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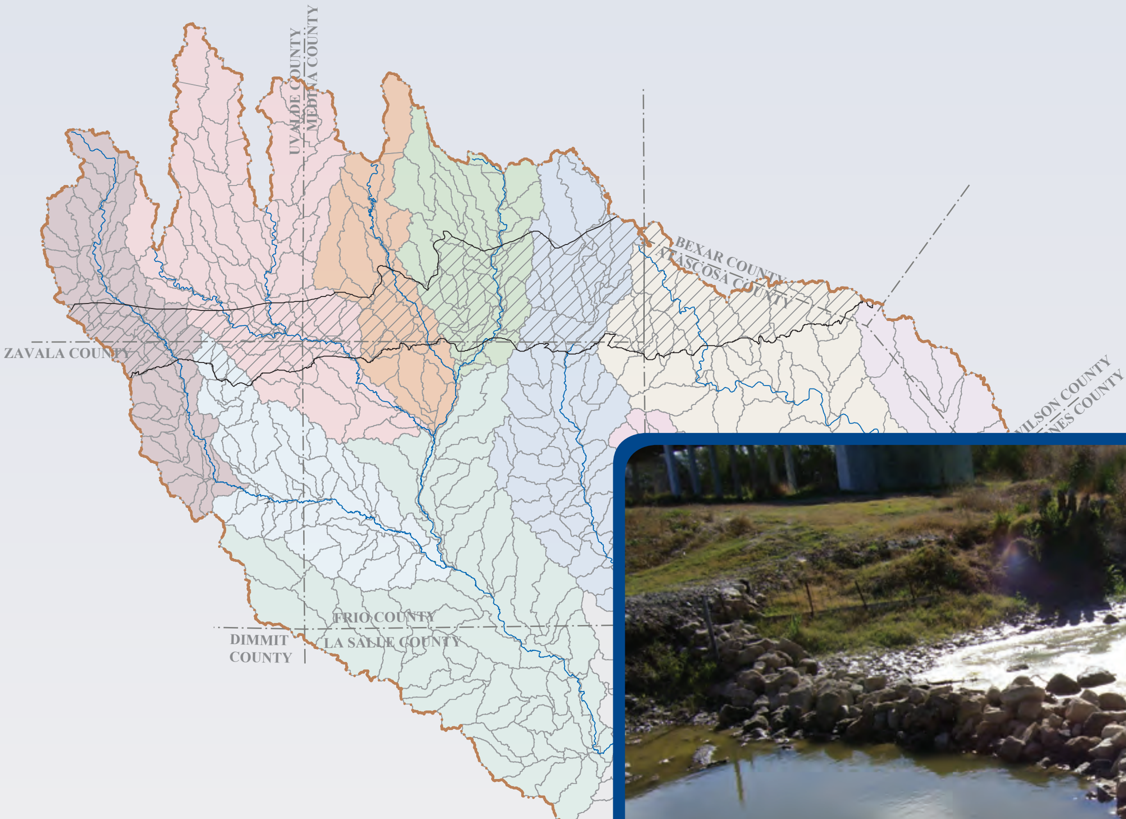
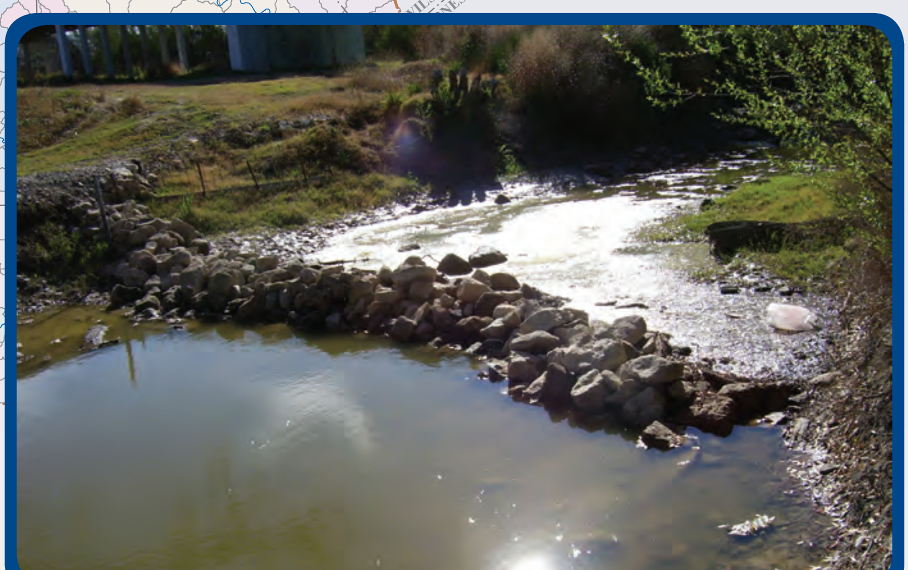
In cooperation with the U.S. Army Corps of Engineers, Fort Worth District; City of Corpus Christi; Guadalupe-Blanco River Authority; San Antonio River Authority; and San Antonio Water System

Simulation of Streamflow, Evapotranspiration, and Groundwater Recharge in the Lower Frio River Watershed, South Texas, 1961–2008





Scientific Investigations Report 2011–5093

U.S. Department of the Interior
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Cover, Near U.S. Geological Survey continuous-streamflow measuring station 0820660, Frio River at Tilden, Texas (photograph by Charles A. Hartmann, U.S. Geological Survey, March 6, 2006).

