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Monthly river flows in Texas for natural and developed conditions

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ABSTRACT

River flow characteristics and computational methods for converting sequences of monthly flows between natural and regulated conditions are explored based on experience in assessing water availability throughout the state of Texas in the United States. Diverse climate, hydrology, economic development, and water management practices across the state combined with continual population growth and implementation of a statewide water availability modeling system makes Texas an excellent case study of stream flow characteristics and modeling and analysis methods that are relevant worldwide. Stream flow is extremely variable, subject to severe multiple-year droughts, intense floods, seasonality, and continuous fluctuation. The effects of population and economic growth, water resources development and management, and climatic variability on river flows vary with different conditions found across the state. The modeling system provides capabilities for adjusting observed river flows to represent natural conditions, simulating regulated flows representing specified conditions of development, and performing statistical frequency and reliability analyses.

1. Introduction

Compilation and analysis of sequences of monthly means of observed, naturalized, and simulated regulated stream flows are fundamental to water resources planning and management in the state of Texas in the United States as well as elsewhere. Monthly flows are commonly employed in water supply reliability studies as contrasted with daily, hourly, or shorter averaging intervals typically considered in flood risk mitigation studies. This paper is concerned with river/reservoir system water availability for supplying agricultural, municipal, industrial, electrical energy, and environmental needs and thus focuses on series of monthly flows. The term “naturalized” refers to flows for natural conditions with no human impact or for a defined level of minimal development. Observed flows at a gauge site represent actual conditions of river basin development that typically have changed over time. Observed flows are computationally adjusted to approximate natural conditions. A simulation model is applied to convert naturalized flows to regulated flows representing a constant specified scenario of development.

Variability and stationarity exhibited by sequences of monthly river flows spanning periods greater than at least 75 years are explored in this paper. Flows in rivers throughout Texas are highly variable with continuous, storm event, seasonal, and multiple-year fluctuations reflecting extremes of droughts and floods as well as more frequent but less severe variations. Large volumes of reservoir storage are essential for developing supplies with acceptable levels of reliability. Stream flow variability is driven largely by variability in precipitation and evaporation. Permanent or long-term changes in flow characteristics result primarily from changes in water use and construction of river regulation structures and water resources development projects. The impacts of human activities on low flows are typically very different than on high flows. Regulation of rivers by dams reduces flood flows but may increase low flows at downstream locations. The effects of a dam on flows just below the dam are less evident further downstream.

Websites maintained by state and federal agencies providing convenient free-of-charge access to large databases, numerous technical reports, computer software, and other information are essential to the work of the professional water management community of Texas. Likewise, the research reported in this paper relies on datasets, simulation and statistical analysis computer programs, and technical reports found at several of these websites, which are listed in Table 1.

The objectives of this paper are to both (1) contribute to a better understanding of river flow characteristics and alterations thereto and (2) present modeling techniques for developing river flows representing alternative conditions of development. Analyses of statewide observed 1940–2019 monthly precipitation and 1954–2019 reservoir evaporation rates indicate these variable have been essentially stationary. Analyses of observed gauged flows, adjusted naturalized flows, and simulated specified-condition regulated flows indicate that water development, regulation, and use have significantly altered river flows, with the alterations varying greatly with the characteristics of the different river

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Table 1
Relevant websites.

Texas Water Development Board (TWDB) water planning reports and datasets	https://www.twdb.texas.gov/waterplanning/index.asp
Texas Water Development Board (TWDB) monthly precipitation and evaporation databases	http://www.twdb.texas.gov/surfacewater/conditions/evaporation/evapinfo/index.asp
Texas Commission on Environmental Quality (TCEQ) water availability modeling (WAM) system	https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html
Texas A&M University (TAMU) Water Rights Analysis Package (WRAP) modeling system software, manuals, reports, and datasets	https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm
Texas A&M University (TAMU) Texas Water Resources Institute (TWRI) technical reports (TRs)	http://twri.tamu.edu/publications/
United States Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) software	https://www.hec.usace.army.mil/
United States Geological Survey (USGS) National Water Information System (NWIS)	https://waterdata.usgs.gov/nwis

systems. The modeling and analysis methods and software employed are generalized for application to river systems located anyplace worldwide.

2. Water management in Texas

Texas has an area of 682,000 km^2 that includes 15 major river basins and eight coastal basins located between the major rivers. Climate, hydrology, economic development, water use, and water management practices vary dramatically across the state from the arid to semiarid desert of the western one-third of the state to humid eastern forests, from sparsely populated rural regions to the metropolitan areas of El Paso, San Antonio, Austin, Houston, Fort Worth, and Dallas shown in Fig. 1 [1,2]. The state population increased from about three million people in 1900 to 9.6 million in 1960 to 21 million in 2000 and 30 million in 2020. Declining groundwater supplies combined with population growth have resulted in intensified demands on limited surface water.

About half of the total water used in Texas to supply municipal, industrial, and agricultural needs is from groundwater aquifers and the other half is supplied from rivers and reservoirs impounded by constructed dams [1,2]. River flows are also important for hydroelectric energy generation, environmental flows, and recreation. Although agricultural operations throughout Texas rely upon irrigation from groundwater to varying extents, the majority of the irrigation supplied from groundwater occurs in the upper Canadian, Red, and Brazos River Basins of northern Texas (Fig. 1). Development of surface water is very limited in this flat semiarid region. The city of San Antonio and adjacent smaller cities rely almost totally on groundwater for municipal and industrial supply. Houston and vicinity has historically been supplied mainly from groundwater, but aquifer depletion has necessitated a shift toward a greater reliance on surface water during recent decades. Municipal and industrial water use by the almost one-fourth of the Texas population that resides in the more than 70 cities of the Dallas and Fort Worth metropolitan area are supplied from surface water stored in reservoirs on the Trinity River and its tributaries, with little use of groundwater. Austin and nearby smaller cities as well as farmers in the lower Colorado Basin are supplied primarily from reservoirs on the Colorado River.

Ground and surface water are very different from the perspectives of both hydrologic processes and water management [3]. Water in the rivers and lakes of Texas is owned by the state, and its use is regulated through a statewide water rights permit system administered by the Texas Commission on Environmental Quality (TCEQ). With about 3000 employees, TCEQ is the largest state environmental regulatory agency in the United States. Like most states in the western United States, surface

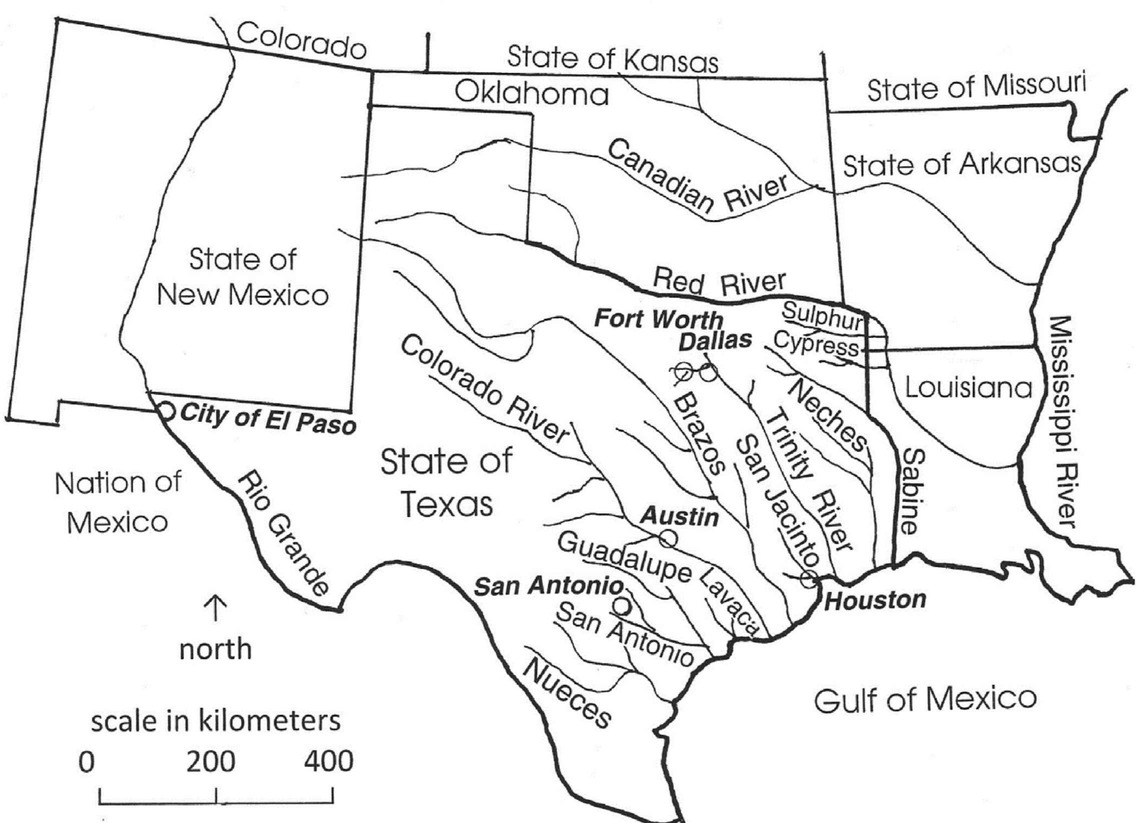

Fig. 1. Map of major rivers and largest cities in Texas.

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 right permits are granted. Groundwater in Texas belongs to the owner of the overlying land, with relatively minimal state and local regulation. Thus, conjunctive management of surface and groundwater is difficult [3].

Comprehensive water management legislation enacted by the Texas Legislature as its 1997 Senate Bill 1 (SB1) is a milestone in the history of water management in Texas [2,4,5]. The 1997 SB1 authorized a regional and statewide planning process and creation of the water availability modeling (WAM) system employed in this paper. The Texas Water Development Board (TWDB) is the lead agency for the SB1 planning process, which consists of developing 16 regional water plans and a consolidated statewide plan in a five year planning cycle that considers a 50 year future planning horizon. The 2002, 2007, 2012, and 2017 regional and statewide water plans are documented by detailed reports available at the TWDB website noted in Table 1. Information regarding ongoing work on the next updates is also publicly accessible at the website.

