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Storage and Regulation of River Flows by Dams and Reservoirs

Ralph A. Wurbs[1]

Abstract: Water management in Texas is driven by dramatic spatial and temporal hydrologic variability, continual rapid population growth, declining groundwater supplies, and intensifying demands on surface water resources. Dams and reservoirs are essential for providing reliable water supplies and reducing flood risks. Numerous reservoir projects, most constructed during the 1940s through 1980s era of large-scale water project construction nationwide, are operated throughout the state to store and regulate extremely variable river flows for beneficial purposes. This paper explores river system hydrology in Texas, operation of dams and reservoirs statewide to deal with extreme flow fluctuations, and associated complexities, issues, and water management strategies. The central focus of the paper is the role of large reservoirs in managing hydrologic variability and associated future uncertainty in an environment of growing demands on limited resources.

Keywords: dams, reservoir/river systems, hydrologic variability

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Terms used in paper

Acronym/Initialism	Descriptive Name
ASCE	American Society of Civil Engineers
AWRA	American Water Resources Association
BRA	Brazos River Authority
cfs	cubic feet per second
CRMWD	Canadian River Municipal Water District
DSS	data storage system
EFS	environmental flow standard
FWD	Fort Worth District of USACE
GBRA	Guadalupe-Blanco River Authority
HEC	Hydrologic Engineering Center
IBWC	International Boundary and Water Commission
LCRA	Lower Colorado River Authority
M&I	municipal and industrial
NF	naturalized flows
NFIP	National Flood Insurance Program
SB	Senate Bill
SRA	Sabine River Authority
SWPA	Southwest Power Administration
TRWD	Tarrant Regional Water District
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
TWRI	Texas Water Resources Institute
TRA	Trinity River Authority
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
WAPA	Western Area Power Administration
WAM	water availability model
WRAP	water rights analysis package

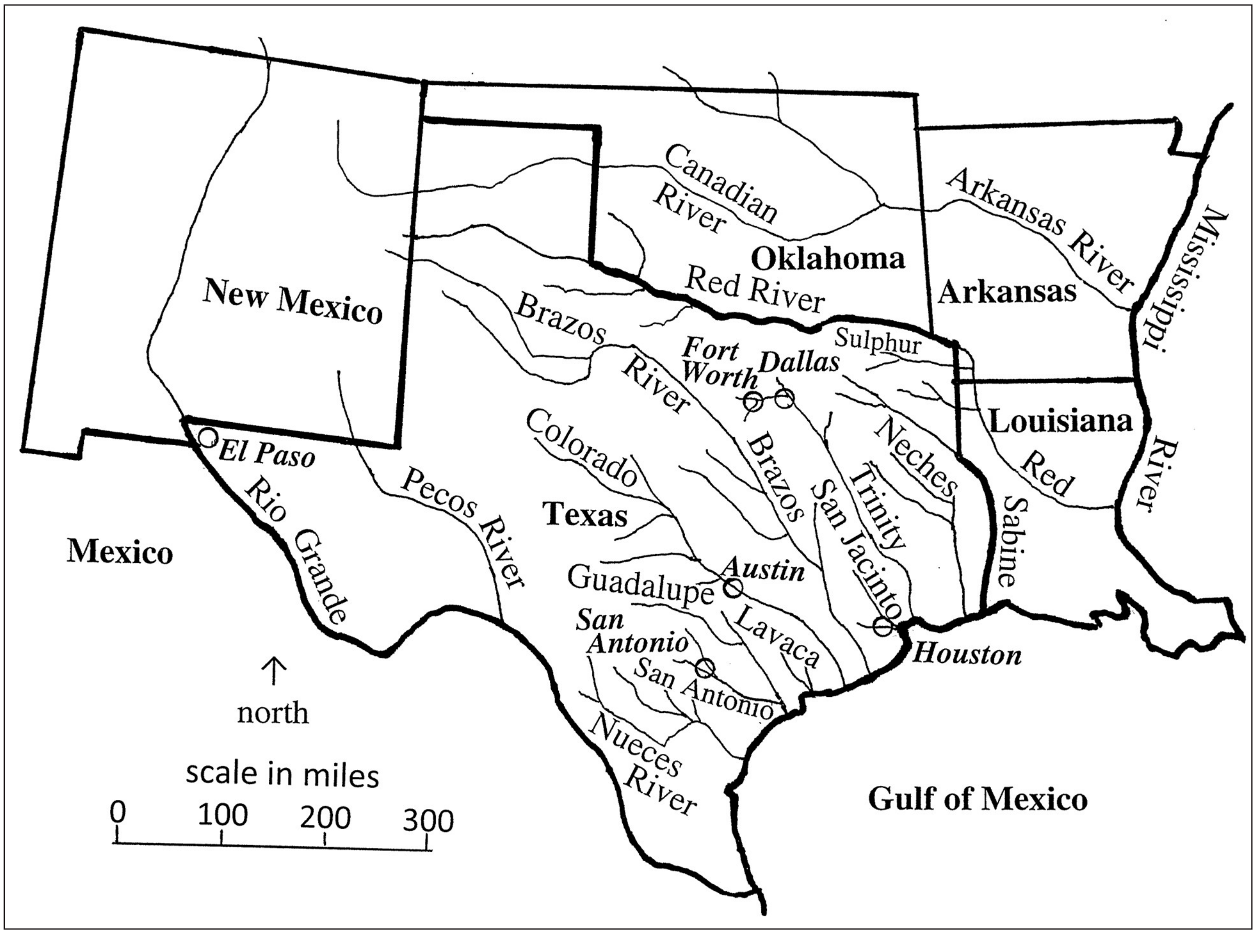

Figure 1. Major rivers and largest cities of Texas.

INTRODUCTION

This paper describes the major reservoirs of Texas and the hydrologic and institutional environment for reservoir operations and explores river regulation purposes, practices, challenges, and concerns. Dam and reservoir projects are fundamental to water management in Texas. Reservoir water conservation storage capacity is necessary to use highly fluctuating water resources of river basins for beneficial purposes such as municipal and industrial water supply, agricultural irrigation, hydroelectric power generation, and recreation. Constructed dams and appurtenant structures also regulate rivers to reduce damages caused by floods. Water quality, erosion and sedimentation, and protection and enhancement of fish, wildlife, and other environmental resources are important considerations in managing reservoir/river systems.

Climate, geography, economic development, water use, and water management practices vary greatly across Texas from the arid western desert to humid eastern forests, from sparsely populated rural regions to the metropolitan areas encompassing the cities shown in Figure 1. The state population increased from about 3,000,000 people in 1900 to 14,200,000 in 1960, 21,000,000 in 2000, and 29,500,000 in 2020, and is projected by the Texas Water Development Board (TWDB) to increase to 46,400,000 by 2060 (TWDB 1984, 2017). Municipal and industrial (M&I) water use continues to steadily increase along with a leveling off of agricultural irrigation due largely to limited water availability. Instream flow for ecosystem preservation is a major concern (National Research Council 2005; Wurbs 2017a). Declining groundwater supplies combined with population growth are resulting in intensified demands on surface water resources (TWDB 2017). Water supply was about 60% from ground water and 40% from surface water sources in 1980 (TWDB 1984). Water use data collected by the TWDB indicate that water use during 2018 was supplied from groundwater (54%), surface water (43%), and reuse (3%).

Hydrology in Texas varies dramatically from the extremes of devastatingly intense floods to costly multiple-year droughts, along with seasonal and less severe random between-year and within-year fluctuations in precipitation and stream flow. Construction of dam and reservoir projects has significantly reduced stream flow variability while increasing supply availability and reliability, but flows are still extremely variable. The hydrologically most severe drought since before 1900 for most of the state began gradually in 1950 and ended in April 1957 with one of the greatest floods on record. Major droughts in the 1910s and 1930s also affected large areas of Texas. More recent droughts were much more economically costly due to population and economic growth. The 2008–2014 drought is comparable in hydrologic severity to the 1950–1957 drought in some areas of the state (Winters 2013). For more than half of Texas, 2011 had the lowest annual precipitation since the beginning of official precipitation records in 1895 (Nielson-Gammon 2012). On the other extreme, 2015 was one of the wettest years on record, with multiple major floods. The several very costly floods since 2015 include those resulting from Hurricane Harvey in 2017 (ASCE 2018), Tropical Storm Imelda in 2019, and several storms during 2020.

Much of the quantitative information presented in this paper is from the water availability modeling (WAM) system maintained by the Texas Commission on Environmental Quality (TCEQ; Wurbs 2005; Alexander and Chenoweth 2020). The TCEQ WAM system consists of the Water Rights Analysis Package (WRAP) and simulation input datasets for all of the river basins of Texas. The WRAP modeling system (Wurbs 2019a, b, c; Wurbs and Hoffpauir 2019) developed at Texas A&M University (TAMU) is generalized for application to any river/reservoir system. Wurbs (2020b) describes the institutional framework for developing and implementing the WRAP/WAM modeling system in Texas. WRAP software and documentation are available at the TAMU WRAP website (https://wrap.engr.tamu.edu/), which links with the TCEQ WAM website, which provides an array of information including WRAP input datasets for all Texas river basins (https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html). The generalized WRAP simulation model combined with an input dataset from the TCEQ WAM system for a particular river basin is called a water availability model (WAM).

The 20 WAMs covering all of Texas simulate over 3,400 reservoirs and other constructed water control and conveyance facilities, institutional systems for allocating and managing water resources, and river system hydrology. Eighty-two reservoirs with storage capacities exceeding 50,000 acre-feet account for about 92% of the total permitted conservation storage capacity of the over 3,400 reservoirs. WAM datasets are available for alternative water use scenarios. The authorized use scenario is based on the premise that all water right permit holders use the full amounts authorized in their permits. The current use scenario is based on recent actual water use.

The WAM system is used by TCEQ staff and water right permit applicants, or their consultants, in administration of the water rights system and the TWDB and regional planning groups, or their consultants, in regional and statewide planning. River authorities apply the modeling system in operational planning studies for their specific reservoir systems. The WAM system is employed in this paper to investigate the characteristics of river/reservoir system hydrology and water management capabilities throughout the state.

A data storage system (DSS) developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) is integrated in the WRAP modeling system to manage time series data. The DSS interface HEC-DSSVue (HEC 2009) is employed to manage data and create the time series plots presented in this paper.

INVENTORY OF DAMS AND RESERVOIRS

Many thousands of reservoirs are scattered throughout Texas. Most of the storage capacity is contained in a relatively few of the largest reservoirs. The TWDB and this paper define a major reservoir as having a storage capacity of 5,000 acre-feet or larger at its normal operating level. This definition generally does not include flood control storage capacity that remains empty except during and immediately following floods.

The TWDB has delineated the 15 major river basins and eight coastal basins of the state and inventoried the reservoirs in each river basin with descriptive information. This inventory includes the 188 major water supply reservoirs and 20 other major reservoirs that serve no water supply function (https://www.twdb.texas.gov/surfacewater/rivers/reservoirs/index.asp). Map locations and historical and current storage levels and statistical storage data for 114 large reservoirs that represent 96% of the total conservation storage capacity of the 188 water supply reservoirs are available at https://www.waterdatafortexas.org/reservoirs/statewide.

The Texas state water plan includes discussions of both existing and proposed new reservoirs. The 1984 Texas state water plan (TWDB 1984) included 44 proposed new reservoirs to supply growing water needs. Over 4,500 individual strategies recommended by regional planning groups are included in the 2017 Texas state water plan for developing new water supplies by 2060 (TWDB 2017). These recommendations include 14 major reservoirs for future construction that would account for about 12% of new water supplies at a capital cost of about 16% of the total capital cost for new supplies.

Table 1. Reservoirs with total storage capacities of 500,000 acre-feet or greater.

	Reservoir/dam	River of dam	Owner	Initial storage	Area (acres)	Storage capacity (acre-feet)		
						Conservation	Flood control	Total
1	Texoma/Denison	Red River	U.S. Army Corps of Engineers (USACE) Tulsa District	1943	78,400	2,441,000	2,660,000	5,101,000
2	International Amistad	Rio Grande	International Boundary and Water Commission (IBWC)	1968	66,500	2,977,000	1,744,000	4,721,000
3	Toledo Bend	Sabine River	Sabine River Authority (SRA)	1966	182,500	4,453,000	–	4,453,000
4	Sam Rayburn	Angelina River	USACE	1965	112,600	2,888,000	1,099,000	3,987,000
5	International Falcon	Rio Grande	IBWC	1953	85,200	2,648,000	910,000	3,558,000
6	Wright Patman	Sulphur River	USACE Fort Worth District (FWD)	1956	18,200	145,000	2,509,000	2,654,000
7	Whitney	Brazos River	USACE FWD	1951	23,200	561,000	1,372,000	1,933,000
8	Travis/Mansfield	Colorado River	Lower Colorado River Authority (LCRA)	1940	19,000	1,132,000	779,000	1,911,000
9	Livingston	Trinity River	Trinity River Authority (TRA)	1969	32,600	1,740,000	–	1,740,000
10	Meredith/Sanford	Canadian River	Canadian River Municipal Water District CRMWD	1941	16,400	808,000	543,000	1,351,000
11	Richland-Chambers	Richland Creek	Tarrant Regional Water District (TRWD)	1987	43,400	1,109,000	–	1,109,000
12	Belton	Leon River	USACE FWD	1954	12,100	433,000	640,000	1,073,000
13	Ray Roberts	Elm Fork Trinity	USACE FWD	1987	28,600	796,000	265,000	1,061,000
14	Lewisville	Elm Fork Trinity	USACE FWD	1954	27,200	614,000	363,000	977,000
15	Buchanan	Colorado River	LCRA	1937	22,100	889,000	–	889,000
16	Tawakoni/Iron Bridge	Sabine River	SRA	1960	37,300	885,000	–	885,000
17	Lake O' the Pines	Cypress Creek	USACE FWD	1957	16,900	241,000	587,000	828,000
18	Canyon	Guadalupe River	USACE FWD	1964	8,310	372,000	395,000	767,000
19	Waco	Bosque River	USACE FWD	1965	8,190	207,000	506,000	713,000
20	Lavon	East Fork Trinity	USACE FWD	1953	20,600	419,000	292,000	711,000
21	Choke Canyon	Frio River	Corpus Christi	1982	26,000	693,000	–	693,000
22	Lake Fork	Lake Fork Cr	SRA	1979	27,300	636,000	–	636,000
23	Twin Buttes	South Concho	San Angelo	1962	8,450	178,000	454,000	632,000
24	Cedar Creek	Cedar Creek	TRWD	1965	1,560	631,000	–	631,000
25	Stillhouse Hollow	Lampasas River	USACE FWD	1968	6,480	224,000	391,000	615,000
26	Kemp	Wichita River	Wichita Falls	1922	15,400	318,000	248,000	566,000
27	Possum Kingdom	Brazos River	Brazos River Authority (BRA)	1941	16,700	552,000	–	552,000

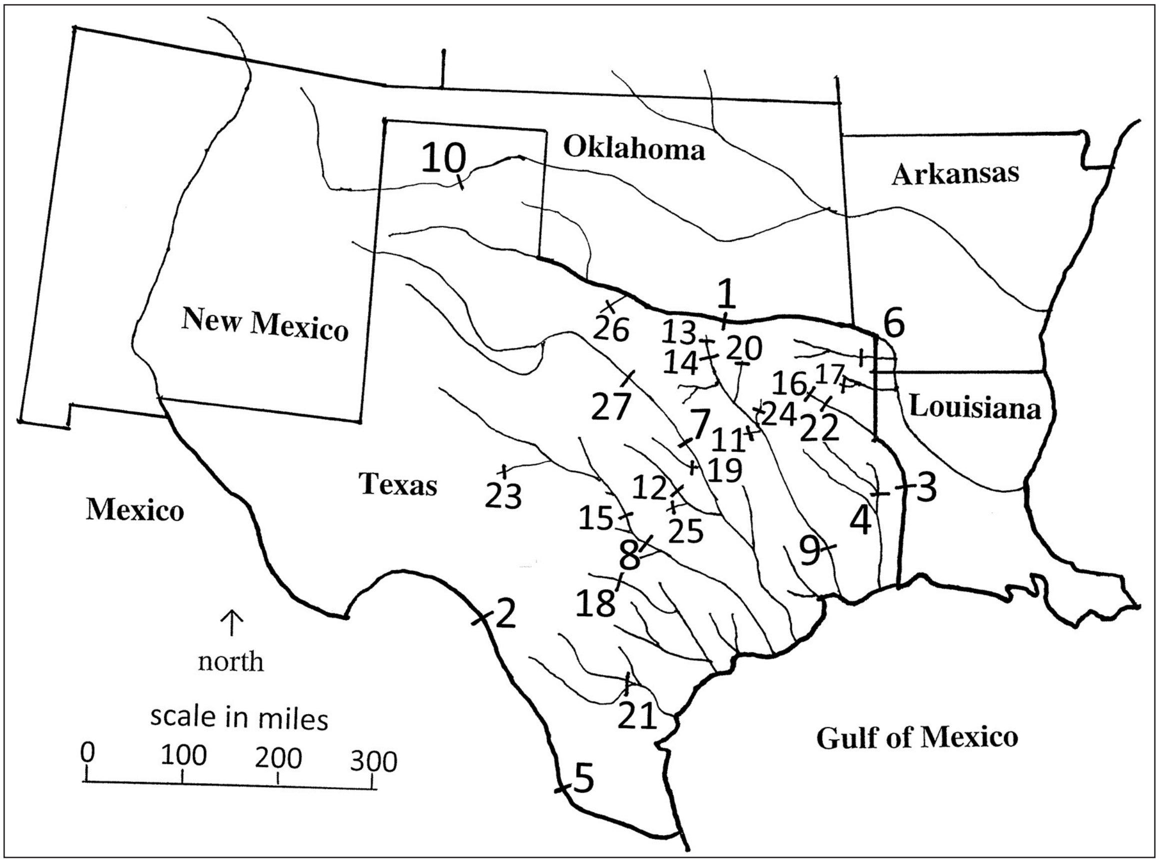

Figure 2. Locations of the dams of the 27 largest reservoirs in Texas listed in Table 1.