Simulation of Streamflow, Evapotranspiration, and Groundwater Recharge in the Lower Frio River Watershed, South Texas, 1961–2008

By Joy S. Lizárraga and Darwin J. Ockerman

In cooperation with the U.S. Army Corps of Engineers, Fort Worth District; City of Corpus Christi; Guadalupe-Blanco River Authority; San Antonio River Authority; and San Antonio Water System

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U.S. Department of the Interior
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Conversion Factors, Datums, and Water-Quality Units

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04391	cubic meter per second (m^3/s)
inch per hour (in/hr)	0.0254	meter per hour (m/hr)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North American Vertical Datum of 1988 (NAVD 88). Altitude, as used in this report, refers to distance above the vertical datum.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

List of Abbreviations and Acronyms

DSN	Dataset number
ET	Evapotranspiration
FTABLE	Function table
GAM	Groundwater Availability Model
GIS	Geographic Information System
HRU	Hydrologic response units
HSPF	Hydrological Simulation Program—FORTRAN

INFILT	Model parameter index to infiltration capacity of soil
IMPLNDs	Impervious land segments
MAE	Mean absolute error
NLCD	National land cover data
NS	Nash-Sutcliffe
NWS	National Weather Service
PERLNDs	Pervious land segments
PEVT	Potential evapotranspiration
RCHRESs	Stream or reservoir reaches
RMSE	Root Mean Square Error
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WDM	Watershed data management

Simulation of Streamflow, Evapotranspiration, and Groundwater Recharge in the Lower Frio River Watershed, South Texas, 1961–2008

By J.S. Lizárraga and D.J. Ockerman

Abstract

The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, Fort Worth District; the City of Corpus Christi; the Guadalupe-Blanco River Authority; the San Antonio River Authority; and the San Antonio Water System, configured, calibrated, and tested a watershed model for a study area consisting of about 5,490 mi^2 of the Frio River watershed in south Texas. The purpose of the model is to contribute to the understanding of watershed processes and hydrologic conditions in the lower Frio River watershed. The model simulates streamflow, evapotranspiration (ET), and groundwater recharge by using a numerical representation of physical characteristics of the landscape, and meteorological and streamflow data. Additional time-series inputs to the model include wastewater-treatment-plant discharges, surface-water withdrawals, and estimated groundwater inflow from Leona Springs.

Model simulations of streamflow, ET, and groundwater recharge were done for various periods of record depending upon available measured data for input and comparison, starting as early as 1961. Because of the large size of the study area, the lower Frio River watershed was divided into 12 subwatersheds; separate Hydrological Simulation Program—FORTRAN models were developed for each subwatershed. Simulation of the overall study area involved running simulations in downstream order. Output from the model was summarized by subwatershed, point locations, reservoir reaches, and the Carrizo-Wilcox aquifer outcrop. Four long-term U.S. Geological Survey streamflow-gaging stations and two short-term streamflow-gaging stations were used for streamflow model calibration and testing with data from 1991–2008. Calibration was based on data from 2000–08, and testing was based on data from 1991–99. Choke Canyon Reservoir stage data from 1992–2008 and monthly evaporation estimates from 1999–2008 also were used for model calibration. Additionally, 2006–08 ET data from a U.S. Geological Survey meteorological station in Medina County were used for calibration.

Streamflow and ET calibration were considered good or very good. For the 2000–08 calibration period, total simulated flow volume and the flow volume of the highest 10 percent of simulated daily flows were calibrated to within about 10 percent of measured volumes at six U.S. Geological Survey streamflow-gaging stations. The flow volume of the lowest 50 percent of daily flows was not simulated as accurately but represented a small percent of the total flow volume. The model-fit efficiency for the weekly mean streamflow during the calibration periods ranged from 0.60 to 0.91, and the root mean square error ranged from 16 to 271 percent of the mean flow rate. The simulated total flow volumes during the testing periods at the long-term gaging stations exceeded the measured total flow volumes by approximately 22 to 50 percent at three stations and were within 7 percent of the measured total flow volumes at one station. For the longer 1961–2008 simulation period at the long-term stations, simulated total flow volumes were within about 3 to 18 percent of measured total flow volumes. The calibrations made by using Choke Canyon reservoir volume for 1992–2008, reservoir evaporation for 1999–2008, and ET in Medina County for 2006–08, are considered very good.

Model limitations include possible errors related to model conceptualization and parameter variability, lack of data to better quantify certain model inputs, and measurement errors. Uncertainty regarding the degree to which available rainfall data represent actual rainfall is potentially the most serious source of measurement error. A sensitivity analysis was performed for the Upper San Miguel subwatershed model to show the effect of changes to model parameters on the estimated mean recharge, ET, and surface runoff from that part of the Carrizo-Wilcox aquifer outcrop. Simulated recharge was most sensitive to the changes in the lower-zone ET (LZETP), the fraction of groundwater inflow to deep recharge (DEEPFR), and the interception storage capacity (CEPSC). Of the changes to these three model parameters, the changes to the CEPSC parameter, which is related to vegetative cover, had the least effect on the surface runoff from the outcrop pervious area.