The TCEQ is the lead agency for developing and maintaining the water availability modeling (WAM) system. The initial version of the WAM system was created during 1998–2003 pursuant to the 1997 SB1 by the TCEQ, TWDB, university researchers, and consulting engineering firms working under contract with the TCEQ [4]. The modeling system has been greatly expanded with updates, improvements, and new additions through the present and continuing [5]. The WAM system consists of the Water Rights Analysis Package (WRAP) modeling system developed at Texas A&M University (TAMU), which is generalized for application to river basins anywhere in the world, and WRAP input datasets for all of the river basins of Texas. The generalized WRAP combined with an input dataset from the WAM system for a particular river basin is called a water availability model (WAM).

The 15 major river basins of Texas and eight coastal basins between the major rivers flowing to the Gulf of Mexico are modeled as 20 WAMs. Three WAMs each contain two adjacent basins. Activities of numerous water management entities operating 3450 dams/reservoirs and other constructed facilities in accordance with treaties between the United States and Mexico, five interstate compacts, two versions of a water right permit system with 6200 active permits, contracts for storage in federal reservoirs, and other institutional arrangements are simulated [5].

The TWDB, TCEQ, and Texas water management community use the term “major reservoir” to refer to a reservoir, lake, or storage facility having a storage capacity of 6,168,000 m^3 (5000 acre-feet) or greater at its normal operating level. This definition does not include flood control and surcharge storage that remains empty except during and immediately following flood events. All of the 210 major reservoirs in Texas are impounded by dams constructed since 1900.

Many thousands of farm ponds, stormwater detention structures, recreation lakes, and other storage facilities are scattered throughout the state. Most of the total storage capacity is contained in a relatively small number of large reservoirs. The 3450 reservoirs included in water right permits and thus included in the 20 WAMs include 210 major reservoirs, which account for 98.0% of the total storage capacity of the 3450 reservoirs. The 58 reservoirs with conservation storage capacities of 6.17×10^{11} m^3 (100,000 acre-feet) or greater contain 89.3% of the total permitted storage capacity of the 3450 permitted reservoirs. Dams impounding storage capacities of 247,000 m^3 (200 acre-feet) or less can be constructed for domestic and livestock purposes without a water right permit. Flood control and surcharge storage are not included in water right permits. Essentially all designated flood control storage in Texas controlled by human operation of gated outlet structures is contained in 27 reservoirs owned and operated by the U.S. Army Corps of Engineers (USACE) and two reservoirs on the Rio Grande owned and operated by the International Boundary and Water Commission (IBWC). The conservation storage capacity of these large multiple purpose reservoirs are included in the water right permits and WAMs.

Authorized and current use scenario datasets for each of the 20 WAMs are available at the TCEQ WAM website (Table 1). The authorized use scenario assumes all water right permit holders use the full amount of water to which they are legally entitled, subject to water availability. Many water right permits include projected future water needs. The current use scenario represents actual recent water use. The TWDB has developed WAM datasets representing projections of future water needs. Model users modify the WAM datasets to reflect projected water needs, proposed projects, and management strategies of interest in their particular applications.

TCEQ staff and water right permit applicants, or their hired consulting firms, apply the WAMs in the water right permitting process to assess reliabilities of proposed water supply plans and impacts on other water rights [5]. TWDB staff and regional planning groups, or their consultants, apply the modeling system in regional and statewide planning studies to assess water supply capabilities. River authorities and other entities use the WAMs for operational planning studies and other water management endeavors. The modeling system has also been applied in a variety of university research studies including the research reported by this paper.

3. Water Rights Analysis Package (WRAP) modeling system

The WRAP modeling system is a collection of methodologies for assessing capabilities of river/reservoir systems in meeting specified water management and use requirements for given sequences of naturalized stream flows and reservoir net evaporation less precipitation rates. Wurbs [6] reviews the literature and compares WRAP with other computer modeling and analysis systems for assessing operations of reservoirs and river regulation strategies.

The generalized WRAP modeling system provides capabilities for performing the following tasks required in assessments of water availability: (1) compilation of datasets representing natural river system hydrology, (2) organization of data representing defined scenarios of water resources development, allocation, regulation, and use, (3) execution of simulations that combine the hydrology and water management datasets, and (4) organization of simulation results including computing supply reliability and flow and storage frequency metrics.

A specified scenario of water management is combined with natural historical hydrology. Since the future is unknown, historical stream flows adjusted to reflect natural conditions are used to statistically capture the hydrologic characteristics of a river basin. The water management and use scenario might be actual current water use, projected future conditions, the premise that all water right permit holders use their full authorized amounts, or some other scenario of interest. Simulation results are organized in optional formats including tabulations and plots of entire time sequences, summary tables, water budgets, frequency relationships, and various types of reliability and frequency metrics. Water management capabilities are expressed in terms of the likelihood (reliability) of meeting water supply targets or portions thereof and stream flow and reservoir storage frequency relationships.

The WRAP software can be downloaded from the TAMU WRAP website listed in Table 1. WRAP manuals [7–11] and other WRAP related Texas Water Resources Institute (TWRI) publications are available at both the TAMU WRAP and TAMU TWRI websites in Table 1. WAM information including WRAP datasets for all Texas river basins and a link to the TAMU WRAP website is available at the TCEQ WAM website in Table 1.

The U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) has developed many generalized simulation modeling systems and other software that are extensively applied throughout the United States and abroad. Most HEC simulation models share a common data storage system (DSS) that is also integrated into the WRAP programs for managing time series data including data discussed in this paper. The WRAP programs create, read, and store data in DSS files. The DSS interface HEC-DSSVue [12] available at the USACE HEC website

(Table 1) is an integral component of the WRAP modeling system.

WRAP software includes a program named HYD containing a variety of routines for compiling and updating hydrology input datasets, the monthly SIM and daily SIMD river/reservoir system simulation models, and a collection of routines in a program called TABLES for organizing simulation results and performing frequency and reliability analyses. HEC-DSSVue is used to manage time series data that includes both simulation input and results. These programs are employed in the work presented in this paper.

The 2019 version of WRAP includes options for using a daily time step in order to incorporate reservoir flood control operations and high pulse flow components of environmental instream flow requirements in the simulation [11,13]. The same WAM monthly naturalized flow datasets are used in both monthly SIM and daily SIMD simulations. In a daily simulation, monthly naturalized flows are disaggregated to daily within the simulation based on input datasets of daily pattern hydrographs while preserving the monthly volumes. The new daily simulation model is designed to supplement, not replace, the monthly simulation model.

4. Monthly precipitation and reservoir evaporation rates

Precipitation and evaporation drive stream flow. TWDB maintains annually updated datasets of monthly precipitation beginning in January 1940 and monthly reservoir surface evaporation rates from January 1954 for a grid of 92 one-degree latitude by one-degree longitude quadrangles that encompass the state, which is accessible at the second website listed in Table 1. The number of gauge sites has varied over time, but now includes about 3960 precipitation and 100 evaporation stations, most managed by the National Weather Service (NWS). The TWDB uses Thiessen networks in computing means for each of the 92 quadrangles for each month. The monthly reservoir evaporation depths are estimated based on measurements from standard NWS evaporation pans and lake/pan multiplier coefficients that vary over the 12 months of the year and with location. Precipitation is almost all rainfall. Infrequent snowfall and sleet melts quickly.

The WRAP hydrology program HYD includes a feature that computes basic statistics including linear regression coefficients for each of the 92 quadrangles and the statewide mean precipitation and evaporation rates [10]. Monthly quantities, annual totals, and annual series of the minimum and maximum value each year of moving averages for any specified number of months are computed. Time series plots are prepared with HEC-DSSVue [12].

The 1940–2019 statewide average precipitation is 71.44 cm/year. The statewide means of the monthly precipitation depths are plotted in Fig. 2. Statewide mean annual precipitation and the minimum and maximum single month precipitation in each year of 1940–2019 are plotted as Fig. 3. The January 1954 through December 2019 statewide

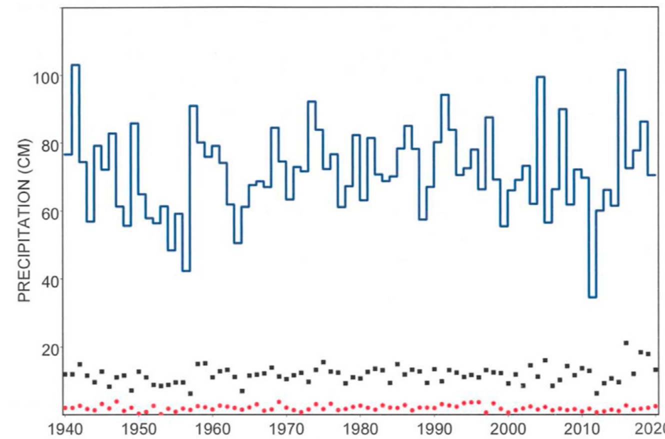

Fig. 3. Statewide annual (blue solid line) and maximum monthly (black squares) and minimum monthly (red circles) precipitation in each year in cm.

mean reservoir evaporation rate is 151 cm/year. Reservoir evaporation rates are plotted in Figs. 4 and 5. Precipitation and reservoir evaporation rates exhibit great variability seasonally, between years, and continuously. Fluctuations between years is much greater for precipitation than evaporation. Seasonality is more pronounced for evaporation than precipitation. Temporal variability tends to be greater for individual quadrangles than for statewide averages.

Table 2 provides a summary of trend slopes from standard least-squares linear regression of 1940–2019 annual precipitation, minimum and maximum one-month precipitation during each year, and similarly 1954–2019 regression slopes for reservoir evaporation annual depths and annual one-month maximum and minimum depths. A linear regression line through the 80 years of annual statewide 92-quad area-weighted mean precipitation depths has a slope of 0.0340 cm/year or 0.0476% of the 71.44 cm/year mean. The trend slopes for annual precipitation are negative for 26 of the quads and positive for the other 66. Counts of positive and negative regression slopes for six annual time series variables for the 92 quads are shown in the last two columns of Table 2.