Largest reservoirs

Reservoirs located partially or completely in Texas with total capacities of 500,000 acre-feet or larger are listed in Table 1. The reservoir name is followed by the name of the dam if the names are different. These 27 largest reservoirs have conservation (water supply, hydropower, recreation), operator-controlled flood control, and total storage capacities totaling 28,990,000, 15,757,000 and 44,747,000 acre-feet, respectively, which represents about 71%, 97%, and 78% of the totals for all reservoirs located partially or completely in Texas. The total water surface area at top of conservation pool for the 27 reservoirs is 882,790 acres. Major portions of the storage capacity of International Lakes Amistad and Falcon on the Rio Grande, Lake Texoma on the Red River, and Toledo Bend on the Sabine River (Figures 1 and 2) are controlled by Mexico, Oklahoma, and Louisiana.

The conservation storage capacity estimates listed in Table 1 are primarily from the TCEQ current use scenario WAMs. The reservoir flood control storage capacities are from USACE and International Boundary and Water Commission (IBWC) information. The numbers in the first column of Table 1 reference the dam site locations on the map of Figure 2 as well as relative size ranked by total storage capacity.

Reservoirs with and without water right permits

The TCEQ WAM datasets include all reservoirs associated with water right permits. A dam with a storage capacity of up to 200 acre-feet can generally be constructed for domestic and livestock purposes without a permit subject to requirements in Texas law. Water right permits are not required for flood control storage. The fully authorized and current use scenario datasets include 3,460 and 3,446 reservoirs, respectively (Wurbs 2019a). The full authorization WAMs include existing and permitted but not yet constructed reservoirs. The current use datasets include only existing reservoirs. The 210 major reservoirs with 5,000 acre-feet or greater conservation storage capacities in the authorized and current use datasets contain 98.0% and 97.8% of the total conservation storage capacity of the 3,460 and 3, 446 reservoirs. The respective 62 and 58 reservoirs with capacities of 100,000 acre-feet or greater contain 89.3% and 89.5% of the total conservation capacity in the authorized and current use datasets (Wurbs 2019a).

The storage capacities of most of the reservoirs in the full authorization scenario WAMs reflect conditions at the time of construction. Capacities of many of the reservoirs for which sediment surveys have been performed have been updated in the current use scenario WAMs.

Thousands of farm and recreation ponds, urban storm water detention basins, and other storage facilities smaller than 200 acre-feet are not included in water right permits and the TCEQ WAM system. Flood control storage does not require a water right permit. The Natural Resource Conservation Service (NRCS) has constructed about 2,000 flood retarding dams in rural watersheds of Texas that are empty or have only minimal storage content during non-flood periods. Addicks and Barker Dams in Houston, with capacities of 204,500 and 207,000 acre-feet, are operated by the USACE Galveston District for flood control, storing water only during and after floods. Releases from Addicks and Barker Reservoirs are controlled by USACE personnel by operation of gated outlet structures. Flows through numerous storm water detention facilities and the approximately 2,000 NRCS flood retarding dams are controlled by ungated outlet structures without human operators.

Oldest and newest major reservoirs

Caddo Lake on Cypress Bayou on the Texas/Louisiana border is the only natural lake in Texas with storage capacity of 5,000 acre-feet or greater. However, a dam was constructed by a private company in 1914 to raise the water level and then reconstructed by the USACE in 1968–1971 to preserve the lake. Caddo Lake has a storage capacity of 129,000 acre-feet and surface area of 26,800 acres.

Wurbs (1985) inventories and describes conservation and flood control operations of the 187 major reservoirs in Texas that were either existing or under construction as of 1985. Although a few small dams were constructed in Texas before 1900, with the exception of Caddo Lake, Eagle Lake is the oldest of the major reservoirs still in existence (Dowell and Breeding 1967). Eagle Lake, with impoundment beginning in 1900, is a 9,600 acre-feet irrigation reservoir in the Colorado River Basin. The 35 major reservoirs in operation in 1935 were relatively small projects constructed for irrigation, M&I water supply, and/or hydroelectric power.

Lake Gilmer, constructed during 1999–2001 in northeast Texas, is the newest major reservoir in Texas that is actually in full operation. Lake Gilmer is owned by the City of Gilmer and has a water supply storage capacity of 12,720 acre-feet with a surface area of 895 acres.

The Lower Colorado River Authority (LCRA) Arbuckle Reservoir was substantially completed in 2019, but additional remedial work is required to mitigate seepage problems before water can be stored. The off-channel reservoir located in Wharton County will have a storage capacity of 40,000 acre-feet and cover an area of 1,100 acres.

Construction of the Bois d'Arc Reservoir project began in 2018 and is still underway in late 2020. This reservoir being developed by the Northeast Texas Municipal Water District will have a water supply storage capacity of 368,000 acre-feet and water surface area of 16,640 acres.

Construction of the Lake Ralph Hall municipal water supply project by the Upper Trinity Regional Water District is scheduled to begin in 2021 with water delivery expected by 2025. This lake on the North Sulphur River will have a surface area of 7,600 acres.

RIVER SYSTEM HYDROLOGY

Variability and stationarity of precipitation, reservoir evaporation, and stream flow are key considerations in the development and operation of reservoir projects. Hydrology varies greatly both temporally and spatially across Texas. Hydrologic variability over time includes multiple-year, year-to-year, seasonal, storm-event, and continuous fluctuations that include the extremes of floods and droughts as well as more frequent but less severe variations in weather and stream flow. Hydrologic variability and associated water supply reliability, flood risk, and future uncertainty are fundamental to water management. Stationarity, or lack thereof (non-stationarity), refers to long-term homogeneity over time with no permanent changes or trends. Stationarity, as well as variability of precipitation, evaporation, and stream flow, is important in exploring reservoir operations and other aspects of hydrology and water management.

Precipitation and reservoir evaporation depths

Precipitation and watershed evapotranspiration are climatic drivers of river flows, including inflows to reservoirs. Lake surface evaporation significantly contributes to the drawdown of the volume of water stored in a reservoir. The net difference between precipitation falling on the water surface and evaporation from the water surface is a major component of reservoir water budgets. General observations regarding variability and stationarity of precipitation, lake surface evaporation rates, and net lake evaporation less precipitation rates are presented as follows.

The TWDB maintains annually updated datasets of monthly precipitation rates beginning in January 1940 and monthly reservoir surface evaporation rates beginning in January 1954 for 92 one-degree latitude by one-degree longitude quadrangles comprising a grid that encompasses the state (https://waterdatafortexas.org/lake-evaporation-rainfall). The number of gages has varied over time, but now includes about 3,960

			16.9 60.2	17.8 67.3	18.7 67.2	21.0 64.6	24.1 59.9						
			16.8 63.4	18.5 66.0	20.4 66.3	24.0 64.1	27.8 59.2						
			16.7 62.8	18.3 63.6	20.7 65.8	22.2 65.9	26.0 64.2	30.9 59.0					
			16.0 63.4	18.1 65.4	22.8 68.1	23.0 70.0	25.5 64.6	29.8 60.8	34.7 55.4	41.0 53.4	46.3 52.6	49.1 43.3	51.2 39.7
			15.5 68.2	17.2 71.2	20.7 70.3	22.7 65.8	26.4 63.3	30.2 59.3	33.9 57.4	38.8 56.9	43.7 54.8	47.8 49.2	50.8 45.6
10.9 69.7	14.5 70.4	14.7 64.9	11.7 67.9	13.5 70.9	18.1 68.7	21.4 66.0	24.8 65.9	29.1 56.6	33.1 56.3	38.5 59.1	44.2 52.8	49.3 47.3	53.5 48.7
9.29 70.0	15.6 62.6	13.8 55.6	15.0 58.0	13.7 63.1	19.0 63.1	22.5 61.9	25.4 57.2	30.4 54.0	33.2 52.2	40.0 53.8	46.9 49.9	54.7 45.5	57.1 46.6
		20.1 55.9	14.7 55.7	11.8 65.5	16.9 68.9	24.5 67.0	26.7 56.7	31.4 53.6	34.5 52.6	41.7 49.9	47.6 47.0	49.3 46.0	57.4 45.7
						20.7 67.1	22.0 59.5	25.4 57.1	35.0 52.8	39.7 50.2	44.5 48.4		
							20.4 65.1	23.9 63.4	29.4 59.1	34.8 54.5			
							17.8 64.7	21.8 61.2	25.9 61.8				
									26.2 60.7				

Figure 3. Mean annual precipitation and reservoir evaporation depths in inches.

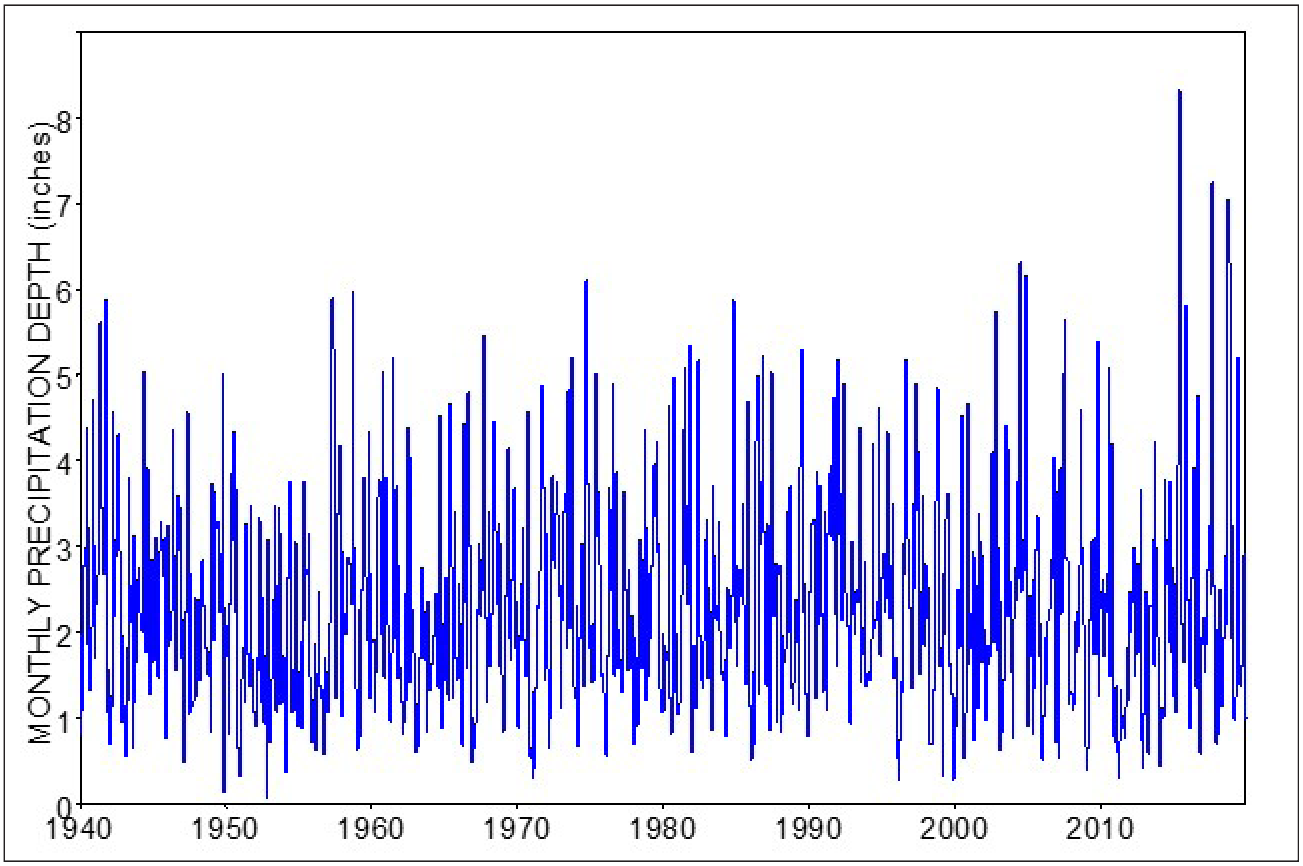

Figure 4. Statewide average 1940–2019 monthly precipitation depths in inches.

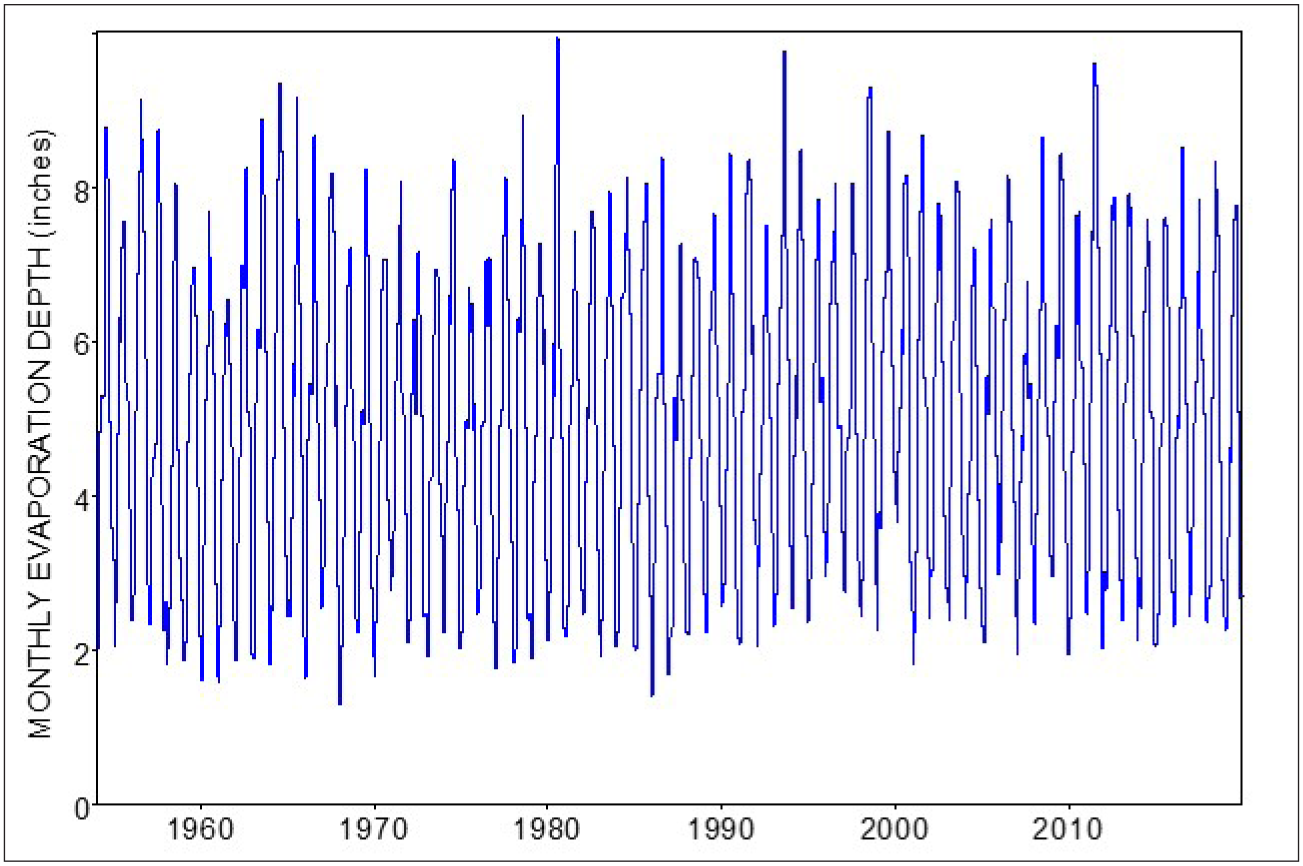

Figure 5. Statewide average 1954–2019 monthly reservoir evaporation depths in inches.

precipitation and 100 evaporation stations, most managed by the National Weather Service. The TWDB uses Thiessen networks for computing means for each of the 92 quadrangles for each month. The reservoir evaporation depths are estimated based on measurements from standard evaporation pans and lake/pan multiplier coefficients that vary over the 12 months of the year and with location.