Selected results of the model include streamflow yields for the subwatersheds and water balance information for the Carrizo-Wilcox aquifer outcrop area. From 2000–08, estimated mean streamflow yields from 11 of the 12 subwatersheds, not including the Choke Canyon subwatershed, ranged from -0.1 to 2.8 inches per year (in/yr). For this area, the estimated mean streamflow yield from 2000–08 was

1.1 in/yr. From 1961–2008, the mean annual rainfall at 12 National Weather Service rainfall stations within or near the study area ranged from 22.2 to 28.2 inches (in.), and the estimated mean annual rainfall on the Carrizo-Wilcox aquifer outcrop was 26.5 in. Estimated mean annual groundwater recharge to the Carrizo-Wilcox aquifer from 1961–2008 was 1.8 in., less than 7 percent of mean annual rainfall. Estimated mean annual recharge generally increased from west to east across the study area, ranging from 1.0 to 2.7 in/yr by sub-watershed. Estimated annual groundwater recharge in the aquifer outcrop area varied from 0.1 to 7.1 in. depending on the amount of rainfall. The estimated mean annual ET from 1961–2008 from the aquifer outcrop area is 24.3 in/yr, about 92 percent of the mean annual rainfall. The estimated mean annual surface-water runoff from the aquifer outcrop area is 0.5 in., less than 2 percent of mean annual rainfall.

Introduction

The Frio River is a major tributary to the Nueces River in south Texas (fig. 1), serving multiple users and riparian ecosystems within and downstream from the Frio River watershed. The Frio River watershed, which is west of San Antonio and northwest of Corpus Christi, Tex., composes approximately 41 percent of the Nueces River Basin and is an important source of flow to the Nueces River and to several bays and estuaries on the Gulf Coast (including Nueces Estuary, Nueces Bay, and Corpus Christi Bay). Flows generated from the Frio River watershed are impounded and regulated by Choke Canyon Reservoir, except for flows from the Atascosa River and its tributaries. The confluence of the Atascosa River with the Frio River is downstream from the reservoir, about 6 miles (mi) upstream from the confluence of the Frio and Nueces Rivers.

The U.S. Army Corps of Engineers (USACE), Fort Worth District began a study of the Nueces River watershed in 2002 to identify opportunities for ecosystem restoration. Restoration activities include aquifer recharge enhancement, flood damage reduction, and watershed management through multipurpose projects (HDR Engineering, 2002). The first phase of the USACE study consists of working with Federal, State, and local partners to establish and document the existing hydrologic, engineering, economic, and environmental conditions of the Nueces River watershed. As part of this phase, the U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers (Fort Worth District), the City of Corpus Christi, the Guadalupe-Blanco River Authority, the San Antonio River Authority, and the San Antonio Water System developed a hydrologic model of the lower Frio River watershed. The model of the lower Frio River watershed (hereinafter the Frio model) contributes to the understanding of watershed processes and hydrologic conditions in the Nueces River Basin, and complements existing surface-water and groundwater models being used by State and local agencies in Texas.

The modeled watershed area begins near the southern boundary of the Edwards aquifer outcrop, coincident with a network of USGS streamflow-gaging stations and extends to the Frio River and Nueces River confluence downstream from Choke Canyon Reservoir. The lower Frio River watershed overlies part of the Carrizo-Wilcox aquifer outcrop; the Frio model is formulated to simulate groundwater recharge estimates in the study area. The Carrizo-Wilcox aquifer underlying the study area is modeled as part of the Texas Water Development Board's southern Carrizo-Wilcox Queen City-Sparta groundwater availability model (GAM) (Kelley and others, 2004). The GAM uses an empirical model to estimate groundwater recharge to the aquifer system.

Purpose and Scope

This report describes the numerical simulation (model) of streamflow, evapotranspiration (ET), and groundwater recharge in the lower Frio River watershed. The Frio model was developed by using input data collected during 1961–2008 and is used to simulate streamflow, ET, and groundwater recharge for the same period. The functionality of software and the input data are described, followed by the configuration, calibration, and testing of the Frio model. Calibration and testing of the Frio model were done by using measured and simulated streamflow at four long-term and two short-term USGS streamflow-gaging stations. For streamflow, the calibration period was from 2000–08, and the testing period was 1991–99 at the long-term stations. Simulated ET was calibrated with measured ET computed by using data collected from October 2006 through December 2008 at one USGS meteorological station in Medina County. Simulated reservoir volume from 1992–2008 was calibrated with reservoir volume computed from stage measurements at Choke Canyon Reservoir, and simulated reservoir evaporation was calibrated by using 1999–2008 monthly evaporation estimates computed by using pan evaporation measurements at the Choke Canyon Reservoir dam. Major components of the simulated water budget for the pervious land of the Carrizo-Wilcox aquifer outcrop are presented for the years 1961–2008, and limitations of model-simulated estimates of streamflow, ET, and groundwater recharge are described.