Fig. 6 is a schematic of the 92 quadrangles that encompass Texas. The top number in each of the 92 cells is the 1940–2019 mean annual precipitation for the quad expressed as a percentage of the statewide mean precipitation of 71.44 cm/year. The bottom number is the slope of the linear regression trend line for 1940–2019 annual precipitation expressed as a percentage of the annual mean precipitation for that individual quad. The mean precipitation for individual quadrangles varies

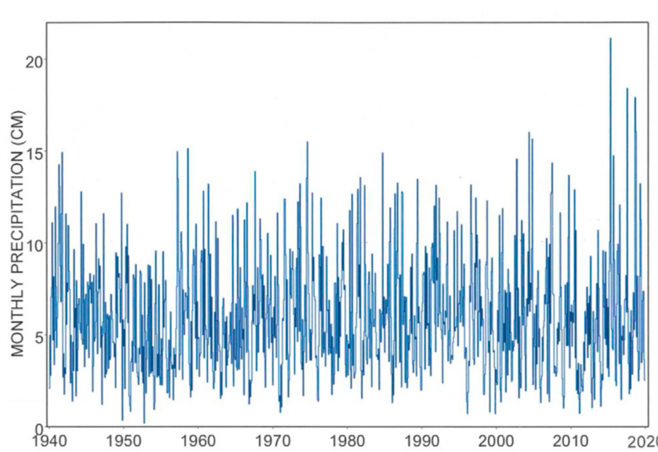

Fig. 2. Statewide 1940–2019 monthly precipitation in cm/month.

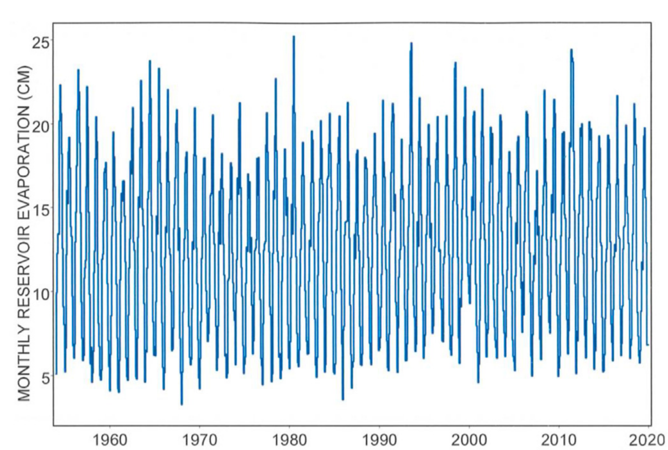

Fig. 4. Statewide 1954–2019 monthly reservoir evaporation rates in cm/month.

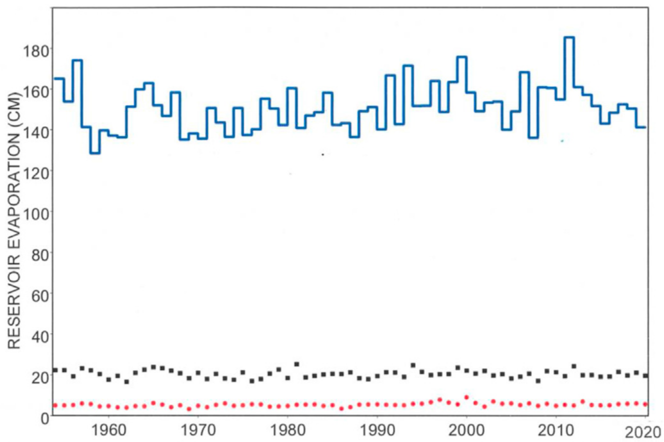

Fig. 5. Statewide annual (blue solid line) and maximum monthly (red dots) and minimum monthly (red circles) reservoir evaporation rates in each year in cm.

Table 2
Means and linear regression slopes for statewide annual total and annual one-month minimum and one-month maximum precipitation and reservoir evaporation.

Time Series Variable	Mean (cm)	Slope (cm/year)	Slope (% mean)	Positive Slopes	Negative Slopes
annual precipitation	71.44	0.0340	0.0476%	66	26
minimum month	2.003	−0.00187	−0.0934%	25	67
maximum month	11.79	0.0289	0.245%	74	18
annual evaporation	151.0	0.142	0.0943%	62	30
minimum month	5.43	0.0206	0.379%	82	10
maximum month	20.45	0.000690	0.00338%	52	40

from 23.6 cm/year (33.0% of the statewide mean) in the extreme west increasing from west to east to 146 cm/year (204% of the mean) in southeast Texas.

No long-term changes in precipitation or evaporation characteristics are evident from time series plots and regression analyses of the data in the TWDB monthly quadrangle database [10]. Precipitation has small negative and positive slopes for the 80 annual minimum and maximum one-month depths, respectively. The three 66-year annual evaporation series have positive slopes. However, the small regression slopes switch between increasing versus decreasing with different sub-periods of the 1940–2019 precipitation or 1954–2019 evaporation. Permanent long-term trends, if they exist, are hidden by the great continuous variability.

The preceding discussion addresses past 1940–2019 climate. Potential effects of future climate change scenarios on stream flow and water supply several decades into the future were explored by combining an early version of the Brazos River Basin WAM with global climate model output and the Soil and Water Assessment Tool (SWAT) watershed precipitation-runoff model [14,15]. Modeling uncertainties were found to be too great to derive meaningful conclusions regarding potential changes in stream flow due to climate change 50 years in the future.

Cook et al. [16] and Cook et al. [17] predict that weather will be more highly variable and droughts likely more severe in the American Southwest and Central Plains, including Texas, in the future due to long-term climate change. Nielsen-Gammon et al. [18] investigate 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 or more years.

Evaporation is a major component of reservoir water budgets. Simulated long-term mean annual evaporation from the over 3400 reservoirs in the statewide current use scenario WAMs have been estimated to be an annual volume equivalent to 61% of the total agricultural water use or 126% of the total municipal water use from all surface and groundwater sources in Texas during the year 2010 [19].

5. Observed flow at gauge sites

Flow of rivers throughout Texas naturally exhibit dramatic fluctuations including severe multiple-year droughts and intense floods. Construction and operation of dam and reservoir projects, water supply diversions, return flows from surface and groundwater supplies, and other aspects of population and economic growth significantly affect river flow [20].

Long-term decreases in mean flows are evident at some gauges, increases in mean flows are evident at others, many exhibit both increases in low flows and decreases in high flows, and flows at many gauges show no permanent changes. The characteristics of the changes vary significantly between daily and monthly flows. Long-term changes also differ greatly between high flows and low flows. Stream flows immediately below dams are greatly affected by reservoir operations, but the effects diminish with distance downstream.

Observed flows at four USGS gauge sites plotted in Figs. 7–11. These sites on the Canadian, San Antonio, Trinity, and Brazos Rivers have watershed areas of 59,200 km^2, 5470 km^2, 33,200 km^2, and 51,800 km^2. Daily flows were downloaded from the USGS NWIS (Table 1) as DSS files, aggregated to monthly, plotted, analyzed, and managed within HEC-DSSVue [12].

Dramatic decreases in the flow of the Canadian River illustrate the impacts of development of irrigated agriculture in a dry region. Most of the water used for irrigation is supplied from the Ogallala Aquifer. Drawdown of groundwater as well as surface water use is affecting streamflow. Monthly flows of the Canadian River at a site about 130 km downstream of the border between New Mexico and Texas are plotted in Fig. 7. Intensive agricultural production in the arid Rio Grande Valley is dependent on irrigation supplied by the Rio Grande. The Rio Grande has experienced severe decreases in flows due to reservoir construction during the 1950's and 1960's and accompanying development of irrigated agriculture.

Illustrating the opposite extreme, flow of the San Antonio River below the City of San Antonio increased significantly over the last 100 years as a result of wastewater treatment effluent accompanying increased water supply from the Edwards Aquifer and increase impervious land cover due to urbanization, as demonstrated by flows at a gauge on the San Antonio River about 80 km downstream of downtown San Antonio (Fig. 8). Flows of tributaries of the San Jacinto River in the Houston metro area have similarly increased over the past century in response to return flows from municipal and industrial water use supplied by groundwater and inter-basin import and increased storm-water runoff due to urban development.

Fig. 9 is a plot of monthly flows at a USGS gauge on the Trinity River near Oakwood which is about 130 km downstream of downtown Dallas. The Fort Worth-Dallas metro area in the upper Trinity River Basin has a population of 6.8 million and has been one of the fastest growing metro areas in the nation during the past several decades. Many reservoir projects were constructed on the Trinity River and its tributaries during the 1950s–1980s. Interestingly, average flows of the Trinity River have changed relatively little. Low flows have increased with increases in wastewater treatment discharges. Flood flows have been significantly decreased by eight large USACE flood control reservoirs. However, decreases in daily flood flows are dissipated in monthly flows.

Plots of mean daily and monthly flows of the Brazos River just downstream of the City of Waco in Figs. 10 and 11 illustrate the effects of the choice of time interval. Flood control operations of three large reservoirs located upstream are based on a maximum allowable flow rate of 708 m^3/s at this gauge. Initial impoundment for these three reservoirs occurred in 1951, 1965, and 1983. The storage attenuation effects of flood control operations are clearly evident in the daily flows (Fig. 10) but are dissipated in the monthly flows (Fig. 11).