The WRAP modeling system includes a feature that accesses the TWDB database and computes basic statistics including linear regression coefficients for each of the 92 quadrangles and area-weighted statewide average precipitation and reservoir evaporation rates (Wurbs 2019c). Monthly quantities, annual totals, and annual series of the minimum and maximum monthly value each year or moving averages for any specified number of months are computed and plotted.

The 92 quadrangles that encompass Texas are delineated in Figure 3, with each cell representing a quadrangle. The 1940–2019 mean annual precipitation and 1954–2019 reservoir evaporation depths in inches/year of each individual quad are tabulated in the upper and lower half of each of the cells. The extreme spatial variability of rainfall, evaporation, and evaporation less rainfall is illustrated by these quantities. One of the quadrangles in West Texas has a mean annual evaporation rate of 70.9 inches and annual precipitation of 13.5 inches, as contrasted with a quadrangle in East Texas with an annual evaporation of 45.5 inches and annual precipitation of 54.7 inches.

Both temporal variability and stationarity are illustrated by the time series plots of Figures 4 through 7 and the regression metrics of Table 2. The statewide averages of the 1940–2019 precipitation and 1954–2019 reservoir evaporation rates are 28.1 and 59.4 inches/year, respectively. Precipitation and reservoir evaporation rates exhibit great variability seasonally, between years, and continuously. Fluctuations between annual amounts are 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.

The statewide averages of the 1940–2019 monthly precipitation and 1954–2019 monthly evaporation depths are plotted in Figures 4 and 5, respectively. Statewide annual precipitation and evaporation depths are plotted in Figure 6. The minimum and maximum monthly depths for any month in each year (January through December) are plotted in Figure 7.

Regression statistics for statewide averages for 1940–2019 annual precipitation, 1954–2019 annual evaporation, 1954–2019 annual net evaporation less precipitation, and annual

Table 2. Linear regression analysis results for nine annual time series variables.

Variable	Mean (inches)	Intercept (inches)	Slope (inches/year)	Number of slopes	
				Positive	Negative
annual precipitation	28.12	27.58	0.013391	66	26
minimum monthly precipitation	0.789	0.818	-0.000736	25	67
maximum monthly precipitation	4.640	4.179	0.011387	74	18
annual evaporation	59.39	57.51	0.056016	62	30
minimum monthly evaporation	2.139	1.867	0.008105	82	10
maximum monthly evaporation	8.051	8.042	0.000272	52	40
annual evaporation-precipitation	31.19	30.09	0.032897	51	41
minimum monthly evaporation-precipitation	-0.530	-0.287	-0.007259	44	48
maximum monthly evaporation-precipitation	6.152	6.084	0.002040	56	36

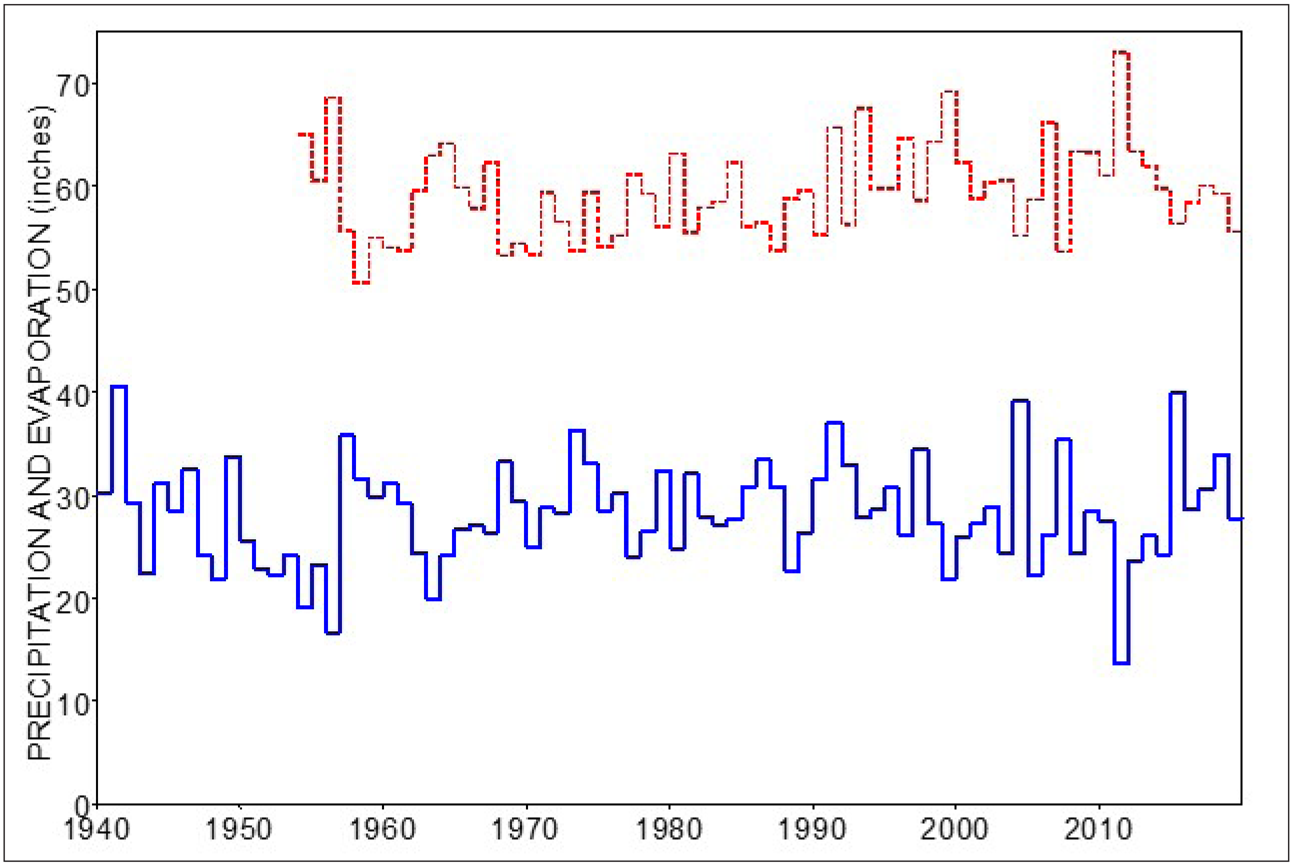

Figure 6. Statewide average of annual precipitation (blue solid) and annual evaporation (red dashed) in inches.

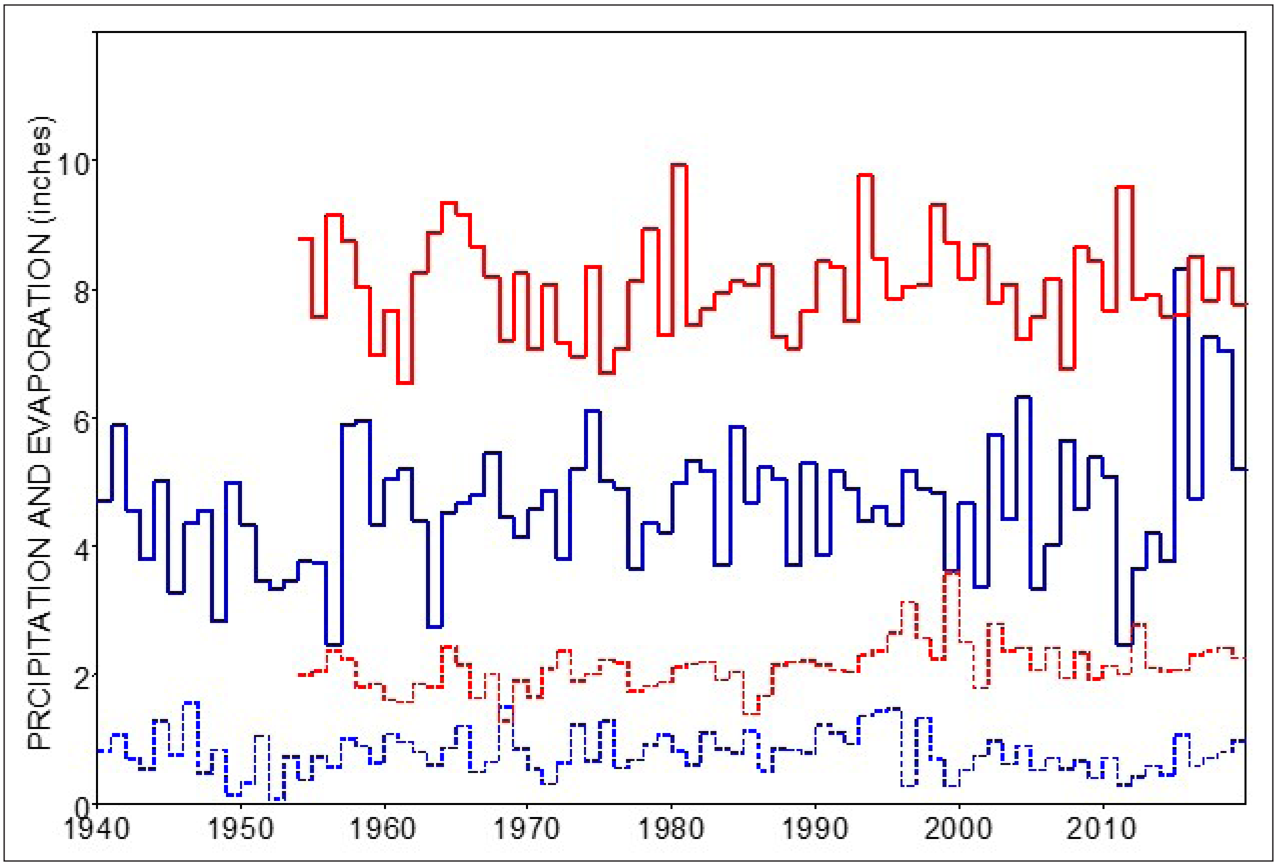

Figure 7. Statewide average of annual maximum (blue solid) and minimum (blue dash) monthly precipitation and maximum (red solid) and minimum (red dash) monthly evaporation.

monthly maxima and minima are tabulated in Table 2. In linear regression, an intercept equal or near to the mean and a slope of zero or near-zero implies the time series data exhibits no long-term trend. A positive or negative slope indicates an increase or decrease over time.

A linear regression trend line through the 80 years of annual statewide mean precipitation depths has a slope of 0.01339 inch/year tabulated in Table 2. Counts of positive and negative slopes for the nine annual time series variables for the 92 quadrangles are shown in the last two columns of Table 2. The trend slopes for total annual precipitation are positive for 66 of the 92 individual quadrangles (Figure 3) and negative for the other 26 quadrangles. The means of the minimum and maximum monthly statewide average precipitation depths (Figure 7) during each of the 80 years of 1940–2019 are 0.789 inch and 4.64 inches, respectively.

Analyses of time series plots and standard linear regression metrics provide meaningful insight regarding occurrence or non-occurrence of long-term trends. Permanent long-term trends, if they exist, are hidden by the great continuous variability in precipitation and evaporation. Regression slopes switch between increasing versus decreasing with different sub-periods of the 1940–2019 precipitation or 1954–2019 evaporation records. The statewide annual precipitation of 13.6 inches in 2011 and 40.0 inches in 2015 are notable. The statewide lowest annual precipitation and highest evaporation in the database occurred in 2011. The 2015 precipitation of 40.0 inches is exceeded only by the 1941 precipitation of 40.6 inches. Hydrology in Texas has always fluctuated dramatically. However, any past long-term trends or changes in the characteristics of monthly precipitation and evaporation rates have been minimal compared to the effects of water resources development and management on river flows discussed in the next section.

Cook et al. (2015), Cook et al. (2019), and others have predicted 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. (2020) assess future impacts and management strategies associated with droughts in Texas during the latter half of the 21st century that may be more severe than those experienced during the past hundred years or perhaps past multiple hundreds of years.

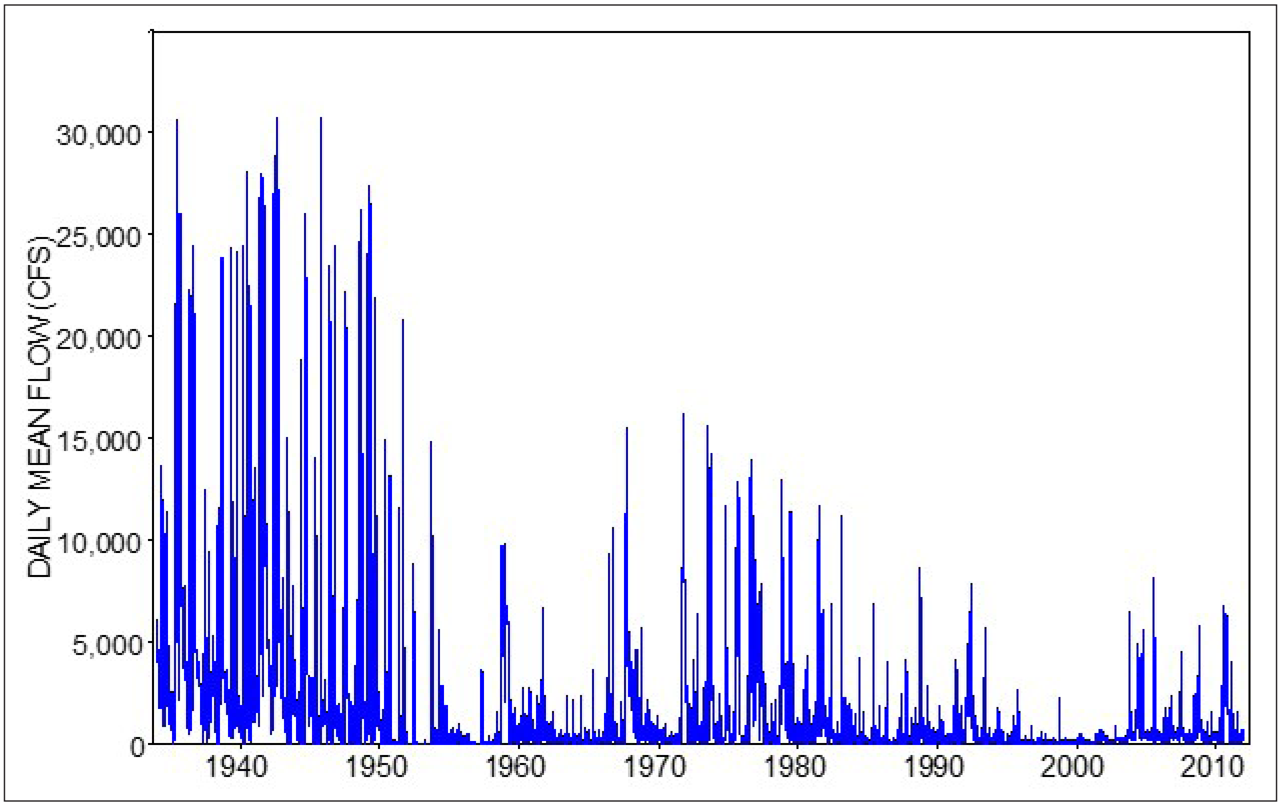

Figure 8. Daily flows of the Rio Grande at Brownsville from January 1934 through December 2011.