Description of the Study Area

The study area is approximately 5,490 square miles (mi^2) of the Frio River watershed (fig. 2) and includes all or parts of 12 counties in south Texas (Atascosa, Bexar, Dimmit, Frio, Karnes, La Salle, Live Oak, McMullen, Medina, Uvalde, Wilson, and Zavala). The northern boundary of the study area was largely determined by the location of existing USGS streamflow-gaging stations (table 1) and inflow from an existing model (Ockerman, 2005) for an ungaged area of Verde Creek (fig. 2). The study area includes the drainage area downstream from these stations and the Verde Creek model

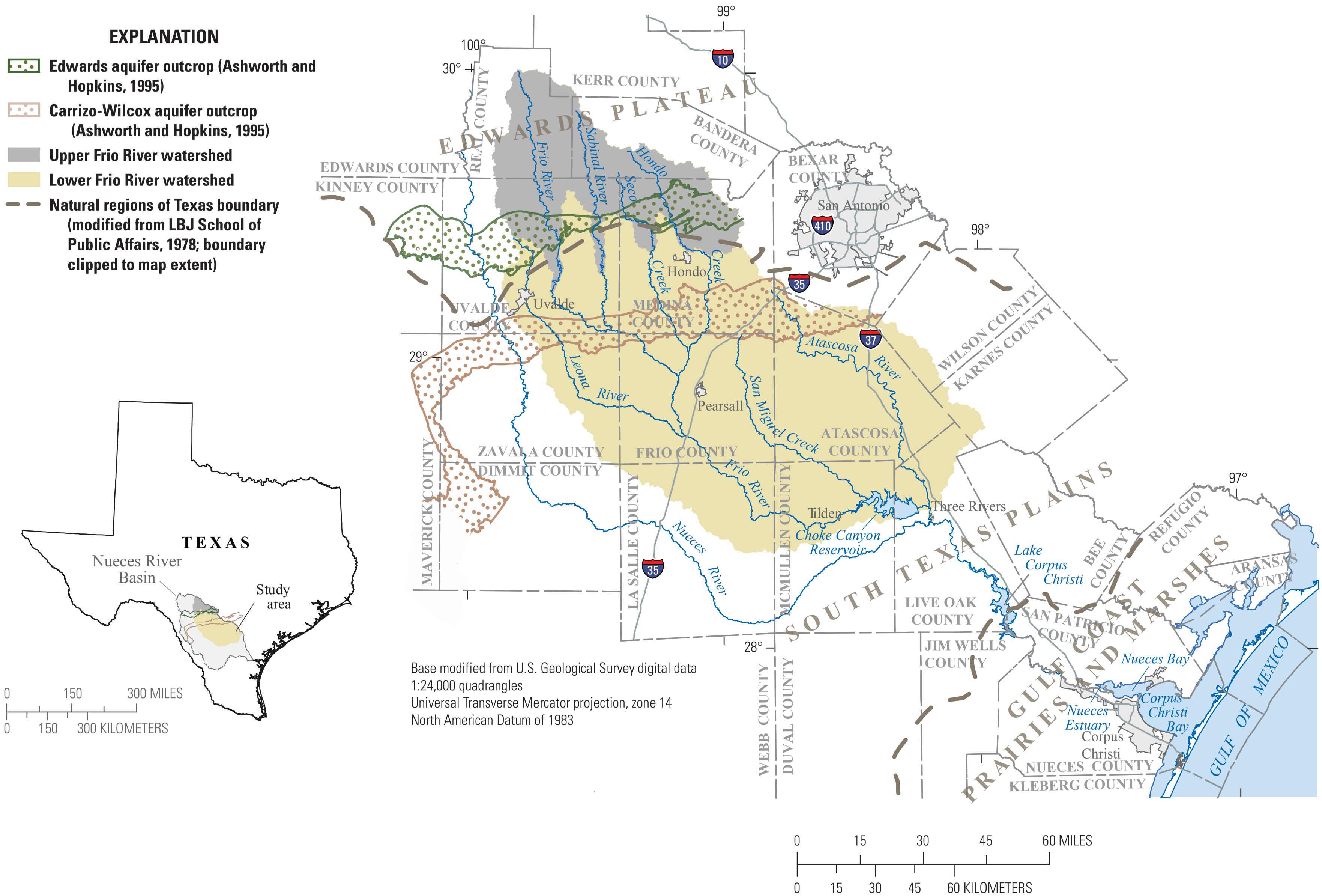

Figure 1. Frio River watershed, south Texas.