			59.9 -0.013	63.3 -0.199	66.6 -0.111	74.9 0.102	85.9 0.086						
			59.6 -0.289	65.6 -0.020	72.6 -0.029	85.3 0.039	98.9 -0.086						
			59.5 0.113	65.3 0.114	73.5 0.0439	78.9 0.159	92.5 0.096	110 0.058					
			57.1 -0.009	64.5 0.108	81.0 -0.176	81.8 0.205	90.5 0.116	106 0.138	123 0.180	146 0.136	165 -0.067	174 0.057	182 0.030
			55.2 -0.121	61.1 -0.111	73.5 -0.126	80.9 0.050	93.9 0.080	108 0.165	121 0.147	138 0.127	155 0.013	170 0.075	181 0.081
38.8 -0.109	51.4 -0.104	52.3 -0.106	41.5 0.119	48.1 0.074	64.5 -0.135	76.1 0.118	88.1 0.230	103 0.133	118 0.269	137 0.115	157 0.077	175 0.095	190 0.096
33.0 0.042	55.6 -0.240	49.1 0.034	53.4 -0.025	48.8 0.134	67.4 -0.210	80.0 0.087	90.3 0.062	108 0.055	118 0.200	142 0.039	167 0.038	194 0.166	203 0.218
		71.5 -2.50	52.1 -1.04	41.9 -0.060	60.1 0.049	87.3 0.071	95.0 0.206	112 0.104	123 0.094	148 0.071	169 0.262	176 0.418	204 0.140
						73.7 -0.108	78.2 -0.062	90.2 0.017	125 -0.079	141 0.022	158 0.209		
							72.5 0.020	85.1 0.067	105 0.117	124 -0.025			
							63.3 0.288	77.4 0.053	92.2 0.014				
									93.2 0.120				

Fig. 6. 1940–2019 mean annual precipitation for each of the quads as a percentage of the statewide mean of 71.44 cm/year and linear regression slope as a percentage of the annual mean for each of the individual quadrangles.

6. Developing datasets of monthly flows representing natural conditions

Period-of-analysis series of naturalized monthly stream flow quantities representing natural hydrology unaffected or negligibly affected by people are fundamental to many modeling applications worldwide including Texas [6]. Naturalized monthly flows are developed for the Texas WAM system by adjusting observed flows at gauge stations to remove the effects of human activities and then transferring the flows to relevant ungauged sites [7–10]. The 20 WAMs include naturalized flows at about 500 gauge sites stored in simulation input files available at the TCEQ WAM website that are distributed to over 12,000 other sites during executions of the simulation model based on watershed parameters also stored in the input datasets. The datasets are periodically extended as additional years of stream flow observations are accumulated.

6.1. *Sources of stream flow data*

The hydrologic engineering and water management communities of the 50 states of the United States, including Texas, rely greatly on the

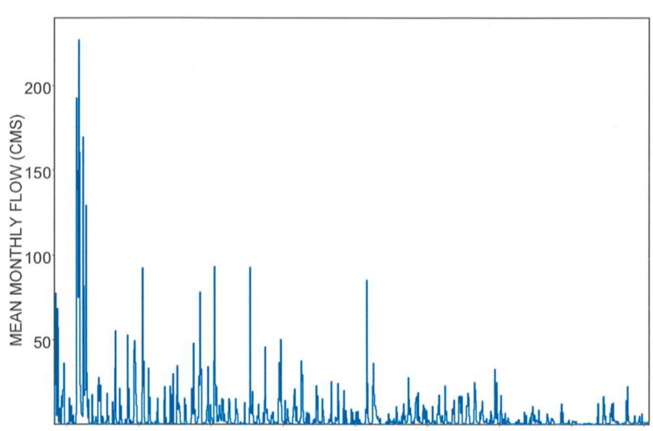

Fig. 7. Observed mean monthly flow of Canadian River near Amarillo during April 1938 through September 2020 in m^3/s.

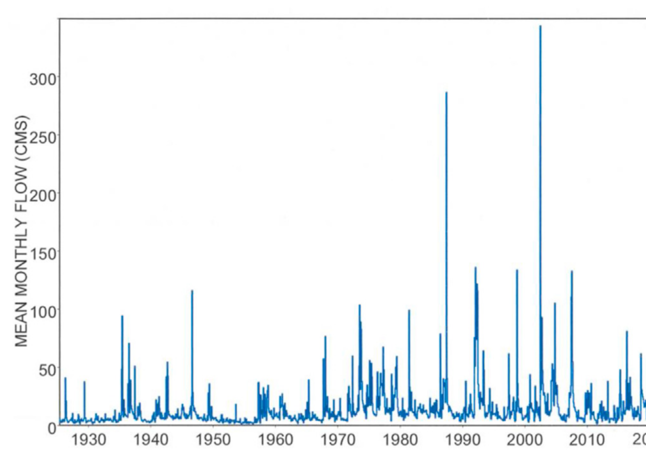

Fig. 8. Observed mean monthly flow of San Antonio River downstream of City of San Antonio during May 1925 through September 2020 in m^3/s.

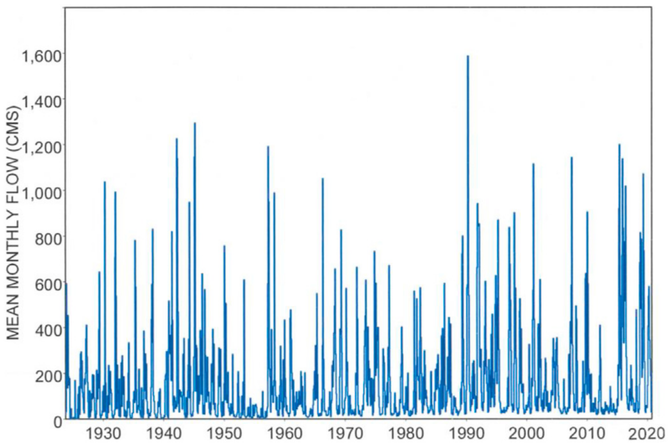

Fig. 9. Observed mean monthly flow of Trinity River at Oakwood during October 1923 through September 2020 in m^3/s.

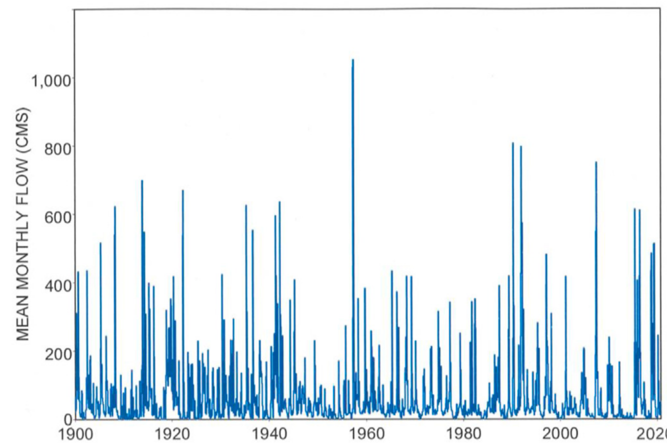

Fig. 11. Observed monthly mean flow of Brazos River below City of Waco during January 1900 through September 2020 in m^3/s.

extensive datasets available at the National Water Information System (NWIS) website noted in Table 1 maintained by the U.S. Geological Survey (USGS). The strategy of compiling naturalized flows based on adjusting gauged flows was adopted in developing and implementing the Texas WAM system. Although not necessary for the Texas WAM endeavor, in the absence of measured flow data, watershed modeling systems that convert precipitation to stream flow are widely employed [21].

The USGS NWIS contains a massive nationwide collection of an array of various types of measured water quantity and quality data that includes 17,549 gauge sites, including 1055 gauge sites in Texas, for which historical daily flows are recorded. The longest continuous daily flow records for gauge sites in Texas date back to the 1890's, but most sites have much shorter periods-of-record. Many gauges have gaps of time periods with missing data, which are often addressed in modeling studies by regression with flow data at other gauges located nearby.

Many different watershed precipitation-runoff modeling systems have been used to synthesize various forms of stream flow and related hydrologic and water quality data for watersheds throughout the world [21]. Research at Texas A&M University (TAMU) sponsored by the TCEQ early in the WAM development process included investigation of the potential role of watershed precipitation-runoff models in compiling WAM monthly naturalized flows [14,22–24]. The widely employed Soil and Water Assessment Tool (SWAT) [15] developed by the United States Agricultural Research Service and TAMU AgriLife Research was employed in the research. Among its many other features, SWAT computes daily stream flows, which can be summed to monthly, for given daily rainfall input datasets and watershed parameters.

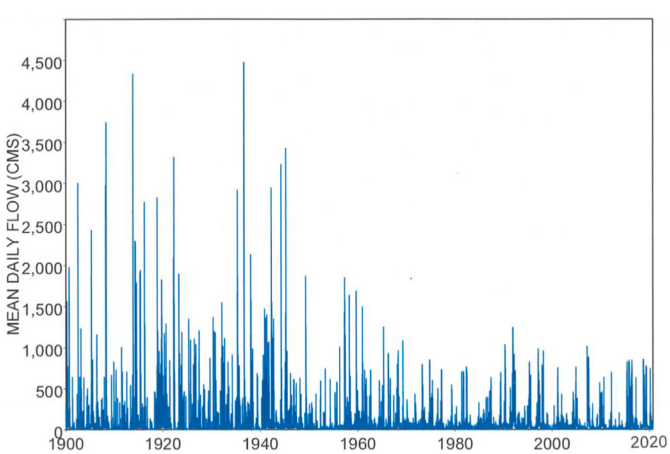

Fig. 10. Observed mean daily flow of Brazos River below City of Waco during January 1, 1900 through October 20, 2020 in m^3/s.

SWAT was investigated for possible use in the WAM system for the following different purposes [22,23]: (1) computing monthly naturalized stream flows, (2) distributing adjusted observed monthly flows at gauge sites to other ungauged sites, and (3) adjusting stream flows to reflect changes in watershed land use. As noted in the previous Section 4, SWAT was also used in exploring the impacts of future climate change scenarios on stream flow [14]. More recently SWAT has been applied at TAMU in a comparative investigation of alternative strategies for developing daily pattern hydrographs for input to the WRAP daily simulation model SIMD [24].