River flows observed at gage stations

River flows throughout Texas exhibit extreme variability, including severe multiple-year droughts and intense floods as well as continuous fluctuations. Flow characteristics have changed over time with construction of reservoir projects and other river regulation structures, increases in water supply diversions and return flows, and land use changes. Permanent or long-term stream flow alterations vary greatly with location. Regulation of rivers by dams reduces flood flows but may increase low flows at downstream locations. Flows immediately below dams are greatly affected by reservoir operations, but the effects diminish with distance downstream.

The National Water Information System (NWIS) website maintained by U.S. Geological Survey (USGS) includes 1,055 gages in Texas with historical daily data and 672 current condition sites with flows recorded at intervals of 15 to 60 minutes. Flow data for the Rio Grande is compiled by the IBWC. One IBWC gage and five USGS gage sites are selected in the following discussion to illustrate river flow characteristics. River flows are plotted in in Figures 8-15 in units of cubic feet per second (cfs).

Dramatic decreases in the flow of the Rio Grande illustrate the impacts of irrigated agriculture and large reservoirs in a dry climate. The Rio Grande Basin encompasses 356,000 square miles, but much of this area is flat desert that contributes no runoff to the river. Daily flows of the Rio Grande at Brownsville, located 49 miles above the river's outlet to the Gulf of Mexico, are plotted in Figure 8. The effects of International Falcon and Amistad Reservoirs on the Rio Grande with impoundment of stream flow beginning in 1953 and 1968 (Table 1) are evident in Figure 8.

The Canadian River is another extreme case of flows decreasing dramatically over the past several decades. Daily flows of the Canadian River at a USGS gage site about 70 miles downstream of Lake Meredith and 20 miles upstream of the Texas/Oklahoma border are plotted in Figure 9. Flows have been depleted by development of irrigated agriculture supplied mainly by groundwater along with municipal water use in this dry region of North Texas and New Mexico.

Illustrating the opposite extreme, flow of the San Antonio River below the City of San Antonio increased significantly over the last 80 years as a result of wastewater treatment effluent accompanying increased water supply from the Edwards Aquifer and increased impervious land cover due to urbanization. Flows of tributaries of the San Jacinto River in the Houston metropolitan area have similarly increased in response to return flows from M&I water use supplied by groundwater and interbasin import and increased runoff due to urban development.

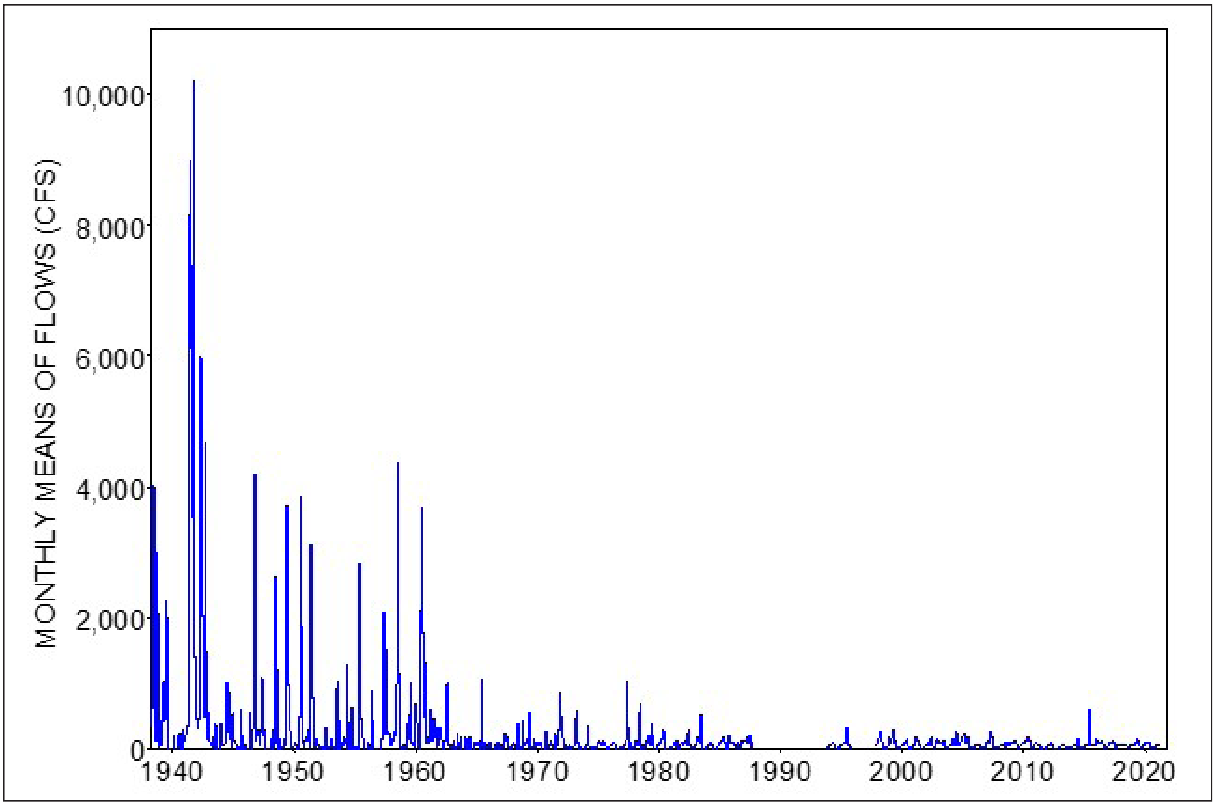

Figure 9. Monthly flows of the Canadian River downstream of Lake Meredith from November 1938 through September 1987; October 1993 through September 1996; and October 1997 through January 2021. Flow data are missing for October 1988 through September 1993 and October 1995 through September 1996.

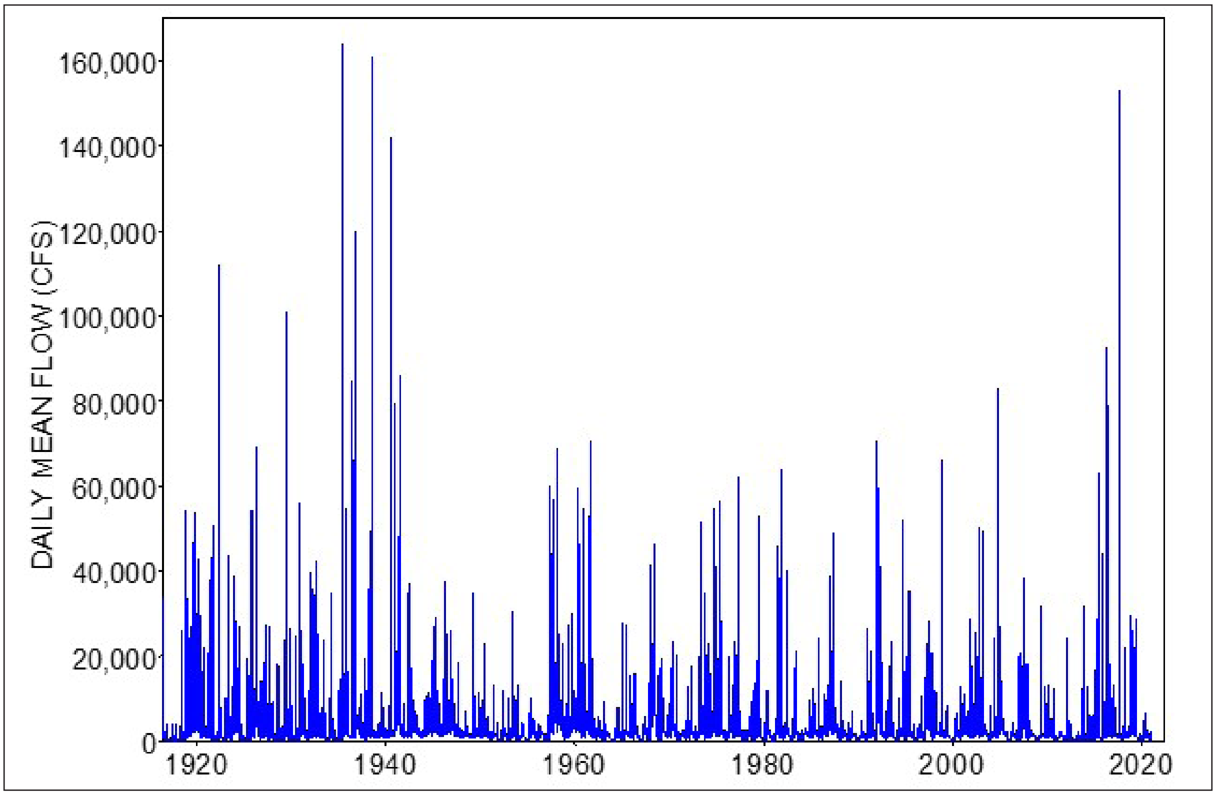

Figure 10. Daily flows of the Colorado River at Columbus from June 1916 through January 2021.

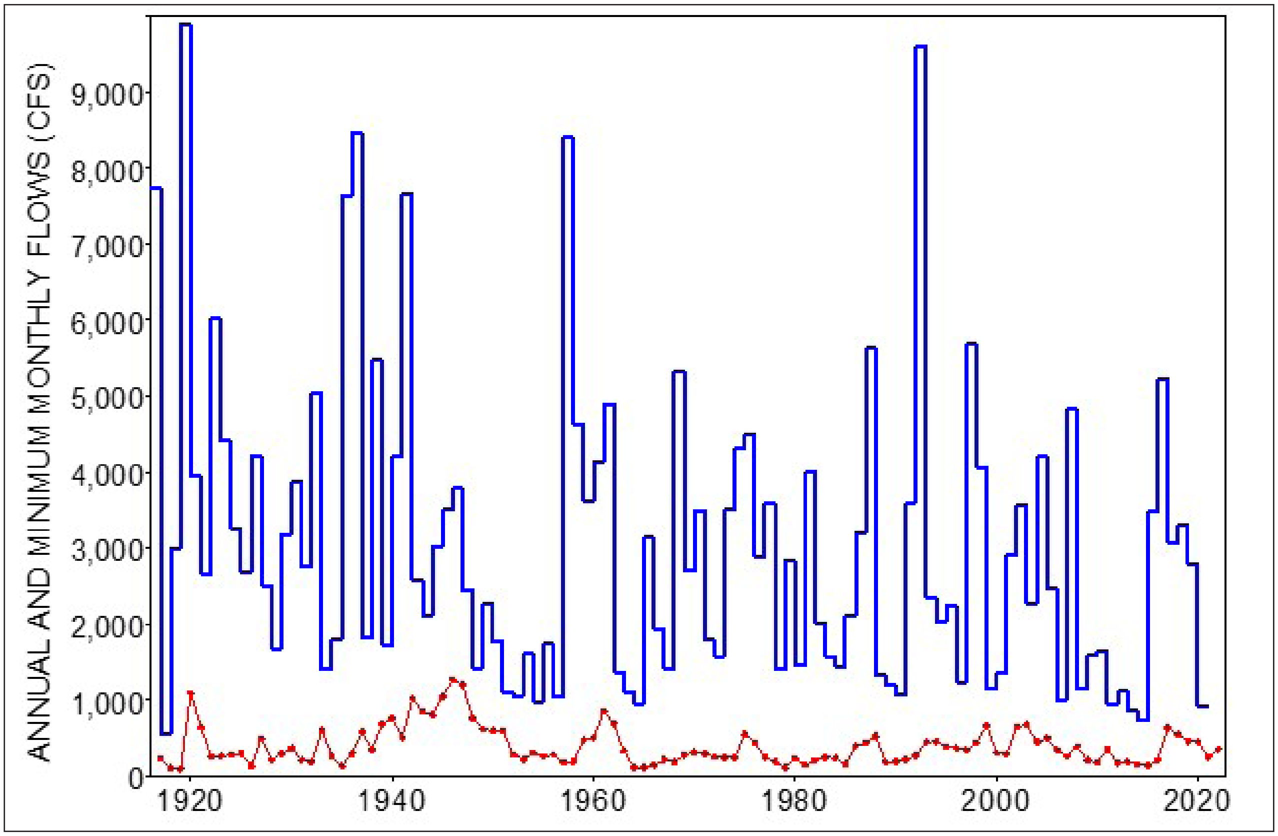

Figure 11. Annual means and annual minimum monthly flows of the Colorado River at Columbus from 1916 through 2020.

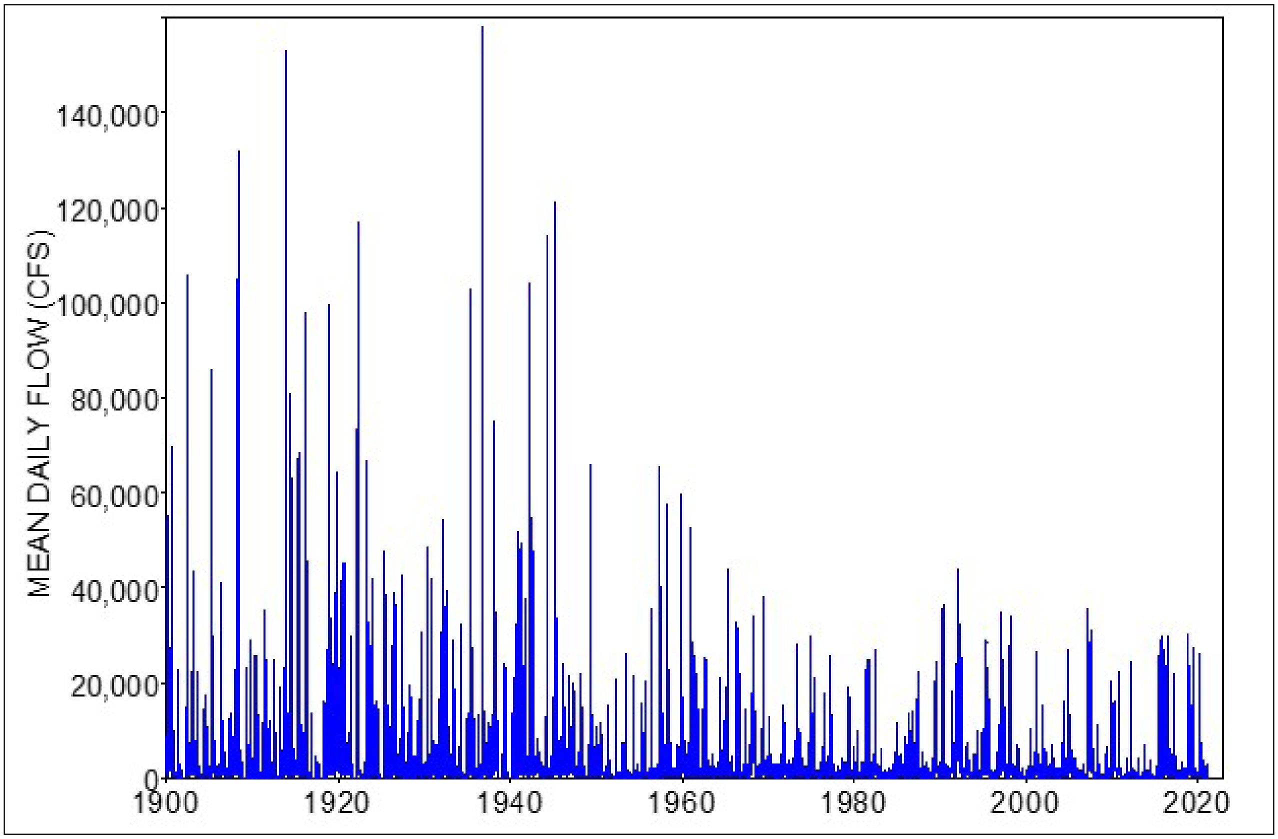

Figure 12. Daily flows of the Brazos River at Waco from January 1900 through January 2021.

