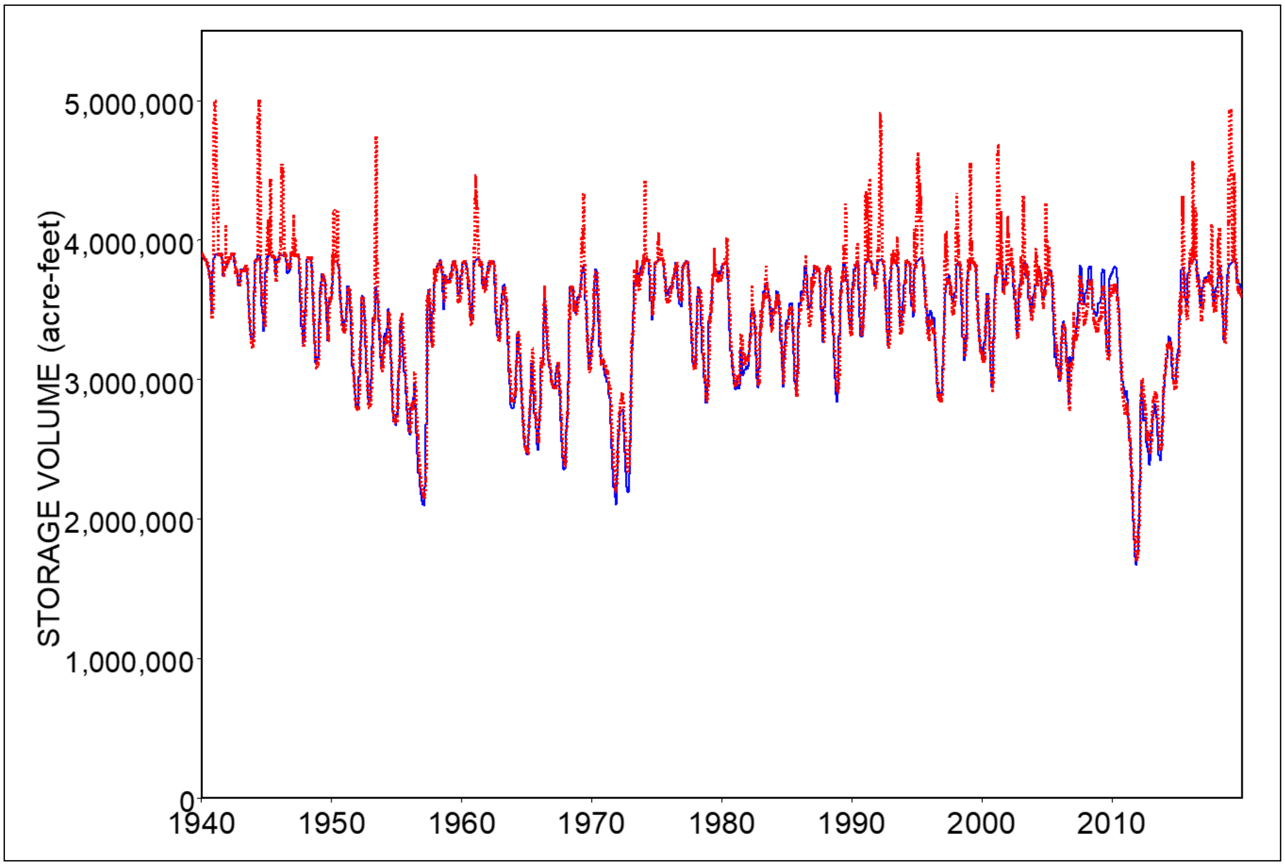

Figure 7. Storage contents of 180 reservoirs in the Neches WAM from monthly SIM (blue solid) and daily SIMD (red dotted) simulations.

ities totaling 4,746,300 acre-feet, 7,356,200 acre-feet, and 3,904,100 acre-feet. Flood control pools are not included in water right permits and the monthly WAMs. The daily Brazos, Trinity, and Neches WAMs include USACE flood control pools in nine, eight, and one multipurpose reservoirs, respectively. The volume of water in storage provides an insightful drought index and metric of water availability.