Relatively simple methods presented later in this paper for synthesizing stream flow from rainfall are adopted as options for extending and distributing naturalized flow data for the WAMs. However, none of the WAM datasets, other than developmental datasets compiled in research at TAMU, incorporate monthly naturalized flows synthesized with SWAT or other large complex watershed models. Naturalized flow compilation methods based on manipulating observed flows at gauges have been adopted instead. Gauged stream flow data along with the other types of data noted in the following Section 6.2 though limited in availability have been adequate to achieve the modeling objectives of the Texas WAM system. Watershed precipitation-runoff modeling may be the optimal strategy for compiling naturalized flows in other places if gauged stream flow data and/or data required to naturalize the stream flow data is not available.

6.2. Naturalization of measured actual flows

Flow adjustments remove impacts of upstream reservoirs, water supply diversions, return flows from surface and groundwater sources, and other phenomena. Consideration of all human activities is not feasible or necessary. For sites with relatively undeveloped watersheds, little or no adjustments may be necessary. In most major river basins, most storage capacity is contained in a relatively few large reservoirs even though there are numerous other smaller reservoirs. Likewise, relatively few large cities, water districts, and river authorities account for most of the total volume of water diverted from and returned to streams, though there are numerous other smaller water users. After accounting for the relatively large water management entities, the incremental increases in accuracy of including smaller water uses in the computations diminish concurrently with increasing difficulty in obtaining historical water use, storage, and return flow data.

Recorded observed flow data are available at the NWIS website maintained by the USGS. The TCEQ collects and maintains water use data from cities, water districts, and other water right permit holders. The

TWDB also maintains water use, infrastructure, and hydrology databases that are used in the flow naturalization process.

Strategies for further adjustments to naturalized stream flow have been employed in some of the WAMs. For example, the WAMs for the San Antonio, Guadalupe, and Colorado Rivers include stream flow adjustments for changes in spring flows associated with groundwater use estimated based on TWDB groundwater simulation models.

At a particular gauge site, for a particular month during the historical record, the naturalized flow volume (NF) is computed as a function of gauged flow (GF), water supply diversions (D_i), return flows (RF_i), net reservoir evaporation less precipitation (EP_i), and change in reservoir storage (ΔS_i) at locations i upstream of the gauge.

$$NF = GF + \sum D_i - \sum RF_i + \sum EP_i + \sum \Delta S_i \tag{1}$$

Many reservoirs, diversions, and return flows may be located upstream of the gauge. Construction of dams and other water control facilities and changes in water use occur at different times.

Channel losses reflecting seepage and evapotranspiration along a stream reach during a month are estimated as a function of a dimensionless channel loss factor (F_{CL}). Denoting each of the adjustments D_i, RF_i, EP_i, and ΔS_i in Eq. (1) at the upstream end of a stream reach as A_{US}, the adjustment A_{DS} translated to the downstream end of the reach is

$$A_{DS} = (1.0 - F_{CL})\, A_{US} \tag{2}$$

Multiple delivery factors (1.0-F_{CL}) are applied to translate an adjustment through multiple reaches between the diversion, return flow, or reservoir site and the naturalized flow site. Delivery factors are employed in both HYD flow naturalization computations and the SIM simulation model.

The larger WRAP simulation input datasets in the Texas WAM system have hundreds of control points defining stream reaches. For many reaches, channel losses are considered negligible and are not incorporated in the WAMs. Significant channel losses are included in the models for many stream reaches. Channel losses per unit stream length have been estimated based on water budgets between gauges. Rainfall records are combined with the Natural Conservation Service rainfall-runoff relationship (Eq. (3)) to estimate runoff entering reaches between gauges. Reservoir management agencies acquire channel loss information based on experience in releasing for water supply diversions that occur long distances below dams.

Naturalized flows have been plotted and statistically analyzed by the agency and consulting firm staff who developed the WAM datasets and by other investigators [20]. Naturalized flows exhibit long-term permanent changes in flow characteristics even after reasonable efforts at adjustments for the Canadian River, Rio Grande, and reaches of several other streams, mainly in dry flat West Texas. However, in general, no long-term trends are detected in the computed naturalized flows for most of the approximately 500 gauge sites adopted. In general, although the naturalization procedures are necessarily approximate, the naturalized flows at most sites in the Texas WAM system are considered to be homogeneous without permanent long-term trends.

7. Distribution of naturalized flows from gauged to ungauged sites

Sites with naturalized flows in a WAM input dataset are called primary control points. The simulation includes distribution of naturalized flows at primary (gauged) control points to other relevant sites, called secondary control points, based on watershed parameters. The WAMs include the input parameters watershed area, curve number (CN), mean annual precipitation, and channel loss factors for use within the SIM simulation model by alternative methods for distributing naturalized flows [7,8,10,22,23,25]. The input datasets also include specifications defining the incremental watersheds used in the flow distribution computations. Incremental flows are distributed between sites as appropriate based on incremental watersheds and combined with upstream flows. Different alternative naturalized flow distribution methods are employed in the different WAMs and at different sites in the same WAM.

The Natural Resource Conservation Service (NRCS) relationship between precipitation depth (P) in cm or inches and runoff volume equivalent depth (V) in cm or inches [26] is employed in widely used watershed models such as SWAT [15] and the USACE HEC Hydrologic Modeling System (Table 1). This NRCS method is based on Eqs. (3)–(5) where S in cm or inches is the maximum retention after runoff begins, and CN is a dimensionless curve number that varies with land use, soil type, and antecedent moisture. The CN is estimated based on databases developed by the NRCS and others from field experimentation [15,26]. In SWAT, HEC-HMS, and other implementations of the NRCS CN method, as the simulation steps through a daily or other time step, cumulative V is computed as a function of cumulative P. Runoff volume as a depth equivalent (V) is multiplied by the watershed area (A) to obtain the runoff or stream flow volume.

$$V = \frac{(P - 0.2S^2)}{P + 0.8S} \quad \text{if} \;\; P \geq 0.2S \;\; \text{and} \;\; V = 0 \;\; \text{otherwise} \tag{3}$$

$$S = \frac{2,540}{CN} - 25.4 \qquad \text{for} \;\; V, \;\; P, \;\; S \;\; \text{in} \;\; \text{cm} \tag{4}$$

$$S = \frac{1,000}{CN} - 10 \qquad \text{for} \;\; V, \;\; P, \;\; S \;\; \text{in} \;\; \text{inches} \tag{5}$$

One of the several flow distribution options in the WRAP simulation model is an unconventional adaptation of the NRCS relationship [10,23]. The flow distribution algorithm is based on first computing a monthly P with the parameters A and CN for the gauged total or incremental watershed. The computed P, viewed as a precipitation index, is adjusted by multiplying by the ratio of long-term mean precipitation (MP) for the ungauged and gauged watersheds. The naturalized flow for the ungauged watershed is computed for this computed P and parameters CN and A for the ungauged watershed. The method reduces to Eq. (6) if the CN and MP are the same for the gauged and ungauged watersheds.

$$Q_{ungauged} = \quad Q_{gauged} \;\; R_{DA} \tag{6}$$

$$R_{DA} = \frac{DA_{ungauged}}{DA_{gauged}} \tag{7}$$

Eq. (8) can be applied for an ungauged site located upstream of a gauge with channel losses occurring between. If the loss factor F_{CL} defined by Eq. (2) is zero, Eq. (8) reduces to Eq. (6).

$$Q_{ungauged} = \quad Q_{gauged} \left(\frac{R_{DA}}{1 - R_{DA} F_{CL}} \right) \tag{8}$$

Another flow distribution option available in the WRAP simulation model consists providing coefficients a, b, and c in the input dataset for the use in Eq. (9).

$$Q_{ungauged} = \quad a \;\; (Q_{gauged})^b + c \tag{9}$$

This option has been employed in research studies with the coefficients a, b, and c determined by regression analysis for monthly naturalized flows at both gauged and ungauged sites computed using the SWAT watershed precipitation-runoff modeling system [14,23]. Adjusted observed flows were considered to be more accurate than SWAT generated flows at the gauge site, but SWAT was used in this manner to distribute the naturalized monthly flows to ungauged sites.

8. Updating naturalized flow sequences

WRAP input datasets were developed for the 20 WAMs during 1998–2003 by engineering firms under contract with the TCEQ as documented by technical reports available at the TCEQ WAM website. TCEQ staff update the water rights data as new permits are approved and existing permits are amended. The hydrology data has been updated occasionally for individual WAMs using the same methods described in this paper that were employed to develop the original datasets.

Hydrology dataset updates include extending the hydrologic period-of-analysis covered by the naturalized flows and net reservoir evaporation less precipitation rates. Updating naturalized flow datasets employing the methods described earlier in this paper and implemented in the WRAP program HYD requires significant time and effort. The methodology included in HYD described below facilitates expedited periodic updates/extensions of the monthly naturalized flows [10]. With completion of model calibration, the hydrology can be updated annually with minimal effort, though perhaps less accurately, between more detailed but less frequent updates. The methodology is also useful where stream gauges have been discontinued.

The database of monthly precipitation and reservoir evaporation rates discussed earlier in this paper is updated annually by the TWDB. These data are used to update the net evaporation-precipitation input for the WAMs. The same precipitation and evaporation data can be employed with a hydrologic model option included in program HYD [10]. The model is calibrated by relating monthly naturalized flows developed in the past by conventional methods to concurrent monthly precipitation and evaporation. The calibrated model is used to extend the naturalized stream flow sequences periodically as the precipitation and evaporation are updated.

Watershed and quadrangle areas are required for the WRAP-HYD hydrologic model. The watershed above relevant sites may range from a portion of a single precipitation and evaporation quad to all or portions of multiple quadrangles. Precipitation P (i,t) and evaporation E (i,t) volumes are computed as area-weighted summations of depths multiplied by appropriate watershed areas.