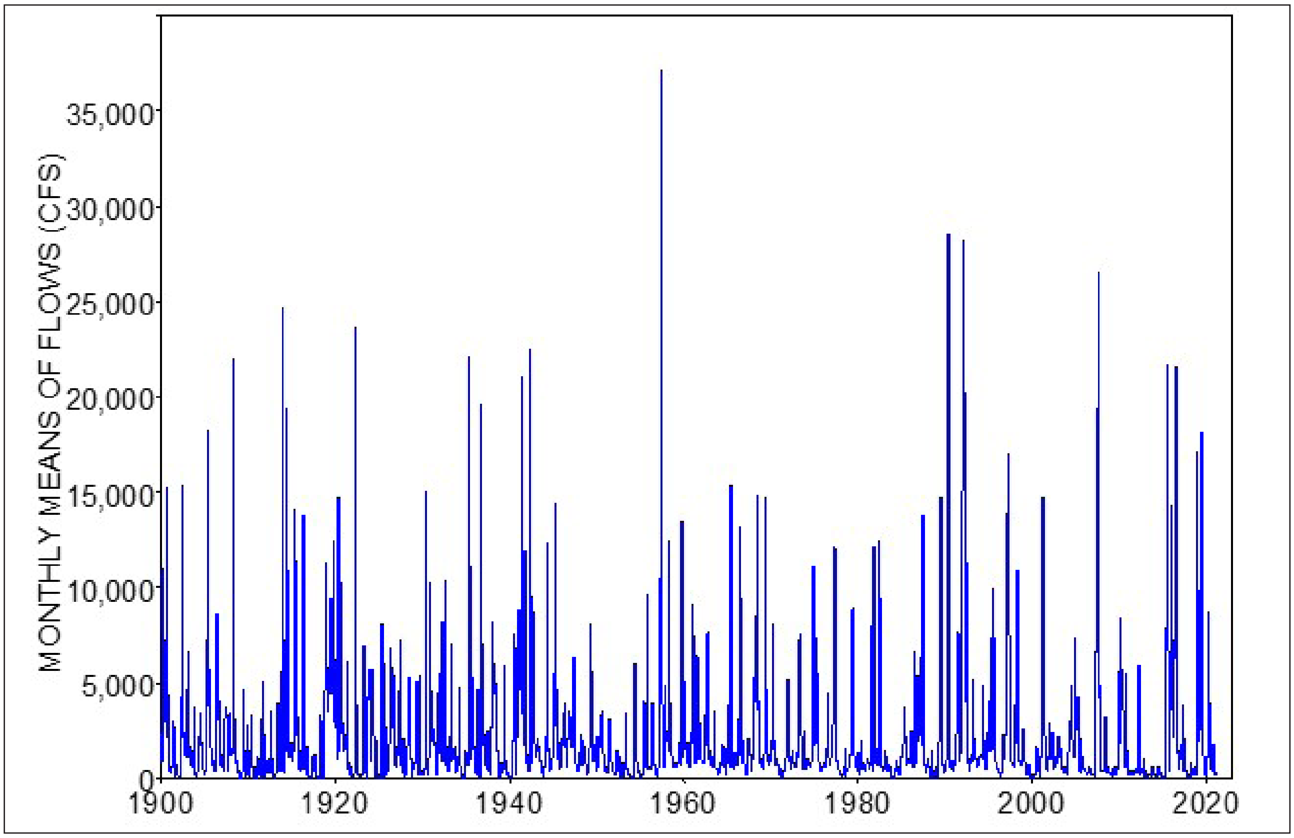

Figure 13. Monthly flows of the Brazos River at Waco from January 1900 through January 2021.

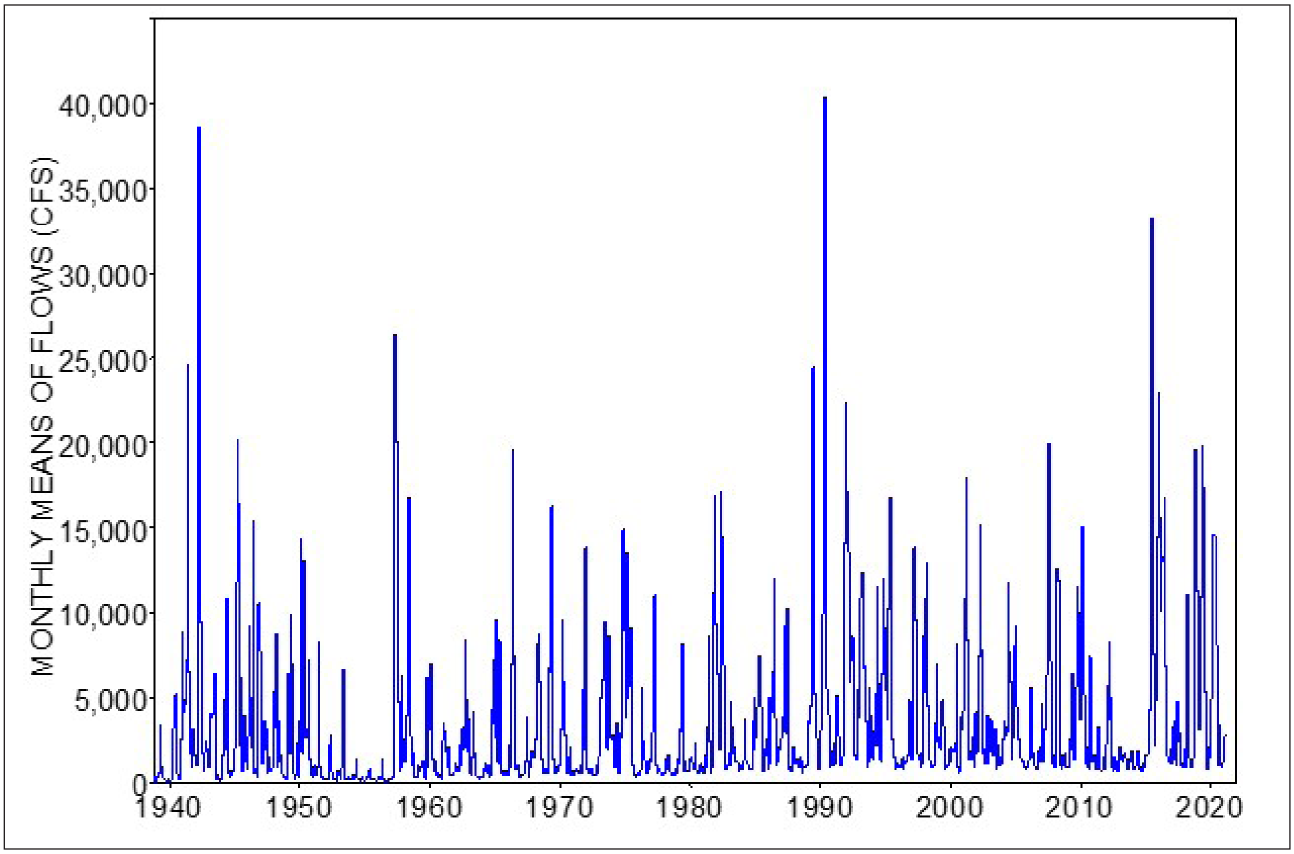

Figure 14. Monthly flows of the Trinity River near Rosser from November 1938 through January 2021.

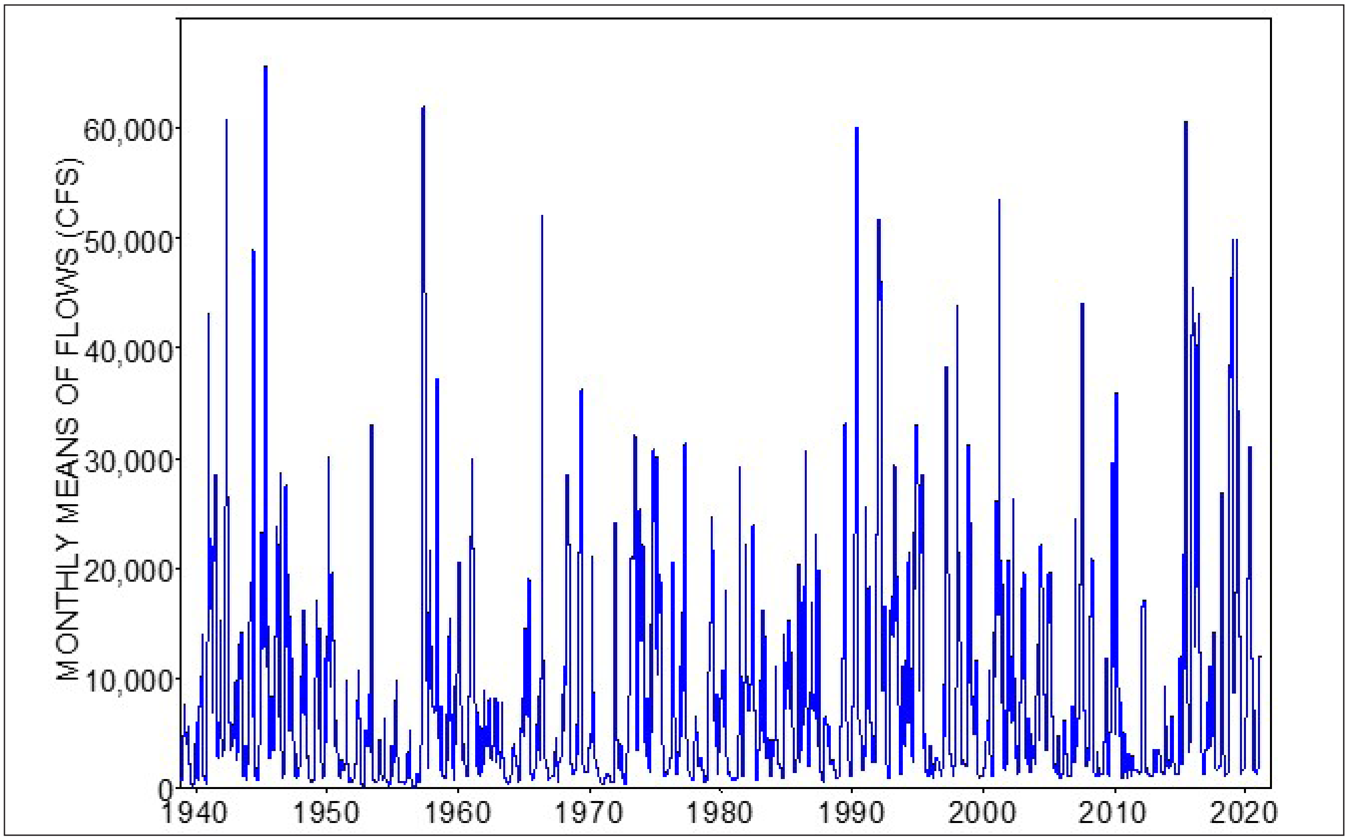

Figure 15. Monthly flows of the Trinity River at Romayor below Lake Livingston from November 1938 through January 2021.

Flows of the Colorado River at Columbus are plotted in Figures 10 and 11. This gage is about 100 miles below downtown Austin and has a watershed area of 41,600 square miles, of which 30,200 square miles contribute flows to the river. Daily means are plotted in Figure 10. Annual means and the minimum monthly flow in each year are plotted in Figure 11.

Flow variability characteristics vary significantly with choice of time interval for averaging flow rates, such as daily, monthly, or annually. Reservoir flood control operations may greatly affect instantaneous and mean daily flow rates with little or no effect on monthly or annual means, as illustrated by Figures 12 and 13. The effects of flood control operations of Whitney, Waco, and Aquilla Reservoirs (Table 1) on daily flows at a downstream gage on the Brazos River at Waco are evident in Figure 12. USACE flood control operations include an allowable flow rate of 20,000 at the Waco gage. These effects are dissipated in the monthly mean flows plotted in Figure 13.

Monthly flows of the Trinity River at Rosser and Romayor are plotted in Figures 14 and 15. These gages on the Trinity River have watershed areas of 8,150 and 17,200 square miles. The Rosser gage is 34 miles downstream of central downtown Dallas. The Romayor gage is 20 miles below Livingston Dam and 50 miles above the river outlet at Galveston Bay. The Dallas-Fort Worth metropolitan area in the upper Trinity River Basin has a population of 6.8 million people 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 to 1980s. The City of Houston, another large continually growing metropolitan area located in the adjoining San Jacinto River Basin, transports water by pipeline from Lake Livingston on the lower Trinity River. Low flows have increased with increases in wastewater treatment discharges. Significant decreases in instantaneous and daily flood flows are dissipated in the monthly flows.

Simulated reservoir storage

WRAP/WAM simulated reservoir storage provides a meaningful drought index as well as measure of water supply capabilities. Even though reservoirs were actually constructed at different times spanning many decades, all reservoirs with water right permits are operated in the simulation for a specified water use scenario continuously during a repetition of historical hydrology.

The summation of daily storage of all reservoirs in daily Brazos, Trinity, and Neches fully authorized scenario WAM simulations are plotted in Figures 16 and 17 (Wurbs 2019d, 2019e, 2020a). These are developmental daily versions of the

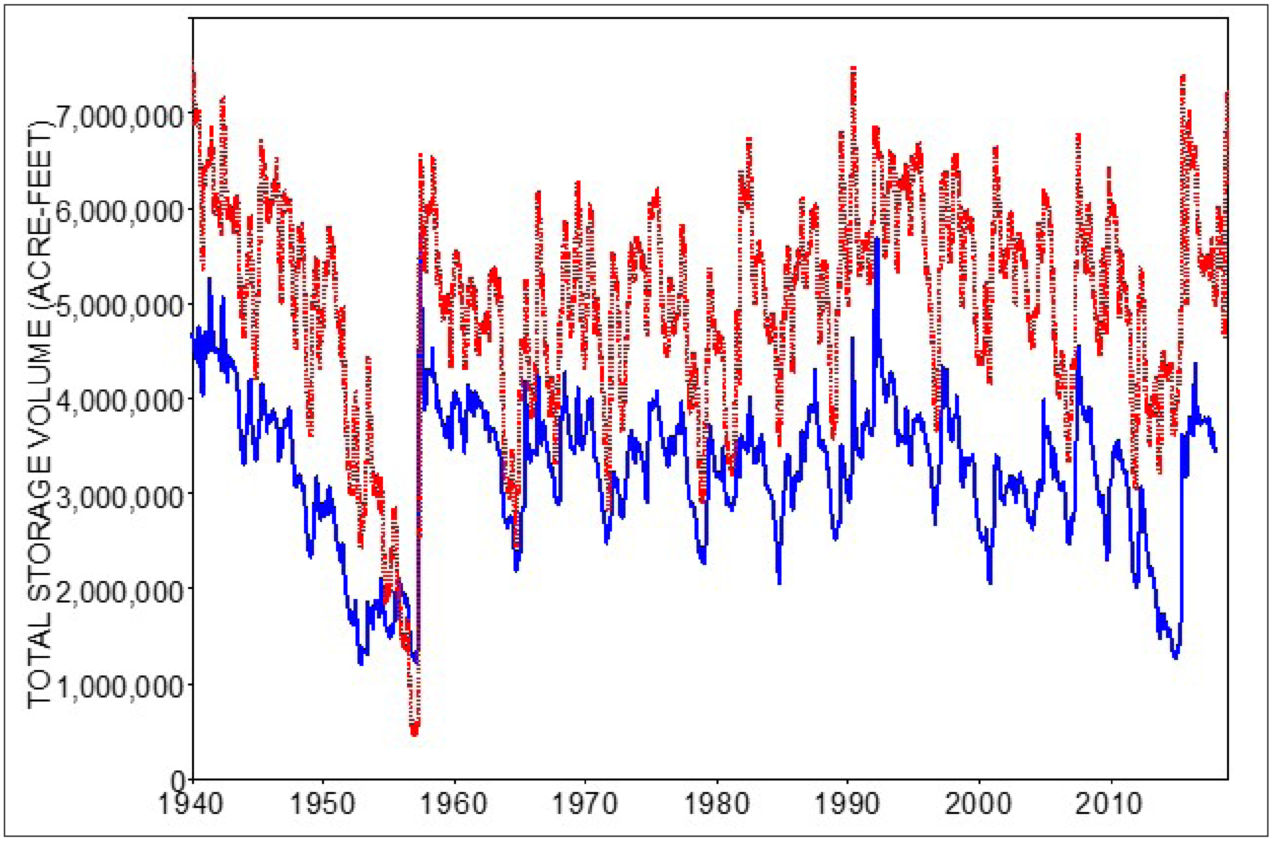

Figure 16. Simulated daily storage contents for the 680 reservoirs in the Brazos WAM (blue solid line) and 697 reservoirs in the Trinity WAM (red dashed).