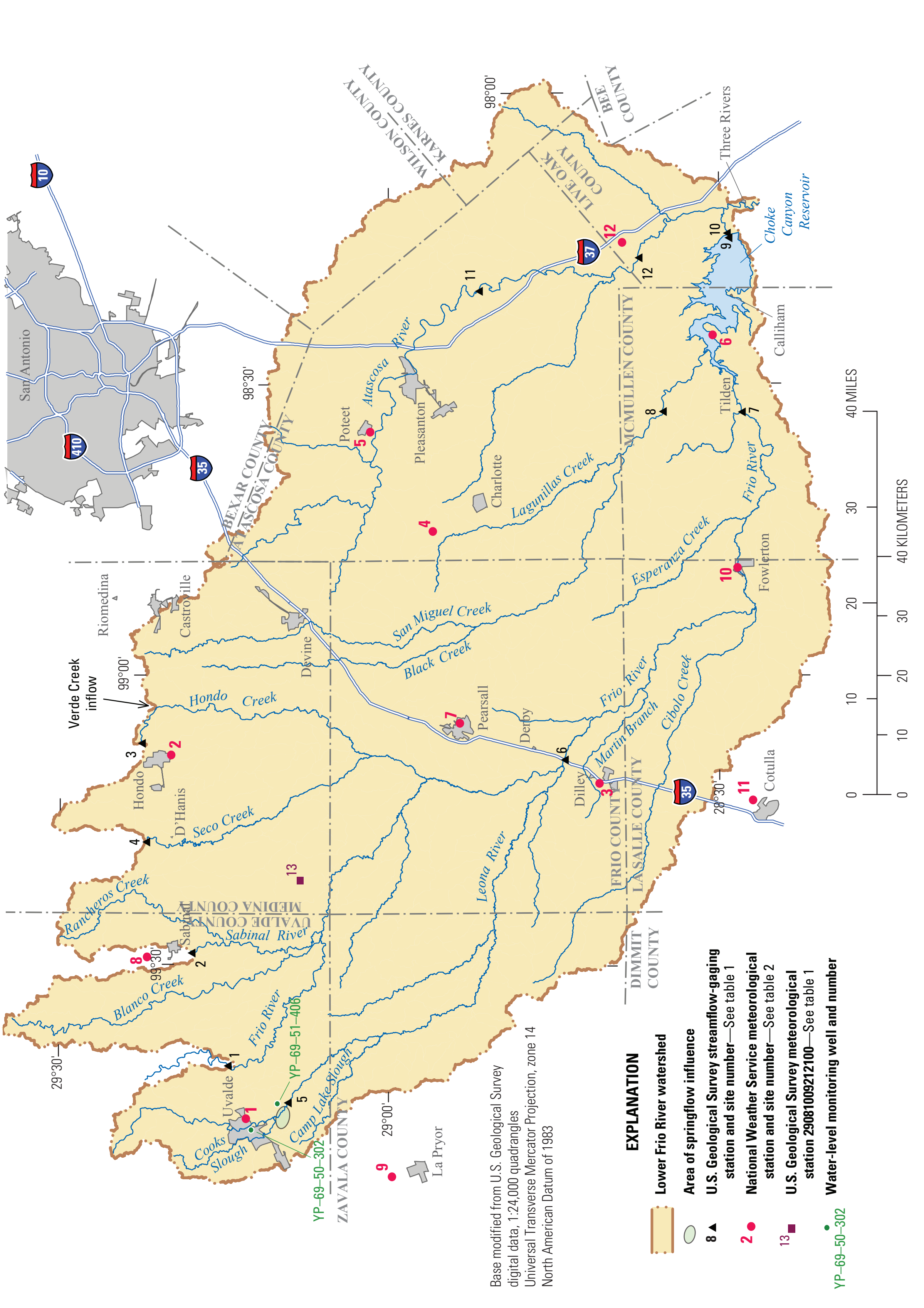

Figure 2. Location of data-collection stations that provided data for the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

Table 1. Description of U.S. Geological Survey stations from which data were obtained for the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

[mi², square miles; dd, degrees; mm, minutes; ss, seconds; NWS, National Weather Service; USGS, U.S. Geological Survey; OWC, Outlet Works Channel; --, not applicable]

USGS site number (fig. 2)	USGS station number	USGS station name	Drainage area (mi²)	Latitude (ddmmss)	Longitude (ddmmss)	Type of data	Period of record used
1	08197500	Frio River below Dry Frio River near Uvalde, Tex.	631	29°14'44"	99°40'27"	Streamflow	1961–2008
2	08198500	Sabinal River at Sabinal, Tex.	241	29°18'51.5"	99°28'49.7"	Streamflow	1961–2008
--	08200700	Hondo Creek at King Waterhole near Hondo, Tex.[1]	150	29°23'26"	99°09'04"	Streamflow	1961–2006
3	08200720	Hondo Creek at State Highway 173 near Hondo, Tex.	157	29°22'34"	99°07'00"	Streamflow	2006–08
4	08202700	Seco Creek at Rowe Ranch near D'Hanis, Tex.	168	29°22'14"	99°17'15"	Streamflow	1961–2008
5	08204005	Leona River near Uvalde, Tex.	132	29°09'15"	99°44'35"	Streamflow	2003–08
6	08205500	Frio River near Derby, Tex.	3,429	28°44'11"	99°08'40"	Streamflow	1961–2008
7	08206600	Frio River at Tilden, Tex.	4,493	28°28'02"	98°32'50"	Streamflow	1978–2008
8	08206700	San Miguel Creek near Tilden, Tex.	783	28°35'14"	98°32'44"	Streamflow	1964–2008
9	08206900	Choke Canyon Reservoir near Three Rivers, Tex.	5,490	28°29'01"	98°14'44"	Reservoir Volume	1999–2008
10	08206910	Choke Canyon Reservoir OWC near Three Rivers, Tex.	5,490	28°29'09"	98°14'29"	Streamflow	1992–2008
11	08207500	Atascosa River near McCoy, Tex.	530	28°51'53"	98°20'17"	Streamflow	2002–08
12	08208000	Atascosa River at Whitsett, Tex.	1,171	28°37'19"	98°16'52"	Streamflow	1961–2008
13	290810099212100	SW Medina County meteorological station near D'Hanis, Tex.	--	29°08'10.3"	99°21'20.5"	Evapotranspiration	2006–08

[1] On July 5, 2006, station was discontinued at this site and moved 3.3 miles downstream and re-established as station 08200720.

inflow to the confluence of the lower Frio and Nueces Rivers, downstream from Choke Canyon Reservoir.

Four groups of springs discharge along a 9-mi stretch of the Leona River south of Uvalde and are collectively known as Leona Springs (Eckhardt, 2010). There is a surficial and an underflow component of the discharge from the springs. Beginning in March 2003, the USGS began collecting continuous streamflow records at USGS streamflow-gaging station 08204005 Leona River near Uvalde, Tex. (hereinafter Leona River near Uvalde station) (USGS site 5; fig. 2 and table 1). The 2003–08 streamflow record at the Leona River near Uvalde station was used to estimate the surficial component of the groundwater discharge from Leona Springs (U.S. Geological Survey, 2010).