Naturalized flow volumes Q(t) at a site in month t are synthesized with the combined Eqs. (10)–(14). Flows may optionally be divided into zones (z) representing low, medium, high, and flood flows. A flow extension model for a site may be developed for total flows or separate models developed for specified zones can be combined [10].

$$\mathrm{Qt)} \quad = \quad \mathrm{U1)} \times \mathrm{RP(t)}^{\mathrm{U(2)}} \quad + \quad \mathrm{BF(t)} \tag{10}$$

$$\mathrm{RP}\left(\mathrm{t}\right) \quad = \quad \sum_{\mathrm{i}=1}^{\mathrm{N}} \Big[\mathrm{Pi,t)} \quad - \quad \mathrm{Xi,1)} \times \mathrm{Pi,t)(i,t)}^{\mathrm{X(i,2)}} \quad - \quad \mathrm{Xi,3)} \times \mathrm{Ei,t)} \quad + \quad \mathrm{PPi,t-1)} \quad - \quad \mathrm{Xi,4)} \times \mathrm{PP(i,t-1)}^{\mathrm{X(i,5)}} \Big] \tag{11}$$

$$\mathrm{PPi,t)} \quad = \quad \mathrm{Xi,1)} \times \mathrm{P(i,t)}^{\mathrm{X(1,2)}} \tag{12}$$

$$\mathrm{BF(t)} \quad = \quad \mathrm{B(m)} \times \mathrm{DI(t)} \times \mathrm{BX(z)} \qquad \text{where DI(t) is the lesser of} \tag{13}$$

$$\mathrm{DI(t)} = 1.0 \quad \text{or} \quad \mathrm{DI(t)} = \mathrm{DX}\left[\left(\frac{\overline{\mathrm{E}}(\mathrm{m}-1)+\overline{\mathrm{E}}(\mathrm{m})}{\overline{\mathrm{P}}(\mathrm{m}-1)+\overline{\mathrm{P}}(\mathrm{m})}\right) \frac{\sum \mathrm{P(i,t-1)}+\mathrm{P(i,t)}}{\sum \mathrm{E(i,t-1)}+\mathrm{E(i,t)}}\right]^2 \tag{14}$$

U (1) and U (2) = dimensionless parameters modeling the nonlinear relationship between precipitation and stream flow; RP(t) = runoff from individual quadrangles in current month t from precipitation in the current and preceding month; BF(m,z) = base flow in each of the 12 months of the year that may reflect precipitation falling before as well as during months t and t-1; U(k) = dimensionless coefficients; N = number of quadrangles partially or completely in the watershed; P (i,t) = precipitation during month t in quadrangle i; PP(i,t) = portion of precipitation not contributing to Q(t) that becomes flow in the next month and/or hydrologic abstractions; E (i,t) = evaporation rates; X (i,j,z) = model parameters consisting of 5 N dimensionless 0.0-to-1.0 coefficients that may vary between zones; B (m,z) = base flow parameters for the 12 months of the year; DI(t) = dimensionless drought index that varies from 1.0 to 0.0 each month depending on the ratio of precipitation to evaporation volume; BX(z) and DX = dimensionless factors; $\overline{\mathrm{P}}(\mathrm{m})$and $\overline{\mathrm{E}}(\mathrm{m})$ = monthly means of precipitation and evaporation volumes for the 12 months of the year.

The flow extension model contains the following 4 (13+5 N)+3 parameters which are calibrated using naturalized flows from the WAM and precipitation and evaporation from the TWDB datasets: B (m,z), BX(z), DX, X (i,j,z), U (1) and U (2). The model regresses flows Q(t) with N time series of precipitation P (i,t) and evaporation E (i,t). The coefficients U (1), U (2), X (i,j,z), B (m,z), BX(z), and DX are determined based on known sequences of P (i,t), E (i,t), and Q(t).

The model components are related to physical processes. B (m,z) × DX(z) represents base flows for each of the 12 months of the year adjusted by a dimensionless drought index that reflects long-term hydrology. U(k) and X (i,j,z) are precipitation-runoff parameters. X (i,j,z) simulates runoff from each of N quadrangles encompassed partially or completely by the watershed above the site of the Q(t). U (1) and U (2) model the nonlinear response of stream flow to rainfall.

Calibration of the flow extension model is the difficult aspect of the process of extending the hydrologic period-of-analysis. Upon completion of the calibration, the calibrated model can be easily applied after the precipitation and evaporation updates each year to extend the naturalized flows without repeating the calibration. The flow extension process is designed to reproduce the statistical characteristics of the naturalized flows. The synthesized natural flow in each individual month is not necessarily highly accurate, but the procedure reasonably accurately replicates means, standard deviations, flow-frequency relationships, and serial correlation. The WRAP-HYD hydrologic model has been calibrated and applied for updates of several of the WAMs, including the Brazos WAM [13]. Wurbs [10] explains the methodology in detail using sites on tributaries of the Brazos River as examples.

9. Simulation model

The term “water right” is used in WRAP to refer to a set of water use requirements and associated constructed facilities and operating rules designed to supply the water use requirements. Many water right permits are modeled simply as WRAP water rights. However, a complicated actual water right permit may be simulated with multiple “model water rights”. Water use requirements and facilities that are not associated with water right permits are also modeled as “model water rights”. Flexibility is provided for simulating complicated water supply, hydropower, and instream flow target setting criteria and reservoir system operating rules.

The simulation model component of WRAP simulates a specified water management and use scenario during a repetition of hydrologic period-of-analysis natural hydrology. Simulation computations are performed in a water rights priority sequence that is embedded within a monthly time step loop that advances through the hydrologic period-of-analysis. For each sequential month of hydrology, water accounting computations are performed as each set of water use requirements (water right) is considered in priority order.

Essentially any configuration of stream tributaries and conveyance systems may be modeled. The 20 WAMs contain over 12,000 control points of which about 500 are primary. The WRAP term “primary” control point refers to a site, usually a gauge, at which naturalized stream flows are stored in the simulation input datasets. Naturalized flows at all other sites are computed in the simulation based on the naturalized flows at the primary control points and watershed parameters contained in the WAM datasets as discussed in Section 7.

Regulated and unappropriated flows are computed in the simulation for all any number of selected locations. Regulated flows represent stream flows hypothetically occurring when historical natural flow sequences are repeated with the water use scenario reflected in the WAM.

Unappropriated stream flows are the quantities still remaining after considering the water use and storage requirements of all water rights. Unappropriated flows may be less than regulated flows due to instream flow requirements and appropriations by senior water rights at downstream sites.

Simulation results time series variables for each month of the hydrologic period-of-analysis include: naturalized, regulated, and unappropriated flows, stream flow depletions, and return flows for each relevant site; channel losses for stream reaches; reservoir storage volume, surface elevation, net evaporation, inflows, releases, and diversions; diversion targets and shortages, return flows, available stream flows, stream flow depletions, and storage for each water supply right; hydropower targets, firm energy produced, secondary energy produced, energy shortages, and storage for each hydroelectric right; and flow target and shortage for each instream flow right.

10. Brazos WAM and flows at the Waco gauge on the Brazos River

The Brazos River Basin, Brazos WAM, and a representative gauge site are used here as an illustrative example. The Brazos River Basin encompasses an area of 123,000 km^2. The Brazos WAM combines the Brazos River Basin and adjoining San Jacinto-Brazos coastal basin. The 3000 km^2 coastal basin is located south of the City of Houston between the Brazos and San Jacinto River Basins. Naturalized monthly flows at 77 primary control points contained in the hydrology input file are distributed to over 3000 other sites with each execution of the simulation model [13].

The Brazos WAM simulates operation of 680 reservoirs and other facilities in accordance with 1220 water right permits which authorize annual diversions totaling 3.01×10^9 m^3/year in the Brazos River Basin (95.2%) and adjoining coastal basin (4.8%) for municipal (47.6%), industrial (30.1%), agricultural irrigation (18.0%), and other (4.3%) uses. The Brazos River Basin contains 673 reservoirs and the coastal basin has seven reservoirs cited in water right permits, of which 43 in the Brazos Basin and none in the coastal basin have conservation storage capacities of 6.17×10^6 m^3 or greater. The total authorized conservation storage capacities of the 680 reservoirs with water right permits is 5.79×10^9 m^3 as shown in the last line of Table 3. The conservation storage is used for water supply, hydroelectric energy, and recreation.

The 14 largest reservoirs in the Brazos River Basin and the Brazos WAM are listed in Table 3. Their locations are shown in the basin map of Fig. 12. These 14 largest reservoirs include all of the flood control storage capacity controlled by human outlet gate operations and 74.3% of the conservation storage capacity of the 680 reservoirs authorized by water right permits.

The West Central Texas Municipal Water District owns and operates Hubbard Creek Reservoir to supply water for several small cities. An electric power company owns and operates Squaw Creek Reservoir for cooling water for a nuclear power plant. Water is transported by pipeline from Granbury Reservoir to maintain a constant water level in Squaw Creek Reservoir. Operations of Whitney Reservoir includes hydroelectric energy generation, but essentially all releases through turbines are diverted at downstream sites on the Brazos for water supply.

The nine reservoirs with flood control storage capacity above the top of conservation storage are owned and operated by the U.S. Army Corps of Engineers (USACE). USACE flood control operations of the nine-reservoir system are based on flows at multiple downstream gauges and storage levels in the reservoirs. The Brazos River Authority (BRA) has contracted for the conservation storage capacity of the nine federal reservoirs. The BRA also owns and operates Possum Kingdom, Granbury, and Limestone Reservoirs. The BRA operates the 12 reservoirs as a system to supply the water needs of many cities, industries, and farmers.

Wurbs [13] documents both monthly and daily versions of the Brazos WAM. The daily version includes the complete monthly input dataset plus added data for disaggregating monthly naturalized flows to daily,

Table 3
Fourteen largest reservoirs in the Brazos River Basin.