The simulations are based on the premise that all permitted water right holders store and divert the full amounts of water authorized by their permits during a hypothetical (computational) repetition of past hydrologic period-of-analysis natural hydrology. The storage plots of Figures 5, 6, and 7 illustrate the need for a long hydrologic period-of-analysis for a meaningful assessment of water supply capabilities. Most of the reservoirs were constructed during the 1960s or later. Almost none of the reservoir storage capacity and associated water needs existed during the 1950–1957 drought, which was the most hydrologically severe drought since before 1940 for the Brazos and Trinity River Basins. This drought began gradually during 1950 and ended with major widespread flooding during April–June 1957. Water users and managers have never experienced a drought as hydrologically severe as 1950–1957 with present conditions of population, economic development, and water resources development in these river basins.

The storage plots also provide a comparison of the three river basins. The Neches River Basin has more abundant water resources relative to demand than the Trinity and Brazos River Basins. The timing and severity of droughts is also different for the Neches. The minimum total storage contents of the 180 reservoirs the SIMD simulation is 43.4% of water supply storage capacity occurring on December 3, 2011. Sam Rayburn Reservoir contains 74.2% of the authorized storage of the 180 reservoirs and is the only reservoir with a flood control pool added in the daily model. Storage in the flood control pool is evident in Figure 7. Likewise, USACE flood control operations of nine and eight large multiple purpose reservoirs in the Brazos and Trinity River Basins are reflected in the daily simulations of Figures 5 and 6.

Figures 5, 6, and 7 also provide a comparison of water availability for daily versus monthly simulations. Differences are due to combinations of various aspects of the simulations.

Frequency analyses of reservoir storage volumes differ from streamflow in regard to effects of different time intervals. End-of-month and end-of-day storage volumes are defined at an

Table 2. Statistics for monthly SIM and daily SIMD naturalized (Nat), regulated (Reg), and unappropriated (Una) flows of the Trinity River at Romayor in cubic feet per second (cfs).

	Monthly SIM Simulation			Daily SIMD Simulation		
	Nat (cfs)	Reg (cfs)	Una (cfs)	Nat (cfs)	Reg (cfs)	Una (cfs)
Mean	9,129	5,986	4,361	9,114	6,204	4,790
Standard Deviation	11,162	8,692	8,710	14,100	11,826	11,748
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
99%	0.00	141	0.00	0.00	0.00	0.00
98%	78.5	415	0.00	53.3	0.00	0.00
95%	275	730	0.00	225	0.00	0.00
90%	585	1,026	0.00	479	0.00	0.00
85%	922	1,132	0.00	723	504	0.00
80%	1,391	1,196	0.00	1,017	834	0.00
75%	1,831	1,370	0.00	1,336	1,016	0.00
70%	2,283	1,513	0.00	1,688	1,127	0.00
60%	3,337	1,897	0.00	2,506	1,434	0.00
50%	4,734	2,288	0.00	3,712	1,891	0.00
40%	7,158	2,668	662	5,638	2,383	0.00
30%	10,593	4,742	3,060	8,826	3,727	1,692
25%	12,264	6,994	4,730	11,052	5,658	3,532
20%	15,349	9,295	7,935	13,908	8,323	6,211
15%	19,038	12,570	10,880	17,770	11,856	10,026
10%	23,251	15,782	14,720	23,871	17,339	15,568
5%	31,122	23,746	22,376	35,660	28,263	26,930
2%	44,629	35,241	33,309	53,662	45,412	44,172
1%	55,634	45,082	43,400	69,862	60,139	58,838
Maximum	81,644	66,272	64,551	204,661	183,101	182,476

instant in time. Flow quantities represent averages over a time interval, which are different for monthly versus daily intervals. Daily flows are more variable than monthly flows, which is not necessarily the case for 28,855 daily versus 948 monthly storage volumes in a 1940–2018 simulation.