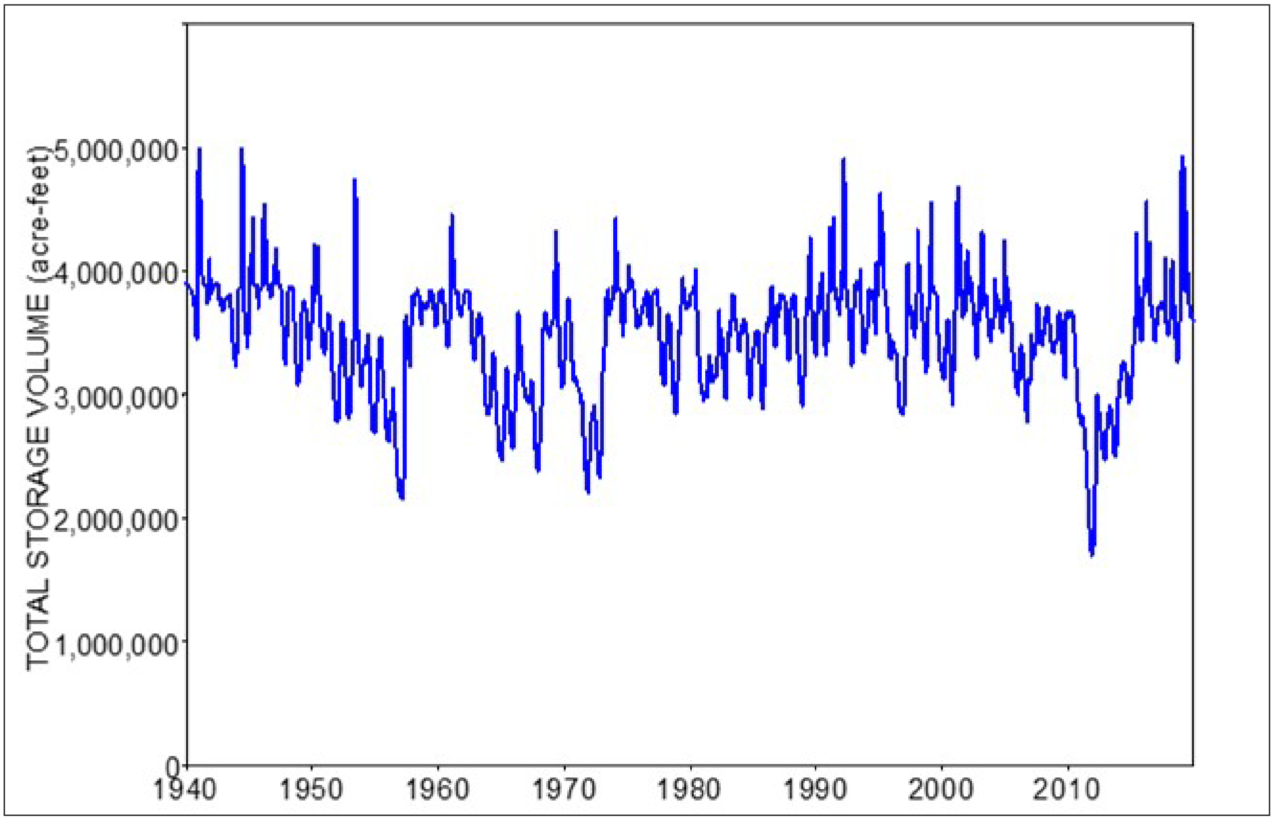

Figure 17. Simulated 1940–2019 daily storage contents for the 180 reservoirs in the Neches WAM.

Table 3. River basin characteristics.

River basin	Drainage area		Annual evaporation (inches)	Annual precipitation (inches)	Mean annual natural flow at outlet		Regulated flow (% naturalized flow)
	Total (miles²)	Texas (miles²)			(% precip)	(acre-feet)	
Rio Grande	182,220	49,390	64.0	16.1	2.60%	1,099,600	6.84%
Nueces	16,700	16,700	59.6	24.8	2.93%	647,930	68.0%
Guadalupe	10,130	10,130	54.1	32.3	12.7%	2,220,140	92.9%
Lavaca	2,310	2,310	50.8	39.7	17.6%	860,400	93.7%
Colorado	41,480	41,280	63.1	24.5	5.79%	3,118,790	61.2%
Brazos	47,010	44,310	60.2	29.4	10.4%	7,246,370	84.2%
San Jacinto	3,940	3,940	49.0	46.6	23.2%	2,270,090	49.3%
Trinity	17,910	17,800	55.1	39.4	17.6%	6,630,280	72.8%
Neches	9,940	9,940	48.5	48.7	24.1%	6,223,550	89.5%
Sabine	9,760	7,570	50.9	47.8	34.4%	6,633,090	93.3%
Cypress	2,930	2,930	48.9	47.2	22.7%	1,675,700	87.9%
Sulphur	3,770	3,580	50.1	46.6	29.1%	2,590,680	86.9%
Red	93,450	24,300	63.4	25.6	–	10,093,270	90.3%
Canadian	47,710	12,870	66.2	19.5	–	217,550	59.0%
Six Coastal	15,150	16,050	59.0	29.6	11.2%	2,902,510	104%
Total	504,410	263,100	59.4	28.1	11.8%	54,429,950	80.9%

WAMs with updated extended hydrology that have not been officially incorporated in the TCEQ WAM system for permitting purposes. The Brazos WAM has a hydrologic period of analysis of 1940–2017 and includes 680 reservoirs with full authorization storage capacities totaling 4,746,330 acre-feet. The Trinity WAM has 697 reservoirs with capacities totaling 7,445,690 acre-feet and a 1940–2018 period of analysis. The Neches WAM includes 180 reservoirs with a total permitted capacity of 3,904,100 acre-feet and 1940–2019 period of analysis. The daily Brazos, Trinity, and Neches WAMs also include operations of flood control pools of nine, eight, and one multiple-purpose USACE reservoirs, respectively. The three daily full authorization simulations are based on the premise that all reservoirs included in water right permits are operated during a hypothetical repetition of past natural hydrology occurring from 1940 to near the present. All water users use the full amounts to which they are legally entitled based on their water right permits, subject to water availability, throughout the simulations.

The timing and magnitude of simulated storage drawdowns for the Brazos and Trinity WAMs in Figure 16 are somewhat similar to each other. The Neches WAM storage plot in Figure 17 is notably different. The 1950–1957 drought and April-May 1957 flood are evident in Figure 16. Although the 2010–2012 drought was economically very costly, the residents of the Brazos and Trinity river basins have never experienced a drought as hydrologically severe as in 1950–1957 with present population and water needs and constructed facilities. The Neches River Basin is characterized by more abundant water supply capabilities relative to permitted use than the Brazos and Trinity river basins. The minimum summation of storage contents of the 180 reservoirs in the Neches WAM during the 1940–2019 hydrologic period of analysis simulation is 1,693,630 acre-feet, occurring on December 3, 2011.

Simulation results for individual reservoirs are of interest in most water availability modeling analyses. In general, storage fluctuations will be greater in individual reservoirs than in the summations plotted in Figures 16 and 17. The timing and magnitude of drawdowns and refilling vary between the different reservoirs. Summing storage contents of numerous reservoirs with locations scattered over the large river basins tends to average out or dampen fluctuations.

RIVER BASIN WATER BUDGETS

The 15 major river basins and eight coastal basins of Texas are modeled as 20 WAMs (Wurbs 2005, 2019a). The San Antonio River flows into the Guadalupe River and is included in the Guadalupe WAM. The Brazos River Basin and San Jacinto-Brazos Coastal Basin are combined as a single WAM. The Brazos-Colorado Coastal Basin is included in the Colorado River Basin WAM. The quantities in Tables 3 and 4 com-

Table 4. Water availability model (WAM) reservoir characteristics by river basin.

WAM river basin	Number of reservoirs		Storage capacity (acre-feet)	Storage capacity (% annual naturalized flow)	Mean storage (% capacity)	Reservoir evaporation (ac-ft/yr)	Diversion targets (ac-ft/yr)	Diversion reliability (%)
	Small	Major						
Rio Grande	73	7	3,499,070	318%	49.0%	304,110	2,228,870	81.7%
Nueces	123	2	959,827	148%	53.0%	201,600	637,040	87.4%
Guadalupe	235	6	756.527	0.034%	79.8%	158,120	420,780	90.9%
Lavaca	19	2	167,718	19.5%	92.6%	106,650	61,620	82.4%
Colorado	452	37	4,709,829	151%	69.5%	628,770	2,235420	82.5%
Brazos	671	45	4,015,865	55.4%	83.0%	1,026,530	1,519,140	93.3%
San Jacinto	110	4	587,529	25.9%	91.2%	2,197,590	520,360	83.2%
Trinity	653	33	7,356,200	111%	79.1%	2,546,030	6,617,850	86.9%
Neches	191	12	3,656,259	58.8%	98.2%	648,870	621,610	81.2%
Sabine	201	12	6,262,314	94.4%	97.6%	216,210	550,280	98.7%
Cypress	78	13	877,938	52.4%	85.9%	42,310	496,230	78.0%
Sulphur	53	4	718,699	27.7%	86.9%	55,810	242,070	99.2%
Red	212	25	3,780,342	37.5%	89.1%	328,420	860,600	97.2%
Canadian	44	3	879,824	404%	69.4%	62,270	94,160	95.4%
Six Coastal	121	5	184,660	6.36%	37.5%	66,220	267,900	95.5%
Total	3,236	210	37,656,830	70.44%	81.5%	10,375,250	17,373,930	86.6%

paring river basin characteristics are from river basin water budget studies based on current use scenario versions of the 20 monthly WAMs combined with information from other sources (Wurbs and Zhang 2014). The hydrologic periods of analysis vary between the different WAMs reflected in the tables, but all exceed 50 years. Six coastal basin WAMs are combined as a single line in Tables 3 and 4 for brevity.

Texas encompasses a total area of 268,310 square miles. Table 3 indicates that the watersheds of Texas have contributing drainage areas totaling 263,100 square miles. Some land in flat dry west Texas does not contribute precipitation runoff to stream flow because essentially all of the precipitation is lost through evapotranspiration and infiltration. A large area of the Rio Grande Basin in Mexico and New Mexico is non-contributing.

The WAM system is designed for assessing water availability and supply reliability in Texas. WAMs for the international and interstate river basins consider the entire basin to the extent necessary to assess water availability in Texas. State borders are treated as the outlets for the Canadian, Red, and Sulphur WAMs. The other rivers discharge into the Gulf of Mexico at their outlets. Although the Rio Grande WAM includes the Mexican share of the storage in Lakes Amistad and Falcon, the data in Tables 3 and 4 include only quantities allocated to Texas. Lakes Amistad and Falcon have total conservation storage capacities of 2,976,970 and 2,648,290 acre-feet, respectively, of which 1,303,910 and 1,096,390 acre-feet are allocated by treaty to the United States and used in Texas. Other interstate river basin data in Tables 3 and 4 include only reservoirs located wholly or partially in Texas but include their total WAM storage capacity.

The annual evaporation and precipitation depths in the fourth and fifth columns of Table 3 are spatially averaged over the area of the river basin encompassed within Texas. WAM naturalized flows (NF) represent natural conditions that would have occurred during the hydrologic period of analysis without water resources development and use. The sixth column of Table 3 expresses the WAM naturalized flow at the outlet as a percentage of the annual precipitation falling on the river basin area in Texas. The outlets are defined as where the flows leave Texas, which are either the Gulf of Mexico or a state border. The last two columns of Table 3 show the mean annual naturalized flow in acre-feet/year and the simulated regulated flow as a percentage of naturalized flow (%NF). The regulated flow of 104% of naturalized flow for the coastal basins reflects return flows from water supplies transported from adjoining river basins.

Table 3 is further explained as follows, using the Brazos River Basin as an example. The contributing drainage area of the Brazos Basin is 47,010 square miles, with 44,310 square miles in Texas and the remainder in New Mexico. The long-term mean annual precipitation and reservoir evaporation depths averaged over the basin are 29.4 and 60.2 inches/year. Without water development and use, the long-term mean natural flow to the Gulf of Mexico would be a calculated 7,246,370 acre-feet/year, which represents 10.4% of the precipitation falling on the basin. Mean current use scenario simulated regulated flow at the basin outlet is 84.2% of the natural flow.

Reservoirs are categorized as small versus major in Table 4 based on whether their storage capacity is less than 5,000 acre-feet. The total storage capacity for all reservoirs included in the WAMs are tabulated in acre-feet and as a percentage of annual naturalized flow at the basin outlet. Mean storage contents are expressed as a percentage of storage capacity.

Referring to Table 4, the 20 current use scenario WAMs include 3,446 reservoirs, of which 210 have capacities of 5,000 acre-feet or greater. Conservation storage capacities of the 3,446 reservoirs in the current use scenario WAMs total 37,656,830 acre-feet. Storage contents fluctuate greatly during the simulations but average 81.5% of capacity. The storage capacities for each river basin are expressed in the fifth column of Table 4 as a percentage of the mean annual naturalized flow shown in Table 3. Diversion targets are supplied in each month of the simulation to the extent that water is available from stream flow or reservoir storage. The last two columns of Table 4 show total volumes of water supply diversion targets for the current use scenario and the percentage of the target volumes supplied.

The long-term mean reservoir evaporation is calculated to be 10,375,250 acre-feet/year, which is 69.0% as large as the mean total water supply diversions. The calculated estimate of net annual evaporation (10,375,000 acre-feet) minus precipitation (7,835,000 acre-feet) is 2,540,000 acre-feet (Wurbs and Zhang 2014). Water surface evaporation is a major component of reservoir water budgets. Measures such as monomolecular films for reducing evaporation in reservoirs throughout the world, including Texas, have been extensively investigated (Barnes 2008; Wurbs and Ayala 2014). However, wind and wave action on the surface of major reservoirs severely constrain the feasibility of monolayer films and other evaporation suppression technologies.

Most of the reservoirs and storage capacity are located in the eastern half of the state. West Texas has low precipitation and high evaporation (Figure 3), with a large portion of the land area flat with minimal runoff and relatively few sites with topography suitable for reservoirs. Most of the reservoir capacity for storing runoff from western watersheds is in International Amistad and Falcon Reservoirs on the Rio Grande and Lake Meredith on the Canadian River. The Lower Rio Grande is the most productive surface water irrigation region of Texas. Agriculture in the Canadian River Basin and adjoining basins in the High Plains relies primarily on irrigation from the Ogallala Aquifer.

INSTITUTIONAL FRAMEWORK FOR RESERVOIR MANAGEMENT

Most of the large dam and reservoir projects in Texas and throughout the United States were constructed during the period from the 1930s through the 1980s, which has been called the construction era of water resources development. Other countries, most notably China, have dominated in building dams in recent decades. Economic, environmental, and institutional considerations severely constrain construction of additional dams in Texas and throughout the United States. Water management policy and practice have shifted to a greater reliance on managing floodplain land use, improving water use efficiency, and optimizing the operation of existing facilities.

Water resources development and management are accomplished within an institutional setting of organizations, traditions, programs, policies, financing mechanisms, and political processes (Wurbs 2015, 2017b, AWRA 2019). Surface water in Texas is a publicly owned resource, and its allocation and use are governed by treaties between the United States and Mexico, five interstate compacts with neighboring states, and two versions of a prior appropriation water rights permit system with 6,200 active permits (Wurbs 2013). The majority of the major reservoirs in Texas are owned and operated by private electrical and water utilities, river authorities, water districts, and cities. The majority of the storage capacity is contained in large federal reservoirs.