Dam/ Reservoir	Stream	Storage Began	Storage Capacity (million cubic meters): Conservation	Flood Control	Total
Hubbard Creek	Hubbard Creek	1962	392	–	392
Squaw Creek	Squaw Creek	1977	187	–	187
Limestone	Navasota River	1978	278	–	278
Possum Kingdom	Brazos River	1941	894	–	894
Granbury	Brazos River	1969	191	–	191
Whitney	Brazos River	1951	785	1682	2467
Aquilla	Aquilla Creek	1983	65	115	180
Waco	Bosque River	1965	255	641	896
Proctor	Leon River	1963	73	388	462
Belton	Leon River	1954	565	790	1354
Stillhouse	Lampasas River	1968	291	487	778
Georgetown	San Gabriel River	1980	46	116	162
Granger	San Gabriel River	1980	81	220	301
Somerville	Yequa Creek	1967	198	428	626
Total Storage Capacity of 14 Reservoirs			4301	4867	9167
Total Storage Capacity of 680 Reservoirs			5792	4867	10,659

tracking pulse flow components of environmental flow standards, and simulating flood control operations of the nine USACE reservoirs. Monthly naturalized flow are disaggregated to daily within the SIMD simulation in proportion to assigned daily pattern hydrographs while preserving the monthly volumes. Daily naturalized flows at over 3000 gauged and ungauged sites are computed in the daily simulation using daily pattern hydrographs provided as input at 58 gauge sites consisting of unadjusted gauged flows combined with gauged flows adjusted by the USACE in their model of flood operations of the nine USACE reservoirs. Simulation results include monthly summations as well as daily quantities.

The authorized use scenario version of the monthly WAM is discussed in the remainder of this section. The original Brazos WAM has a hydrologic period-of-analysis of 1940–1997, which has been extended through December 2015 employing the same conventional procedures based on Eqs. (1) and (2) for adjusting observed flows to obtain naturalized flows. The WAM reflected in Figs. 13–15 and Table 4 includes 2016–2017 flows synthesized with the hydrologic model of Eqs. 9–13. Thus, the hydrologic simulation period is January 1940 through December 2017.

The gauge on the Brazos River just downstream of the City of Waco, which is adjacent to Waco Reservoir (Fig. 12), is adopted here for comparative analyses of observed, naturalized, and simulated regulated and unappropriated flows. This gauge has a drainage area of 51,800 km^2. Mean daily and monthly observed flows in m3/s during 1900–2020 at this site are plotted as the previously discussed Figs. 10 and 11. Mean monthly WAM 1940–2017 naturalized and regulated flows are plotted in Fig. 13. Annual means in m3/s for observed and WAM naturalized and regulated flows are plotted in Fig. 14.

Frequency statistics for the 936 monthly means in m3/s for alternative forms of 1940–2017 flows compared in Table 4 include the mean, standard deviation, minimum, maximum, and quantities that are exceeded during specified percentages of the 936 months of the simulation. The following flows are compared: observed flows measured at the USGS gauge; two alternative sets of naturalized flows; and regulated and unappropriated flows computed in the WRAP/WAM simulation with the first set on naturalized flows. The extreme natural variability characteristic of river flows throughout Texas is illustrated by the plots and frequency metrics. The effects of water resources development and use are also demonstrated.

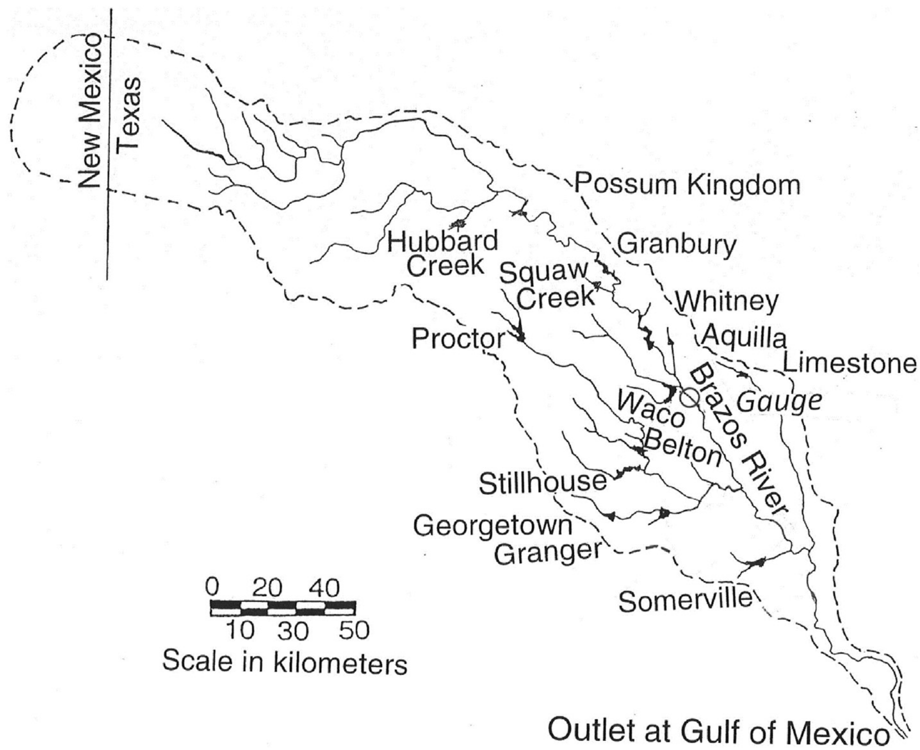

Fig. 12. Brazos River Basin map with fourteen largest reservoirs and gauge near Waco.

Two alternative sets of naturalized flows are compared in the third and fourth columns of Table 4. The third column reflects flows actually adopted for simulation consisting of 1940–2015 naturalized flows developed by adjusting observed flows (Eqs. (1) and (2)) combined with a 2016–2017 extension using Eqs. (10)–(14). Statistics added as the fourth column for comparison reflect 1940–2017 synthesized (Eqs. (10)–(14)) flows developed by calibrating the HYD hydrologic model using original WAM 1940–1997 naturalized flows and then computing 1940–2017 flows with the calibrated model combined with 1940–2017 precipitation and evaporation.

Simulation results in Figs. 13–15 and Table 4 are for the authorized use scenario with all water right permit holders appropriating the full amounts authorized by their permits. The simulated regulated flows combine authorized reservoir storage and water use with a hypothetical repetition of 1940–2017 hydrology. The unappropriated flows in the last column of Table 4 represent the portion of the regulated flow at the Waco gauge remaining for appropriation by additional future water right permit applicants. The metrics for unappropriated flow are much smaller than for regulated flow because much of the regulated flow is passed through the Waco gauge site for downstream water supply diversions and environmental instream flow requirements.

The total storage contents of the 680 reservoirs in the Brazos WAM are plotted in Fig. 15. Contents of individual reservoirs exhibit greater variability than the summations for 680 reservoirs that average out differences in timing of fluctuations between reservoirs. Fig. 15 provides a drought index that is reflective of most of Texas. The most hydrologically severe drought since before 1900 began gradually in 1950 and ended with major statewide flooding in April–May 1957. The lowest annual precipitation since before 1900 occurred in 2011 for over half of Texas. Other significant droughts occurred between the 1950–1957 and 2010–2012 extreme droughts. The state has experienced abundant rainfall and stream flow including major flooding during 2014–2020.

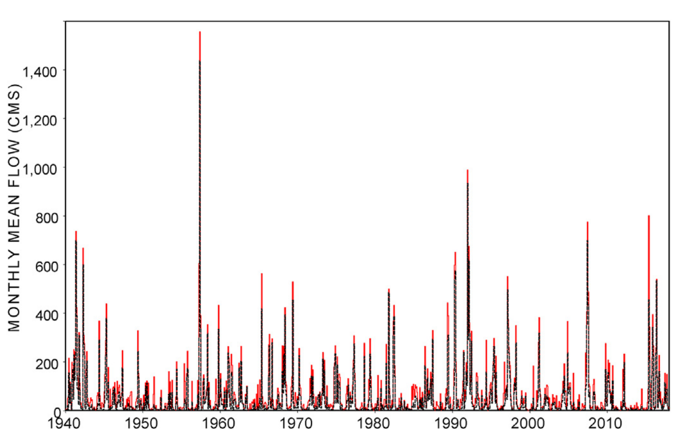

Fig. 13. WAM 1940–2017 monthly naturalized (red solid line) and regulated (blue dashed line) flows of the Brazos River at the Waco gauge in m^3/s.

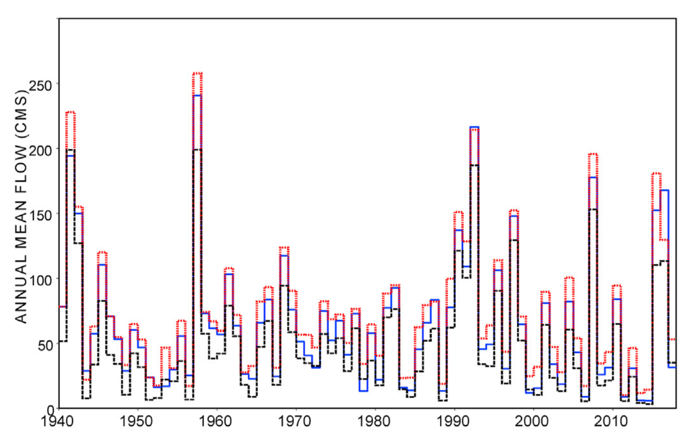

Fig. 14. Observed (blue solid line), naturalized (red dotted line), and simulated regulated (black dashed line) 1940–2017 annual mean flows in m^3/s of the Brazos River at the Waco gauge.

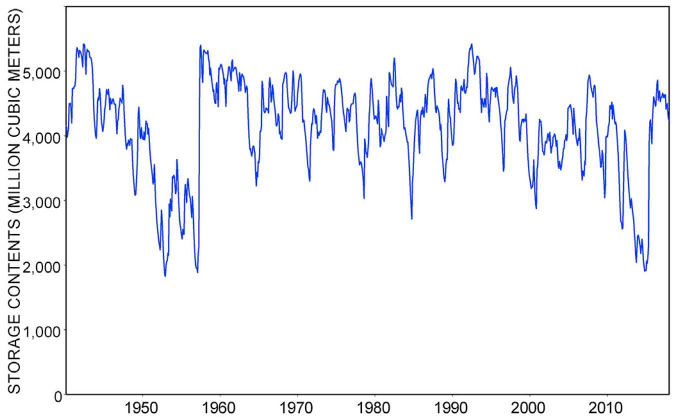

Fig. 15. Summation of simulated storage volume in Mm^3 of the 680 reservoirs in the Brazos WAM for the authorized use scenario and 1940–2017 natural hydrology.