FREQUENCY AND RELIABILITY ANALYSES

The WRAP simulation models SIM and SIMD record time series results in DSS and text file formats that are read by the programs TABLES and HEC-DSSVue. The WRAP program TABLES organizes simulation results and input data in various user-specified formats including time series tabulations of selected variables, summary tables, water budgets, and various types of frequency and reliability metrics. HEC-DSSVue is used for managing time series data, preparing plots, mathematical operations, and statistical analyses.

Statistical frequency analyses

The program TABLES includes flexible statistical analysis features with a variety of options that can be applied to any of the SIM, SIMD, and SALT time series input and simulation results time series variables. HEC-DSSVue also includes statistical analysis features applicable to any time series dataset. Other statistical analysis software can also be employed with WRAP-generated data. The HEC-SSP Statistical Software Package (HEC 2019) was designed originally for detailed flood flow frequency analyses but includes general statistical capabilities. The Indicators of Hydrologic Alteration (IHA) software available from the Nature Conservancy (2009) computes ecologically relevant statistics for daily streamflows for environmental instream flow studies and assessments of changes in streamflow characteristics over time. The Hydrology-based Environmental Flow Regime (HEFR) is a Microsoft Excel spreadsheet based statistical analysis tool with metrics similar to the IHA (Opdyke et al. 2014). These statistical analysis software packages, like the WRAP programs, include HEC-DSS file management capabilities. The programs can be conveniently employed with WRAP time series datasets to perform various types of analyses.

Exceedance frequency computations in TABLES are usually performed based on either Equation 1 or Equation 2, where m is the rank and N is the number of months or days in the period-of-analysis. Alternatively, the normal or log-normal probability functions may be employed. The Equation 1 option has been adopted for most WRAP/WAM applications in Texas.

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

$$\text{Exceedance Frequency} = \frac{m}{N+1}\ (100\%) \tag{2}$$

Frequency metrics can be computed with TABLES for a specific month of interest, for example July, with N equal to the number of years as well as for all months or days. The software has options for computing moving averages and developing annual series of minima or maxima in each year. For example, frequency analyses can be performed for annual series of 7-day (or any number of days) minimum flows derived from a daily simulation. The log-normal or log-Pearson type III probability distributions can be applied to annual series of the maximum daily flow or reservoir storage occurring during each year.

Frequency metrics in Table 2 for daily and monthly naturalized, regulated, and unappropriated flows are computed with TABLES from the monthly SIM and daily SIMD simulation results. The metrics include the mean, standard deviation, minimum, maximum, and quantities equaled or exceeded during specified percentages of the 948 months or 28,855 days of the 1940–2018 hydrologic period-of-analysis (Wurbs 2019d). The quantities are tabulated in cubic feet per second (cfs) rather than acre-feet per month or day to facilitate comparison of the variability of daily versus monthly flows. Daily flows exhibit greater variability due to within-month fluctuations.

SIM and SIMD accommodate any consistent set of flow units, though units of acre-feet per month or day have always been used for applications in Texas. TABLES includes options for converting simulation results to mean monthly or daily flow rates in cfs. Conversions of acre-feet/month to cfs consider variations among 28, 29 (leap year), 30, and 31 days in each month.