Federal reservoirs

The Civil Works Program of the USACE is the largest reservoir construction and management agency in the nation, with 537 reservoirs in operation nationwide (Patterson and Doyle 2018). The U.S. Bureau of Reclamation (USBR) operates 130 reservoirs in the 17 western states and has constructed many other projects turned over to local entities for operation (Billington et al. 2005). The Mexican and U.S. Sections of the IBWC jointly own and operate Amistad and Falcon Reservoirs on the Rio Grande.

The USACE has played a leading role nationwide in constructing and operating major reservoir systems for navigation and flood control. The USACE is responsible for flood control operations at projects constructed by the USBR as well as its own projects. The USBR was created by the Reclamation Act of 1902 to support economic development of the 17 arid and semiarid western states, including Texas, through large scale irrigation projects. The activities of the USACE and USBR have evolved over time to emphasize comprehensive multiple-purpose water resources development and management. Municipal and industrial water supply, hydroelectric power, recreation, and fish and wildlife enhancement are major purposes of USACE and USBR projects.

The USACE has constructed and now owns and operates 27 multiple-purpose lakes in Texas that contain water supply as well as flood control storage capacity, two flood control reservoirs that have no water supply storage, and a brine control dam. These 30 USACE reservoirs contain about 29%, 75%, and 43%, respectively, of the conservation, flood control, and total storage capacity of the major reservoirs of Texas. Twelve of the 30 USACE reservoirs are included in Table 1. Most of the USACE dams and reservoirs in Texas were authorized by omnibus legislative acts passed by the U.S. Congress during the 1940s and 1950s based on comprehensive basin-wide federal planning studies.

Reservoir projects owned by the USACE are maintained and operated by USACE district offices. Lake Texoma on the Red River, the largest reservoir in Texas, is operated by the Tulsa District. The Tulsa District also constructed and operates the multiple-purpose Pat Mayse Lake near Paris, Texas and the Truscott brine control dam in Knox County, both in the Red River Basin. The Addicks and Barker flood control reservoirs in Houston, which have no water supply storage, are owned and operated by the Galveston District. The other 25 USACE reservoirs in Texas are operated by the USACE Fort Worth District.

The USBR constructed the following five reservoir projects in Texas: Mansfield Dam and Lake Travis, Twin Buttes Dam and Reservoir, Palmetto Bend Dam and Lake Texana, Choke Canyon Dam and Reservoir, and Sanford Dam and Lake Meredith. All except Lake Texana are included in Table 1. These five reservoirs contain 7.7%, 9.6%, and 8.3%, respectively, of the conservation, flood control, and total storage capacity of the major reservoirs. Mansfield Dam and Lake Travis on the Colorado River was the first of the large multiple-purpose projects constructed in Texas by the federal government. The USBR constructed the project during 1937–1942. Lake Travis is now owned and operated by the LCRA. The USBR has also constructed water conveyance systems for agricultural and municipal use in the Texas portion of the Rio Grande, Colorado, and Canadian river basins. The USACE is responsible for flood control operations of reservoirs constructed by the USBR. Although the USBR owns and operates many reservoirs in other western states, reservoirs in Texas have been turned over to local sponsors that repaid reimbursable costs to the federal government. The Reclamation Acts of 1902 and 1939 established the policy that costs allocated to irrigation in federal projects be reimbursed by project beneficiaries. Congressional acts authorizing specific USBR projects have sometimes included repayment provisions tailored to the circumstances of the individual project.

Pursuant to the Flood Control Act of 1936, flood control storage in federal reservoirs is fully federally funded without cost-sharing. Nonfederal sponsors contract with the USACE and USBR for municipal and industrial water supply (M&I) storage capacity. All construction and maintenance cost allocated to M&I water supply are reimbursed by nonfederal sponsors in accordance with the Water Supply Act of 1958, as amended by the Water Resources Development Act of 1986 and other legislation (Wurbs 2016; USACE 2016). About 75% of the water supply storage capacity of the 117 USACE reservoirs nationwide that contain M&I supply is in the USACE Southwestern Division, mainly in Texas and Oklahoma (Institute for Water Resources 2003).

The International Boundary Commission was created in 1889. A convention in 1906 provided for the distribution between the United States and Mexico of the waters of the Rio Grande for the 89-mile boundary reach through the El Paso-Juarez Valley. A 1944 treaty distributed the waters of the Rio Grande from Fort Quitman, below El Paso, to the Gulf of Mexico and provided for construction and operation of Falcon and Amistad Reservoirs (Wurbs 1985, 2013). The International Boundary Commission was renamed the International Boundary and Water Commission (IBWC). The Mexico and United States sections of the IBWC are headquartered in Juarez and El Paso.

Three of the USACE reservoirs and the two IBWC reservoirs have hydroelectric power plants. The Western Area Power Administration (WAPA) markets the U.S. electric power generated at the two IBWC reservoirs. The Southwestern Power Administration (SWPA) markets the power from the USACE projects. WAPA and SWPA are two of several agencies of the Department of Energy responsible for marketing hydroelectric power from federal projects in various regions of the nation to electric cooperatives, municipalities, and utility companies.

Reservoir recreation is popular. Prior to 1965, recreation was included in federal projects as a fully federal expense. The Federal Water Recreation Act of 1965 established recreation at federal reservoir projects as a full project purpose subject to nonfederal cost-sharing. USACE lakes include significant areas of project-owned publicly accessible land around the shoreline. Many nonfederal reservoirs have privately owned land adjacent to much of the shoreline. Recreation is the primary purpose of the 18,100 and 8,000 acre-foot Buffalo and Coffee Mill Reservoirs in the Red River Basin owned and operated by the U.S. Fish and Wildlife Service and U.S Forest Service, respectively.

Nonfederal reservoirs

River authorities, water districts, and cities constructed and now own and operate 110 major reservoirs that contain about 45%, 0.1%, and 31% of the conservation, flood control, and total capacities of the major reservoirs. Several of these reservoirs are owned jointly by cities and water districts or river authorities. These numbers do not include the five reservoirs constructed by the USBR that are now owned and operated by nonfederal sponsors and the water supply storage capacity in 27 USACE reservoirs that nonfederal sponsors control through water supply contracts.

The Sabine River Authority (SRA) of Texas and the SRA of Louisiana jointly operate Toledo Bend Reservoir, which is the largest water supply reservoir in Texas. The SRA of Texas also operates Lake Fork and Lake Tawakoni. The LCRA operates the six Highland Lakes on the Colorado River, six hydroelectric power plants, four thermal-electric power plants, and two off-channel reservoirs that provide cooling water for the thermal-electric power plants. Established in 1929, the Brazos River Authority (BRA) is the first authority created in the United States to manage the water resources of a major river basin. The BRA owns and operates three reservoirs and has contracted for water supply storage capacity in nine USACE reservoirs. The Trinity River Authority and City of Houston jointly own and operate Lake Livingston. The Guadalupe-Blanco River authority owns and operates six small hydropower reservoirs on the Guadalupe River and contracts with the USACE for water supply storage capacity in Canyon Reservoir. The Lavaca River Authority owns Lake Texana, which was constructed by the USBR. Thirty-five water supply reservoirs are operated by 31 water districts. Forty-five cities own 48 water supply reservoirs.

Private companies own and operate 36 major reservoirs containing no flood control storage and less than 3% of the conservation storage of the major reservoirs. Most of these projects were constructed by electric companies to provide cooling water for steam-electric power plants.

RESERVOIR SYSTEM OPERATIONS

Managing hydrologic variability, supply reliability, flood risk, and future uncertainty is a central component of water management. Reservoir storage is necessary to manage extreme hydrologic variability to develop reliable water supplies. Dams and appurtenant structures also regulate rivers to reduce damage caused by floods. Reservoir system storage and release or withdrawal decisions can be categorized as operations during the following four conditions: (1) normal hydrologic conditions to optimize present day-to-day, seasonal, or year-to-year use of a reservoir system; (2) normal hydrologic conditions to maintain capabilities for responding to infrequent floods and droughts expected to occur at unknown times in the future; (3) floods; and (4) low flow or drought conditions. A reservoir may include conservation storage, flood control storage, or both (Wurbs 2016).

Reservoir storage pools

Reservoir operating procedures involve dividing the total storage capacity into the designated vertical zones or pool elevations illustrated by Figure 18. Water is normally removed

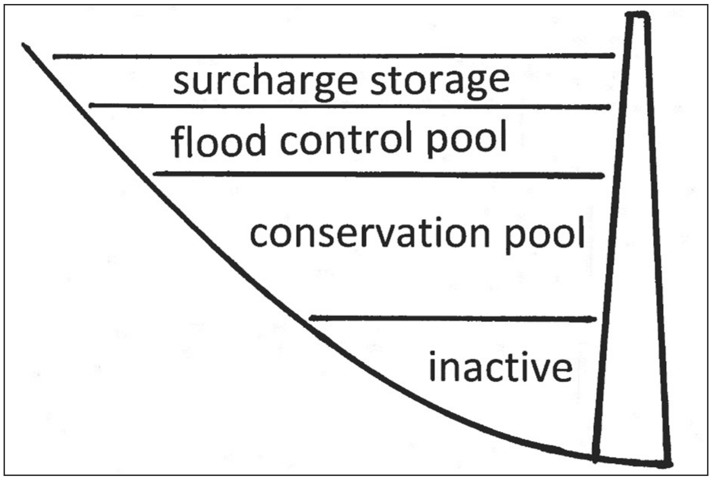

Figure 18. Reservoir storage pools.

from the inactive pool only through natural evaporation and seepage. The top of inactive pool elevation may be fixed by the invert of the lowest outlet or contractually set to facilitate lakeside withdrawals or releases from outlet structures that are higher than the lowest outlet structure. The inactive pool may provide part of the sediment reserve, head for hydroelectric power, and water for recreation and fish habitat.

Conservation storage purposes, such as municipal water supply, thermal-electric cooling water and other industrial supply, agricultural irrigation, hydroelectric power, and recreation, involve storing water during periods of high stream flow and/or low demand for later beneficial use as needed. The reservoir water surface is maintained at or as near the designated top of conservation pool elevation as stream flows and water demands allow. Drawdowns are made as required to meet the various needs for water.

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

Surcharge storage capacity is provided above the flood control pool or above the conservation pool if there is no designated flood control pool. The maximum design water surface, or top of surcharge storage, is established during project design from the perspective of dam safety. Reservoir design and operation are based on assuring that the reservoir water surface never exceeds the designated maximum design water surface elevation. The top of dam elevation includes a freeboard allowance above the top of surcharge pool for wave action and an additional safety factor against overtopping. The storage capacities cited in this paper and most documents referencing storage capacities do not include surcharge storage and dam freeboard.

Sedimentation and sediment reserve

Storage capacity is lost over time due to sediment deposits occurring throughout a reservoir. The rate of sediment deposition varies greatly between reservoirs, depending on stream flow inflow rates, sediment loads, and sediment trap efficiencies. Because sediment transport increases greatly during high flows, reservoir sedimentation varies greatly over time with the random occurrence of floods.

No attempt is made to estimate the volume and location of past or projected future sediment deposits for many smaller reservoirs. For most federal and other large reservoirs, reserve storage capacity is provided for sedimentation estimated to occur over a period of typically 50 to 100 years. The volume and location of the sediment deposition are predicted using methods outlined by the USBR (1987) and USACE (1995). Storage capacity reserved for future sediment accumulation is reflected in water supply contracts and planning.

Reservoir sedimentation surveys are performed occasionally. Because measurements of the bottom topography of lakes are expensive, many reservoirs have existed for decades without sediment surveys ever being performed. The TWDB has operated a hydrographic survey program since 1991. Reservoir owners contract with the TWDB to perform surveys to determine storage capacity, sedimentation rates, updated elevation-area tables, and bathymetric contour maps. Reservoir owners can also perform their own sediment surveys.

Flood control operations

The USACE is responsible for operating most of the large flood control reservoir in Texas and the nation. Flood control regulation plans are developed to address particular conditions for each reservoir and multiple-reservoir system. However, flood control operating rules for most reservoirs follow the same general strategy outlined as follows (Wurbs 1996, 2016; USACE 2017).

Flood control pool operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding, subject to the constraint of assuring that the maximum design water surface of the reservoir is never exceeded. Release decisions depend upon whether or not the flood control pool storage capacity is exceeded (Figure 18). Rules based on downstream flow rates at stream gages are followed as long as sufficient storage capacity is available without the water surface rising above the top of flood control pool. Operation is switched to an emergency operations plan, based on reservoir inflows and storage levels, during extreme flood conditions when the inflows are expected to exceed the remaining flood control pool capacity.

Overflow spillway and outlet conduit gates are closed when a flood occurs and remain closed until the flood has crested and flows are below the target levels specified at each of the downstream gages. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the downstream gages. The allowable flow rate associated with each gage site may be constant or may vary depending on the volume of water in storage upstream in flood control pools. Most flood control reservoirs are components of multiple-reservoir systems operated based on flow rates at several gages located various distances below the dams. Two or more reservoirs may have common downstream gages.

For an extreme flood event, limiting reservoir releases based on allowable downstream flow rates may result in the storage capacity of the flood control pool being exceeded. The overall strategy for operating the outlet works and spillway gates consists of two component types of regulation procedures. The regulation approach discussed above is followed until the release rate dictated by the emergency rules is higher than that indicated by the downstream allowable flow rates. Operations are then switched emergency release rules designed to absolutely assure that the maximum design water surface is never exceeded even though releases contribute to downstream damage. Emergency operating rules are specified as a function of current reservoir inflows and storage levels.

Conservation storage operations

Almost all of the major reservoirs in Texas have conservation pools serving primarily M&I, steam-electric cooling, and/or agricultural water supply. Hydroelectric power plants are operated at about 23 reservoirs. With the exception of Lake Texoma, hydropower generation is essentially limited to releases for downstream water supply diversions. Recreation is popular at most of the major reservoirs. Minimizing storage drawdowns and fluctuations generally enhances reservoir recreation.

Reservoir management in Texas is influenced more by the long-term threat of drought than seasonal fluctuations in stream flow and/or water use. Although storage may be significantly drawn down in several months, critical drought conditions usually involve a series of several dry years.

Essentially all water withdrawn from Texas streams for beneficial use is regulated by dams and reservoirs. Water supply operations are based on meeting demands subject to institutional considerations specified in water right permits, federal storage contracts, contracts between suppliers and customers, and for some reservoir systems, interstate compacts and/or international treaties. Although most surface water is used within the river basin in which it originates, several reservoir systems in Texas include interbasin transfers through pipelines.

Many water suppliers own and operate single reservoirs. System operations balancing storage and releases between multiple reservoirs occur in several river basins. Water supply withdrawals are made through pumping plants with intake structures located in the lake and/or at locations up to several hundred miles below the dams that regulate the flow. River flow at diversion sites may be a combination of releases from one or multiple reservoirs and unregulated flow entering rivers downstream of the dams. Some water users are supplied by run-of-river diversions with no access to reservoir storage. Reliabilities associated with run-of-river (no reservoir storage) water supply are generally very low.

COMPREHENSIVE INTEGRATED WATER MANAGEMENT

Multiple purposes are optimally served through integration of multiple management strategies. Integrated water management has been preached fervently over the past several decades nationwide. Texas has been a notable leader in effectively managing water resources in a comprehensive integrated manner. Reservoir operations are central to multiple objective endeavors. The remainder of this paper highlights current and potential future directions in improving water management in Texas. Successes and remaining challenges are highlighted with a focus on the role of reservoirs in developing and managing water resources.

Pursuant to water management legislation enacted by the 75th Texas Legislature in 1997 with the passage of Senate Bill 1 (SB1), the TWDB and 16 regional planning groups update 16 regional plans and a statewide water plan in a 5-year planning cycle with a 50-year future planning horizon. 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 the 2022 statewide plan is underway. The TCEQ administers a variety of regulatory programs involving water quality protection, water allocation, preservation of environmental resources, and dam safety. Consistency with relevant TWDB statewide and regional plans is a requirement for TCEQ approval of applications for new or amended water right permits.