Rainfall in the study area occurs mostly in the spring, early summer, and fall (Larkin and Bomar, 1983). National Weather Service (NWS) meteorological data were compiled for the study area for 1961 through 2008 (National Climatic Data Center, 2009); rainfall generally increases from west to east. Mean annual rainfall measured during 1961–2008 at 12 NWS meteorological stations in or near the study area ranged from 22.2 in/yr at the La Pryor station about 8 mi west of the study area (NWS site 9; fig. 2 and table 2) to 28.2 in/yr at the Poteet station in the eastern part of the study area (NWS site 5; fig. 2 and table 2); annual rainfall at each NWS site is listed in table 3. During 1961–2008, the mean standard deviation in rainfall at the 12 stations was 8.1 in. The mean of the standard deviations in the annual rainfall during the model calibration period (2000–08) and model testing period (1991–99) were 11.2 and 7.6 inches, respectively, indicating rainfall was more variable during the model calibration period compared to the model testing period (table 3). The largest standard deviation in annual rainfall during the 2000–08 model calibration period was 14.8 in., measured at NWS station 411663 Charlotte 5 NNW (NWS site 4; fig. 2 and table 2) where the annual rainfall during 2000–08 ranged from 10.6 to 57.0 in. (table 3).

The study area is mostly rural and agricultural. Uvalde, Tex., is the largest population center, with about 16,200 residents (U.S. Census Bureau, 2009). Most of the water use is for irrigation, and the major source of water is groundwater from the Edwards and Carrizo-Wilcox aquifers. The study

Table 2. Description of National Weather Service meteorological stations from which data were obtained for the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

[dd, degrees; mm, minutes; ss, seconds; NWS, National Weather Service; --, not available]

NWS site number (fig. 2)	Station number and name	Latitude (ddmmss)	Longitude (ddmmss)	Type of data	Period of record used	Stations and years used to fill missing record
1	NWS 419268 Uvalde	29°11'--"	99°50'--"	Rainfall	1985–2005	Uvalde (NWS 419265) 1905–85, La Pryor June 7,1985, 2005–8
				and air temperature	1985–2003	Uvalde (NWS 419265)1907–85, Hondo (NWS 414256), 2003–8
2	NWS 414256 Hondo	29°22'--"	99°10'--"	Rainfall	1975–2008	Sabinal 1903–75
				and air temperature	1975–2008	Tarpley 1937–65, Uvalde 1965–75
3	NWS 412458 Dilley	29°54'--"	97°53'--"	Rainfall	1910–2008	
				and air temperature	1916–2008	Charlotte 2008
4	NWS 411663 Charlotte 5NNW	28°52'--"	98°43'--"	Rainfall	1962–2008	Pearsall 1902–62
				and air temperature	1962–2008	Dilley 1916–62
5	NWS 417215 Poteet	28°40'--"	97°23'--"	Rainfall	1961–2008	
				and air temperature	1961–2008	
6	NWS 411337 Calliham	29°54'--"	97°53'--"	Rainfall	1978–2008	Three Rivers (NWS 419009) 1922–78
				and air temperature	1999–2008	Dilley 1916–1983, Choke Canyon 1983–99
7	NWS 416879 Pearsall	28°40'--"	97°23'--"	Rainfall	1961–2008	
8	NWS 417873 Sabinal	29°54'--"	97°53'--"	Rainfall	1961–2008	
9	NWS 414920 La Pryor	29°54'--"	97°53'--"	Rainfall	1961–87, 1989–2008	Uvalde (NWS 419268) 1987–89
10	NWS 413299 Fowlerton	28°40'--"	97°23'--"	Rainfall	1961–2008	
11	NWS 412048 Cotulla La Salle Co AP	28°40'--"	97°23'--"	Rainfall	1961–2008	
12	NWS 419717 Whitsett	29°54'--"	97°53'--"	Rainfall	1964–2008	Whitsett 3 SW (NWS 419716) 1961–64

area overlies part of what has historically been one of the most heavily pumped regions of the Carrizo-Wilcox aquifer (Klemt and others, 1976; Ryder, 1996). The study area is in the South Texas Plains natural region (modified from LBJ School of Public Affairs, 1978), which is synonymous with South Texas Brush Country. Land cover has historically been undeveloped rangeland (scrub, grassland) and crops (fig. 3). Except for the addition of Choke Canyon Reservoir in the early 1980s, current (2011) land cover is similar to land cover in the early 1970s (McMahon and others, 1984).

The Choke Canyon reservoir is in the southeastern corner of the study area and was designed and constructed by the Bureau of Reclamation in 1982 to impound the Frio River. In 2003, a volumetric survey estimated the surface area and volume of the reservoir at the normal pool elevation of 220.5 feet (ft) to be 25,989 acres and 695,271 acre-ft, respectively (Texas Water Development Board, 2003). The reservoir is owned by the city of Corpus Christi, the Nueces River Authority, and the city of Three Rivers. The reservoir was constructed primarily as a water supply for the city of Corpus Christi and has a history of "substantial water level fluctuations" (Findeisen and Binion, 2008, p. 2). Regular releases from the reservoir intended to meet the pass-through flow requirements (Nueces River Authority, 2010a) are measured at USGS streamflow-gaging station 08206910 Choke Canyon OWC near Three Rivers, Tex. ([hereinafter station 08206910]; USGS site 10; fig. 2 and table 1). Measurements at station 08206910 were only made below a stage of about 5.02 ft (flow of about 73 cubic feet per second [ft^3/s]) prior to water year 2000. Since 2000, releases generally have ranged from 33 to 1,100 ft^3/s. During high reservoir stages and extreme wet weather, radial arm floodgates can open to release greater flows to the Frio River downstream from station 08206910. These high-flow releases are not gaged in the study area.