Water supply and hydropower reliability analyses

Volume and period reliabilities computed by TABLES from the results of a SIM or SIMD simulation provide concise metrics for evaluating capabilities for meeting water supply and hydroelectric energy requirements. Volume reliability (R_V) is defined by Equation 3 as the ratio of the volume of water supplied or electrical energy produced (v) to the target (V), converted to a percentage. Period reliability (R_P), computed with Equation 4, is the percentage of the total number (N) of periods (days, months, years) of the simulation during which the specified target is either fully supplied or at least a specified percentage of the target is supplied. R_P is an expression of the percentage of time that the full demand target or a specified percentage of the demand target can be supplied. Equivalently, R_P represents the likelihood or probability of the target being met in any randomly selected day, month, or year. Reliabilities may be tabulated with TABLES for all or selected individual water rights, the aggregation of all rights associated with individual control points or reservoirs, or user-selected groups of water rights.

$$R_V = \frac{v}{V}\ (100\%) \tag{3}$$

$$R_P = \frac{n}{N}\ (100\%) \tag{4}$$

In evaluating applications for new water right permits for irrigation, the TCEQ criterion is that an agricultural irrigation right should supply at least 75% of the proposed diversion target at least 75% of the time. Reliabilities of 100% are required for approval of new municipal water right permits subject to certain exceptions in the TCEQ's rules. In May 2020, the TCEQ updated its water availability assessment rules to include criteria for new water rights for aquifer storage and recovery and aquifer recharge.

WRAP provides flexible options for developing a variety of reliability metrics. Frequency and reliability computations for short-term conditional reliability modeling (CRM) are analogous to, but interpreted differently than, the metrics for conventional long-term simulations. A particular water supply diversion target may have an estimated probability (likelihood, frequency, reliability) of 80.0% of being supplied at least 90.0% of the time over some unspecified long planning horizon in a conventional analysis. CRM analyses are organized in terms of the probability or likelihood that various reservoir storage levels will be equaled or exceeded at some time a specified number of months in the future, or water supply demands will be supplied during this period, given a known amount of water presently in storage. For example, for specified reservoir storage contents at the beginning of the irrigation season, the probability of supplying at least 90.0% of a particular agricultural water supply diversion target during the next irrigation season may be estimated in a CRM analysis to be 80.0%.

TABLES creates an optional vulnerability and resiliency table that includes the maximum monthly shortage, average sum of consecutive shortages, maximum number of consecutive shortages, and other shortage indices. This table has not been used very much to date.

Firm yield is commonly computed in planning studies. Firm yield is the maximum demand target that can be supplied with reliabilities (Equations 3 and 4) of 100%, estimated based on the premises reflected in the simulation model. SIM includes an option to compute firm yields based on automated iterative repetitions of the simulation. This feature includes options for computing a safe yield defined as the firm yield that still preserves a storage reserve. The storage reserve may be defined as a specified number of months of water supply or by other quantities.

CONCLUSIONS

The evolution of computer modeling of river/reservoir system development and management that began in the 1950s with predecessors to WRAP and the other modeling systems referenced in this paper is still underway and will continue. Modeling systems continue to be improved and expanded in response to advances in computer technology and intensifying water management and decision support needs. Modeling applications have grown in complexity from both technical and institutional perspectives. Administration of water rights and integration of water resources planning and water allocation have become a central focus of river basin management. Water availability modeling is complex, requiring compilation and management of voluminous datasets and understanding diverse water management practices, but is essential for effective water management.

Implementation of the Texas WAM system, under the leadership of the TCEQ, required collective efforts of the water management community. The WAMs play important roles in water management throughout the state. The shared use of the modeling system has significantly contributed to integrating administration of the water rights permit system; statewide, regional, project, and operational planning; research and development; and other water management endeavors. The system simulation and statistical analysis tools facilitate water availability assessments that combine extremely variable natural river system hydrology, complex operations of extensive constructed infrastructure, and water allocation systems that grow in importance with increasing demands on limited resources.

The generalized WRAP modeling system is readily available and documented in detail for use by engineers, scientists, and other water management professionals for a variety of different types of applications. Comprehensive, flexible modeling and analysis capabilities are provided for applications that may vary from relatively simple to very complex. WRAP capabilities have benefited greatly from the interactive development and application of the modeling system within the very progressive Texas water management community in an environment of extreme hydrologic and economic diversity and diverse water management practices.

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