Flood risk mitigation has been primarily federal and local community responsibilities, with involvement of state agencies focused on information dissemination. The Texas Legislature in 2019 significantly expanded the role of the TWDB in flood risk mitigation planning. The TWDB is presently initiating a statewide and regional flood planning process analogous to the SB1 planning process initiated in 1997. The TWDB is also creating programs to assist local entities in financing flood control projects similarly to long-established TWDB programs for assisting in the financing of water supply projects.

Flood risk mitigation

The federal government has played a dominant role nationwide, including in Texas, in large-scale flood protection through USACE reservoirs on major rivers, smaller reservoirs constructed by the Natural Resources Conservation Service in rural watersheds, and the National Flood Insurance Program (NFIP) administered through the Federal Emergency Management Agency. Local communities are responsible for flood plain management requirements of the NFIP and storm water management and drainage. As noted in the preceding paragraph, the TWDB has recently acquired significantly expanded responsibilities for flood control planning and financing. Additional funding has also been provided to expand TWDB flood data compilation and dissemination programs.

Coordination of floodplain management, reservoir flood control operations, and other structural and nonstructural measures has been a major nationwide endeavor since establishment of the NFIP and its requirements for local floodplain management pursuant to the Flood Disaster Protection Act of 1973. Reservoir storage reduces flood flows. Flood plain management reduces susceptibility of people and property to flood damage. Flood insurance is a risk management strategy. All three are essential. Optimal integration of the three strategies is challenging.

Emergency operations of USACE flood control reservoirs is a potential area for further research and development. The USACE (2017) outlines procedures employed during preconstruction design to establish the emergency operation component of flood control operating plans described earlier in this paper. An academic research study (Rivera 2004; Rivera and Wurbs 2004) explored a risk-based methodology for developing emergency operating rules based on stochastic generation of inflows that preserve the statistical characteristics of historical observed inflows. The Addicks and Barker reservoir system was employed as a case study for this research. Similar strategies using hydrologic data acquired since dam construction could be further investigated in the future.

Operations during major floods must balance flood risks upstream versus downstream of dams. Addicks and Barker Reservoirs in Houston, owned by the USACE, illustrate the problem of urban development adjacent to flood control pools as well as along streams (Wurbs 2002a). Most USACE reservoir projects include significant areas of government-owned land with no commercial or residential development allowed surrounding the reservoir for several vertical feet above the top of flood control pool. However, the planning, design, design revisions, and construction of Addicks and Barker Dams during the 1930s and 1940s resulted in purchase of areas of government-owned land upstream of the dams that may be exceeded by extreme flood events such as Hurricane Harvey in 2017. Likewise, releases from conservation pools of reservoirs with no flood control pool can transfer flooding between floodplains downstream and upstream of dams.

Operations during floods of non-federal water supply reservoirs that have no flood control pool is an important issue. The strategy of pre-flood releases from conservation pools based on flood forecasts has been investigated but is constrained by limited forecast capabilities and the lengthy time typically required to draw down conservation pool storage enough to significantly affect flood flows. Expanded flood forecasting capabilities and reservoir operating practices warrant continued research and development.

Dam safety and rehabilitation of aging structures

Risks of dam overtopping or breaching or structural failures of outlet gates are related to both flood risk mitigation and concerns nationwide and in Texas regarding rehabilitation of aging infrastructure (ASCE 2017). The TCEQ Dam Safety Program is responsible for safety oversight of 3,995 dams (https://damsafety.org/texas). These dams are classified as high hazard (1,352 dams), significant hazard (369), or low hazard (2,274) based on potential damage susceptibility of downstream life, property, and infrastructure. TCEQ dam safety staff inspect dams at 5-year intervals and provide technical information and assistance to dam owners. Dam safety regulatory policies are outlined in the Texas Administrative Code, Part 1 TCEQ, Chapter 299 Dams and Reservoirs, which is accessible online. Safety and rehabilitation concerns grow as dams and appurtenant structures age and watersheds and floodplains urbanize.

Dascher and Meitzen (2020) review the history of dam failures and removals in Texas. Fifty small mostly privately owned dams in Texas were removed between 1983 and 2016. Most were older small dams removed by private owners in response to liability concerns. Dascher and Meitzen (2020) found 328 instances of reported dam failures or related incidents in Texas since 1900. Several of the failures or incidents involve major reservoirs.

The Guadalupe-Blanco River Authority (GBRA) owns, operates, and maintains six dams on the Lower Guadalupe River that were constructed during the 1920s for hydroelectric power. The lakes also provide recreation. A spillway gate at Lake Wood broke loose from the dam in 2016, partially draining the lake. A spillway gate at Lake Dunlap similarly broke loose from the dam in 2019, partially draining Lake Dunlap. The GBRA announced in 2019 a planned systematic drawdown of all six lakes to ensure public safety. This action has been halted by a temporary injunction issued in favor of lakefront property owners interested in preserving the lakes to protect aesthetics and property values. Funding the rehabilitation of dams and appurtenant structures is a key issue.

Water supply reliability

Effective management of extremely variable stream flow requires assessments of water supply reliability. The TCEQ WAM system was implemented pursuant to the 1997 SB1 to support water allocation and planning. Reliabilities in meeting specified percentages of demand targets are computed in evaluating water right permit applications. Planning studies incorporate reservoir firm yield estimates. Firm yield is the maximum target demand that can be supplied continuously based on the premises and data reflected in the WAMs, including repetition of historical natural hydrology. Without reservoir storage, run-of-river firm yields are typically zero or near zero throughout Texas.

WAM simulations demonstrate that the target quantity of water supplied by a reservoir or multiple-reservoir system can be increased greatly by accepting risks of supply shortages during infrequent severe drought conditions. Reservoir operations with less than firm reliability can be combined as necessary with infrequent increased pumping from groundwater or emergency demand management. However, differences between ownership and regulation of groundwater versus surface water constrain these types of conjunctive water management operations (Young et al. 2018).

The BRA systems operation permit and associated water management plan approved by the TCEQ in September 2016 illustrate the significant improvements in water supply capabilities resulting from expanded WAM capabilities for assessing reliabilities of reservoir system operating strategies. Water supply capabilities of the 12-reservoir BRA/USACE system are enhanced by multiple-reservoir risk sharing, combining regulated and unregulated flows and firm and interruptible yield, and reuse of return flows. The BRA system operations permit and water management also includes the proposed Allen's Creek Reservoir in the lower basin that has not yet been constructed. However, the permit and management plan are designed for implementation with or without construction of the Allen's Creek Reservoir project.

The LCRA also combines firm (high reliability) and interruptible (lower reliability) yield in operation of the Highland Lakes to supply water users throughout the Lower Colorado River Basin. Austin and other M&I users contract with LCRA for firm yield. Agricultural irrigators are supplied through contracts based on interruptible yield. Water supply to interruptible customers is curtailed to varying degrees during droughts as the storage contents of Lakes Buchanan and Travis fall below set trigger levels. Reservoir operations are governed primarily by water supply requirements rather than hydroelectric power generation, but water supply releases pass through hydropower plants at the six dams, generating electricity and reducing costs of power production at the LCRA thermal-electric plants. The first version of the water management plan was approved in 1989, and the plan is periodically updated by the LCRA and submitted to the TCEQ for approval.

Several western states have watermaster operations for real-time management of water rights, but most states do not. Watermaster offices provide continuous accounting of water use and administer curtailment actions as necessary to enforce water right permit requirements. TCEQ watermaster offices have been established for some but not all river basins in Texas. For regions without watermaster operations, the TCEQ administers curtailment actions during drought and takes enforcement action anytime to stop reported unauthorized water use but does not otherwise closely monitor water use. Watermaster operations provide more detailed monitoring and accounting. The importance of TCEQ watermaster operations increases as less reliable reservoir water supply commitments are combined with backup plans such as temporary increased groundwater use or emergency demand management strategies.

The TCEQ Rio Grande watermaster office has maintained a detailed accounting for all Texas water right permits of storage in Lakes Amistad and Falcon and diversions from the lower Rio Grande since the 1970s. The South Texas and Concho watermasters patrol diversions for mainly run-of-river rights in the Concho River sub-basin of the Colorado Basin and Nueces, Lavaca, Guadalupe, and San Antonio river basins and adjoining coastal basins. TCEQ initiated a watermaster program in 2016 for the Brazos River Basin downstream of and including Possum Kingdom Reservoir. Establishment of watermaster programs for other river basins to regulate water use in accordance with water right permits continues to be investigated.

The prior appropriation water rights doctrine is a general guiding concept that is not necessarily feasible to implement absolutely with perfect precision in real world water management. For example, most water right permits assign a single priority date to both refilling reservoir storage and water supply diversions. Reservoir operation in Texas is based on long-term storage as a protection against severe multiple-year droughts. The supply reliability of a reservoir is diminished if upstream junior appropriators reduce inflows when the reservoir is not completely full and spilling. However, forcing junior diverters to curtail their water use to maintain inflows to an almost full or even significantly drawn-down senior reservoir is difficult and not necessarily the optimal use of the water resource. The senior reservoir will likely refill to capacity and spill later without failing to supply its own diversion demands even if the junior water supply diversions are not curtailed.

Reservoir storage reallocations

Wurbs and Carriere (1988), Johnson et al. (1990), and Wurbs (1990) outlined strategies for improving reservoir operations in response to changing conditions by reallocating storage capacity between project purposes, such as permanently or seasonally converting portions of flood control or hydropower pools to water supply. Patterson and Doyle (2018) and Doyle and Patterson (2019) explore issues and future potential for storage reallocations at USACE reservoirs nationwide.

Storage reallocations between flood control and conservation purposes are implemented by raising or lowering the designated top of conservation pool shown in Figure 18. The top of conservation pool can be raised and lowered seasonally in response to seasonal variations in flood and drought risks and water demands. Seasonal rule curve operations have been employed at Lake O' the Pines and Lake Wright Patman and occasionally at Lakes Amistad and Falcon. Permanent reallocations have been implemented at several USACE reservoirs in Texas. Reallocations have been studied but not adopted for other projects. In some cases, storage has been reallocated in existing reservoirs in conjunction with construction of other new reservoirs. Lakes Waco and Texoma are examples of several reservoirs where reallocations have been performed without modifying existing dams or constructing new reservoir projects.

Construction of Lake Waco by the USACE Fort Worth District was completed in 1965 with flood control, conservation, and sediment reserve capacities of 553,300, 104,100, and 69,000 acre-feet, respectively. The USACE reservoir inundated an existing nonfederal reservoir constructed in 1929. The conservation pool is committed to supplying water for Waco and adjacent smaller cities. In 2003, at the request of the City of Waco and BRA, the USACE raised the top of conservation pool 7 feet, converting 47,500 acre-feet of the flood control pool to water supply. The conservation capacity in Table 1 reflects the raised pool plus sediment reserve less estimated actual sedimentation.

Lake Texoma on the Red River in Texas and Oklahoma is the oldest and largest USACE reservoir in Texas. The project was constructed for flood control and hydropower while realizing that other purposes could become important in the future. For many years, the conservation capacity was used solely for hydroelectric power and recreation. Natural salt pollution in the Red River Basin has been a constraint to water supply use. However, motivated by growing water needs in both Texas and Oklahoma, hydropower storage has been reallocated to M&I water supply in several increments as needed over the past several decades. Desalination is used with the increased M&I supply.

Water quality

Pollution from agricultural or oil field activities in watersheds or M&I wastewater effluents often cause reservoir water quality problems. Eutrophication is a common problem resulting from excessive addition of organic matter, plant nutrients, and silt to reservoirs at rates sufficient to cause increased production of algae and rooted plants. Natural salinity is the water quality problem causing the greatest constraint on water supply capabilities of large reservoirs in a large region of Texas.

Salinity in lower reaches of Texas rivers may be increased by saltwater intrusion from the Gulf of Mexico, from sources in the upper river basins, or from combinations of multiple sources. Seawater propagates further upstream in rivers during low flows. For example, salinity levels of flows of the Brazos River at water supply pumping plants located about 25 miles and 60 miles upstream of the river outlet are dependent on river flow levels that are affected by reservoir operations.

Shallow geologic formations in the Permian Basin region underlying the upper watersheds of the Rio Grande, Pecos, Colorado, Brazos, Red, and Canadian Rivers in New Mexico, Oklahoma, and Texas contribute large salt loads to the rivers (Wurbs 2002b). The mineral deposits consist largely of sodium chloride, with moderate amounts of calcium sulfate and other dissolved solids. The USACE, USBR, water districts, and river authorities have investigated measures for dealing with the natural salt pollution. Several of the many proposed salt control plans have been implemented, as illustrated by the examples noted below (Wurbs 2002b). Water supply capabilities of many large Texas reservoirs could potentially be significantly increased by further planning, design, and implementation of salinity control strategies.

The Truscott brine storage facility constructed by the USACE Tulsa District in 1987 above Lakes Kemp and Texoma captures and permanently stores salt from a primary salt source watershed. A levee constructed around Estelline Springs prevents high salinity spring flows from entering the Red River. Red Draw, Barber, and Mitchell County Reservoirs are salt pollution control projects constructed in the upper Colorado River Basin to reduce salt loads into Lakes Thomas, Spence, and O. H. Ivie, which are owned by the Colorado River Municipal Water District.

A project implemented by the USBR near the Texas/New Mexico border during the 1980s to reduce salt loads of the Canadian River and Lake Meredith consists of shallow interception wells combined with deep-well injection wells to dispose of the brine. The Canadian River Municipal Water Authority blends high salinity water from Lake Meredith with lower salinity groundwater.

Salt control dams have been proposed by the USACE for the upper Brazos River Basin but have not actually been constructed. Dilution occurs in the middle and lower Brazos River as the BRA's high-salinity releases from their three upper Brazos River reservoirs combine with their releases from low-salinity tributary reservoirs and unregulated flows (Wurbs and Lee 2009).

Numerous desalination plants using reverse osmosis or electrodialysis processes are in operation throughout Texas and neighboring states for treating brackish groundwater and surface water for M&I use. Most are small. The two largest plants use electrodialysis reversal to treat water from Lake Granbury on the Brazos River and Lake Texoma on the Red River.

Environmental flow standards

Protecting instream flows in the river systems of Texas has been a concern for many years. Efforts to establish environmental flow standards have greatly intensified since 2001, when the Legislature authorized the Texas Instream Flow Program to advance scientific knowledge related to environmental flows. In 2007, the 80th Texas Legislature created the Senate Bill 3 (SB3) process to expedite the establishment of environmental flow standards (EFS) for priority river reaches based on the best currently available scientific information and expert opinion. SB3 required TCEQ to adopt EFS through rulemaking. EFS have been established and incorporated into the WAMs through the SB3 process for river systems flowing into the Gulf of Mexico. These standards are published in the Texas Administrative Code, Part 1 TCEQ, Chapter 298, Environmental Flow Standards for Surface Water, which can be accessed online. The SB3 process anticipates future improvements to the flow standards with advances in scientific knowledge.

The EFS established through the SB3 process and incorporated into the TCEQ WAM system are defined based on seasonally varying flow regimes with subsistence flows, base flows, and high flow pulses (Wurbs 2017). Although preexisting water right permits are not subject to the SB3 EFS, applications for new water right permits or modifications to existing permits for new appropriations of water are subject to the adopted standards. Various issues related to interactions between the SB3 EFS and reservoir operations warrant continuing investigation.

CONCLUSIONS

Water resources development and management are driven by spatial and temporal hydrologic variability. Thousands of dams and reservoirs have been constructed in Texas, with most of the storage capacity contained in a relatively small number of the largest federal and non-federal projects. River flow characteristics have been significantly altered by reservoirs, but flows are still extremely variable. Long-term mean river flow volumes are very large, but most of the flow occurs during flood events or infrequent periods of very high flows, separated by long periods of fluctuating low-to-moderate flows that may include severe multiple-year droughts. Conservation storage is essential to provide reliable water supplies. Flood control storage is an essential component of integrated flood risk mitigation. Reservoir operations are central to essentially all aspects of comprehensive water management. Optimizing reservoir operations is an important component of the response to population growth and accompanying intensifying demands on limited water resources and river regulation infrastructure.

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