Table 3. Annual rainfall, in inches, at selected National Weather Service meteorological stations in the lower Frio River watershed, south Texas, 1961–2008.

[NWS, National Weather Service]

Year or period	National Weather Service Meteorological Stations (locations shown on figure 2)											
	Uvalde (NWS site 1)	Hondo (NWS site 2)	Dilley (NWS site 3)	Charlotte 5 NNW (NWS site 4)	Poteet (NWS site 5)	Calliham (NWS site 6)	Pearsall (NWS site 7)	Sabinal (NWS site 8)	La Pryor (NWS site 9)	Fowlerton (NWS site 10)	Cotulla La Salle County Airport (NWS site 11)	Whitsett (NWS site 12)
1961	26.3	27.2	15.8	23.3	24.8	18.9	23.3	27.2	18.7	19.2	14.6	23.9
1962	14.1	13.6	17.0	14.3	16.1	15.5	13.8	13.6	14.2	13.0	11.6	15.3
1963	16.7	19.0	19.3	16.7	17.1	21.3	20.6	19.0	15.1	20.1	17.8	21.1
1964	22.3	23.8	19.0	19.7	19.5	18.5	21.8	23.8	20.6	16.1	14.6	19.0
1965	26.2	29.4	30.0	29.7	30.7	28.2	30.3	29.4	20.9	24.2	17.5	22.8
1966	20.9	21.5	22.5	23.7	22.2	20.8	17.2	21.5	18.7	29.0	16.0	22.1
1967	20.2	23.9	30.2	26.4	28.7	43.8	28.9	23.9	17.0	33.2	25.6	45.2
1968	25.1	33.0	33.2	47.9	42.8	32.0	32.0	33.0	26.3	22.0	22.5	32.8
1969	33.4	33.1	22.8	31.3	28.2	27.0	29.2	33.0	21.6	23.8	22.1	26.4
1970	13.6	22.1	24.6	27.5	23.7	24.2	22.0	22.1	16.4	22.4	15.8	28.5
1971	31.0	31.0	34.4	28.3	26.9	27.4	31.6	31.0	24.3	29.2	37.4	31.2
1972	15.5	21.1	23.1	21.6	29.0	24.8	20.0	21.1	13.7	13.8	23.2	15.3
1973	30.9	40.8	33.1	34.7	45.4	37.4	38.6	40.8	26.2	24.7	37.6	34.5
1974	30.9	37.6	27.1	29.1	35.2	24.5	23.9	37.6	28.7	24.9	31.8	21.8
1975	24.9	30.3	29.6	33.4	32.9	16.3	24.3	23.7	22.5	26.8	21.2	16.3
1976	46.0	45.2	35.5	38.5	40.4	39.5	41.2	40.8	36.7	35.5	33.2	36.5
1977	19.9	19.4	15.5	21.2	23.6	23.5	19.7	17.1	17.3	15.6	15.1	24.4
1978	18.7	24.8	23.6	23.2	23.5	22.6	24.0	21.5	17.0	24.4	26.8	19.7
1979	32.1	28.7	19.7	23.5	31.5	19.5	27.9	31.2	21.0	19.2	15.9	24.6
1980	23.0	21.3	25.1	30.3	30.8	28.3	25.4	22.7	21.3	25.6	20.5	31.5
1981	26.2	27.4	39.3	25.3	31.2	31.7	38.9	30.2	23.0	27.5	32.1	30.3
1982	23.5	22.1	20.3	28.7	28.6	22.2	18.5	18.4	16.2	19.6	18.2	24.4
1983	25.9	24.0	19.4	21.7	21.5	21.2	21.9	23.3	15.6	18.9	16.8	27.2
1984	17.3	23.6	22.8	19.4	27.0	15.7	18.7	20.7	18.6	16.2	15.6	18.4
1985	26.9	29.4	28.9	29.6	32.1	32.9	29.4	23.7	25.3	25.1	34.3	39.7
1986	30.0	37.2	30.4	34.2	33.1	22.5	30.0	35.7	30.4	35.1	26.2	32.4
1987	36.8	40.1	31.9	28.1	30.6	24.3	30.2	38.4	33.7	19.4	22.6	27.8
1988	13.6	14.1	12.6	9.8	9.7	17.1	11.2	13.5	13.6	15.1	11.9	17.5
1989	18.6	16.1	22.1	16.2	15.8	13.3	20.0	17.3	22.8	12.5	20.1	19.5
1990	24.7	27.0	27.1	23.0	27.3	30.1	26.1	30.1	32.5	23.8	25.1	27.5
1991	21.8	34.6	25.7	34.5	36.5	31.8	27.7	35.3	22.1	23.8	21.8	39.8
1992	33.6	45.3	31.5	40.7	38.8	30.7	26.5	38.8	30.1	31.8	27.9	32.4
1993	21.7	16.6	17.8	29.2	36.3	17.6	25.2	13.2	17.3	14.9	13.5	20.1
1994	36.9	25.2	24.9	24.0	26.7	29.0	31.1	29.3	27.1	30.0	24.3	33.3
1995	20.0	24.1	18.0	20.5	22.4	22.8	23.8	27.6	21.8	22.9	21.3	21.8
1996	16.8	17.6	12.3	12.3	10.1	12.9	15.5	14.2	13.4	13.1	18.9	16.1
1997	27.8	34.5	32.8	33.0	32.5	28.9	32.8	35.8	23.8	29.1	25.2	39.9