Table 4
Frequency metrics for monthly flows of the Brazos River at the Waco gauge.

	Observed	Naturalized Flow (m^3/s)		Simulated Flow (m^3/s)	
	Flow (m^3/s)	Eqs. (1)-2)	Eqs. (10)–(14)	Regulated	Unappropriated
Mean	64.0	72.8	78.3	49.8	33.3
Stand Dev	109	121	118	105	99.4
Minimum	0.792	0.00	0.00	0.00	0.00
99%	1.28	0.176	1.02	0.015	0.00
98%	1.95	0.800	1.42	0.143	0.00
95%	3.40	2.35	3.09	0.754	0.00
90%	5.64	4.43	4.60	1.39	0.00
80%	11.6	8.40	9.97	2.82	0.00
70%	16.3	13.1	15.7	4.35	0.00
60%	20.6	18.9	22.3	7.06	0.00
50%	26.6	29.3	34.1	10.6	0.00
40%	34.4	46.1	49.3	18.5	0.00
30%	50.8	66.2	72.2	33.5	1.37
20%	80.0	104	116	63.2	28.6
10%	158	193	207	141	106
Maximum	1050	1550	885	1440	1430

11. Comparison of natural and simulated regulated flows from Texas river basins

River basin characteristics and WAM naturalized and regulated flows near the outlets of the ten rivers that flow directly into the Gulf of Mexico are compared in Tables 5–7. The regulated flows reflect the current use WAM scenario representing recent actual conditions of water use. Water supply targets are less for the current use than authorized use scenario because many permits include projected future water needs. A consistent hydrologic period-of-analysis of 1940–2012 is adopted for the simulations reflected in the tables for six of the WAMs. Periods-of-analysis for the other four WAMs vary but are all longer than 50 years. Metrics illustrating the diverse hydrologic characteristics of the river basins include mean annual precipitation and reservoir evaporation rates, mean river flow at the basin outlet for natural undeveloped conditions as a percentage of mean precipitation, reservoir storage capacity as a percentage of annual natural flow (ANF) at the outlet, and comparisons of frequency metrics for natural and simulated regulated flows for current conditions.

Table 6
Frequency metrics for monthly naturalized flows in m^3/s at the basin outlets.

Basin	Mean	Standard	Flow in m^3/s with Following Exceedance Frequencies				
WAM	(m^3/s)	Deviation	90%	75%	50%	25%	10%
Rio Grande	43.0	39.6	18.8	23.9	31.9	48.6	74.5
Nueces	25.3	59.3	0.68	1.92	5.82	22.4	66.6
Guadalupe	86.8	1118	12.5	27.2	49.2	104	204
Lavaca	33.6	58.0	1.31	3.84	10.4	35.2	97.8
Colorado	122	153	21.5	35.5	66.7	152	283
Brazos	283	369	27.7	61.7	144	345	731
San Jacinto	88.7	119	6.84	15.2	40.8	117	246
Trinity	259	318	14.3	47.2	134	352	674
Neches	243	274	20.3	46.4	135	357	622
Sabine	259	265	27.6	61.0	164	386	627

Quantities in Tables 5–7 for the Rio Grande and Sabine River Basins reflect only the watershed area in Texas and only the stream flow allocated to Texas by treaties and interstate compacts. The Rio Grande is very different than the other rivers. The large arid Rio Grande Basin lies in Mexico and three states in the United States. About half of the watershed contributes no flow to the river. Water resources are severely over-appropriated by allocations between the two nations, three states in the United States, and numerous water users.

The river basins are listed in the tables from west to east (Fig. 1). The San Antonio River is a tributary of the Guadalupe River and is included in the Guadalupe WAM. The mean annual precipitation and reservoir evaporation for each river basin are tabulated in Table 4 in cm/year. The mean annual naturalized flow volume near the basin outlet is shown as a percentage of the annual precipitation volume in Table 5 and in m^3/s in Table 6. The total conservation storage capacity of 2960 reservoirs in both 10^9 m^3 and percentage of the annual naturalized flow (ANF) volume near the basin outlet is tabulated as the last two columns of Table 5. The conservation storage capacity does not include surcharge or flood control storage.

The mean, standard deviation, and flow quantities exceeded with specified frequencies are tabulated in Table 6 for monthly naturalized flows near the river outlets at the Gulf of Mexico. Monthly naturalized flow quantities in Table 6 are in m^3/s. The same metrics are tabulated in

Table 5
Hydrologic characteristics of ten Texas river basins.

River Basin	Watershed Area		Mean	Mean	Natural	Reservoir	
	Total	Texas	Evap	Precip	Flow	Storage Capacity	
	(10^6km^2)	(Mkm^2)	(cm/yr)	(cm/yr)	(%Precip)	(10^9m^3)	(% ANF)
Rio Grande	472,000	128,000	163	40.9	2.60%	4320	318%
Nueces	43,300	43,300	151	63.0	2.93%	1180	148%
Guadalupe	26,200	26,200	137	101	12.7%	934	34.1%
Lavaca	5980	5980	129	82.3	17.6%	207	19.5%
Colorado	107,400	106,900	160	62.2	5.79%	5810	151%
Brazos	123,000	115,000	153	74.7	10.4%	4960	55.4%
San Jacinto	10,190	10,190	124	118	23.2%	725	25.9%
Trinity	46,400	46,400	140	100	17.6%	9080	111%
Neches	25,700	25,700	123	124	24.1%	4510	58.7%
Sabine	25,300	19,600	129	121	34.4%	7730	94.4%

Table 7
Frequency metrics for monthly regulated flows at the basin outlets expressed as a percentage of the naturalized flow metrics in Table 6.

Basin	Mean	Standard	Regulated Flow Metrics as Percent of Naturalized Flow				
WAM	(% Nat)	Deviation	90%	75%	50%	25%	10%
Rio Grande	6.84%	42.6%	0.33%	0.66%	1.02%	1.41%	3.02%
Nueces	68.0%	71.3%	659%	255%	107%	51.4%	48.7%
Guadalupe	92.9%	98.8%	75.0%	79.1%	87.6%	92.8%	97.5%
Lavaca	93.7%	97.9%	99.5%	90.9%	81.5%	92.0%	97.0%
Colorado	61.2%	86.0%	6.9%	27.3%	34.1%	57.7%	68.7%
Brazos	84.2%	97.2%	24.6%	47.4%	64.1%	85.5%	91.9%
San Jacinto	106%	96.1%	332%	184%	115%	95.8%	98.7%
Trinity	72.8%	88.1%	46.2%	22.6%	47.8%	72.1%	82.2%
Neches	89.5%	101%	3.9%	29.8%	77.9%	92.1%	96.4%
Sabine	93.3%	102%	53.4%	61.9%	85.1%	96.8%	98.8%

Table 7 for simulated regulated flows for the WAM current use scenario expressed as a percentage of the metrics for naturalized flows. The percentages in Table 7 vary greatly and informatively. Table 7 demonstrates the impacts of basin-wide water resources development and use on the flows of the rivers at their outlets.

The mean and median (50% exceedance) simulated regulated flow of the Rio Grande are 6.84% and 1.02% of the mean and median of the naturalized flows. Construction of Amistad and Falcon Reservoirs on the Rio Grande and other reservoirs on tributaries and development of extensive irrigated agriculture in this arid region depletes almost all discharge into the Gulf of Mexico. Water supply is highly dependent on filling reservoir storage during infrequent floods.

The mean and median regulated flow of the Colorado River in Table 7 are 61.2% and 34.1% of the corresponding naturalized flow metrics, reflecting extensive agricultural, municipal, and industrial water use in the Colorado River Basin. The mean and median regulated flow of the San Jacinto River are 106% and 115% of the naturalized flow metrics. The City of Houston and adjacent cities obtain much of their water supply from groundwater and imports from other river basins but discharge their wastewater treatment effluent into the San Jacinto River or its tributaries.

12. Conclusions

The WRAP/WAM modeling system supports statewide and regional planning, operational planning, water allocation, research, and other water management endeavors in Texas. Most applications focus on assessment of water availability and supply reliability for specific water users. The modeling system is employed in this paper to explore river flow characteristics throughout the state.

The WRAP modeling and analysis methodologies and software are applicable any place in the world. Modeling and data management software and documentation and datasets discussed in this paper are available at websites referenced and discussed in the paper.

Application of the generalized WRAP modeling system consists of compiling hydrology and water management simulation input datasets that includes adjusting observed flows to represent natural conditions, simulations that result in many time series variables including regulated flows, and statistical analyses of simulation results.

River basin hydrology is characterized by extreme spatial and temporal variability. Temporal variability throughout Texas includes severe multiple-year droughts and intense floods as well as year-to-year, seasonal, and continuous fluctuations. Water resources development and management are governed largely by the extremes of floods and droughts. Large volumes of reservoir storage are essential. Numerous dams and reservoirs have been constructed in Texas, most during the 1940s-1980's. Water use has continued to steadily increase from before the 1940s through the present with continual population and economic growth.

The WAM system and related databases maintained by water agencies in Texas provide unique opportunities to explore long-term changes in river/reservoir system hydrology. Permanent long-term changes in monthly 1940–2019 precipitation and 1954–2019 reservoir evaporation rates are not evident and are considered minimal if such changes have occurred at all. Stream flows have been significantly altered for many but not all reaches of the rivers of the state by water resources development and use. The alterations in flow characteristics vary greatly with location. Long-term changes in daily flows may differ greatly from changes in monthly flows at the same site. Changes in median flows versus low flow characteristics versus flood flows are very different.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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