Table 3. Annual rainfall, in inches, at selected National Weather Service meteorological stations in the lower Frio River watershed, south Texas, 1961–2008.—Continued

[NWS, National Weather Service]

Year or period	National Weather Service Meteorological Stations (locations shown on figure 2)											
	Uvalde (NWS site 1)	Hondo (NWS site 2)	Dilley (NWS site 3)	Charlotte 5 NNW (NWS site 4)	Poteet (NWS site 5)	Calliham (NWS site 6)	Pearsall (NWS site 7)	Sabinal (NWS site 8)	La Pryor (NWS site 9)	Fowlerton (NWS site 10)	Cotulla La Salle County Airport (NWS site 11)	Whitsett (NWS site 12)
1998	30.0	30.9	34.0	33.8	28.8	27.1	34.9	33.9	21.9	27.4	24.1	40.3
1999	24.0	15.8	20.1	17.9	19.5	16.2	19.0	20.7	23.5	16.9	15.9	21.9
2000	20.2	26.5	19.9	25.6	34.0	27.5	20.6	22.9	18.8	25.0	15.5	22.3
2001	21.2	24.5	17.0	21.3	26.7	21.3	17.9	24.1	18.8	18.8	13.8	31.2
2002	35.9	35.7	48.1	44.3	44.8	41.8	37.7	30.1	36.3	49.4	36.5	38.7
2003	21.6	19.1	29.6	27.5	25.7	32.6	32.6	25.8	34.0	35.2	23.3	28.4
2004	32.0	38.5	42.6	42.9	44.6	33.4	35.5	38.7	36.4	42.7	42.8	35.5
2005	16.1	22.0	20.2	20.4	15.5	19.7	19.1	23.9	15.7	16.5	19.6	20.2
2006	13.0	11.9	13.4	10.6	12.9	18.9	10.3	11.1	13.0	20.1	23.3	15.5
2007	29.9	42.2	38.1	57.0	47.8	39.1	40.0	37.5	29.9	47.5	38.1	46.5
2008	13.4	12.5	17.3	21.5	20.8	13.8	17.1	14.7	13.4	17.8	13.3	18.0
1961–2008 annual mean	24.4	26.8	25.4	27.0	28.2	25.2	25.6	26.3	22.2	24.1	22.6	27.1
1961–2008 standard deviation	7.4	8.7	8.1	9.5	9.1	7.7	7.6	8.2	6.7	8.5	7.8	8.4
2000–08 annual mean	22.6	25.9	27.4	30.1	30.3	27.6	25.6	25.4	24.0	30.3	25.1	28.5
2000–08 standard deviation	8.3	11.0	12.7	14.8	13.1	9.8	10.8	9.2	10.0	13.5	11.2	10.4
1991–99 annual mean	25.8	27.2	24.1	27.3	28.0	24.1	26.3	27.6	22.3	23.3	21.4	29.5
1991–99 standard deviation	6.7	10.0	7.6	9.2	9.4	7.0	6.3	9.5	4.9	6.9	4.6	9.6

Simulation of Streamflow, Evapotranspiration, and Groundwater Recharge

To simulate streamflow, ET, and groundwater recharge in the lower Frio River watershed, a continuous simulation software program was needed that would take into account all of the water-budget components and watershed processes. The Hydrological Simulation Program—FORTRAN (HSPF), version 12 (Bicknell and others, 2001), was selected for modeling the study area watershed because it is one of the most comprehensive watershed software packages available and can simulate a wide variety of stream and watershed conditions with reasonable accuracy (Donigian and others, 1995). HSPF is an integrated basin-scale software package that combines watershed processes with in-stream fate and transport in one-dimensional characterization of stream channels. HSPF has been used successfully in south Texas to represent complex hydrologic systems, simulate streamflow, and estimate groundwater recharge (Ockerman, 2002, 2005, 2007; Ockerman and McNamara, 2003; Ockerman and Roussel, 2009; Lizárraga and Ockerman, 2010).

Functional Description of Hydrological Simulation Program—FORTRAN[1]

The HSPF model software (version 12) is distributed as part of the BASINS 4.0 (Better Assessment Science Integrating Point and Nonpoint Sources) system and was developed by the U.S. Environmental Protection Agency (2007) to support watershed management. BASINS 4.0 serves as an umbrella-like package, providing pertinent geodatabases, ancillary datasets, and software programs to facilitate user

[1] This section modified from Lizárraga and Ockerman (2010, p. 7–8).

Figure 3. Land cover in the lower Frio River watershed, south Texas.

interaction with the models and to help the user better understand the hydrologic characteristics of a watershed. Time-series input data and time-series model-generated output data are stored in a Watershed Data Management (WDM) file. The WDM database holds binary files accessed by the computer program GenScn (GENeration and analysis of model simulation SCeNarios) (Kittle and others, 1998) and by the program WDMUtil (Hummel and others, 2001). Downloaded versions were GenScn 2.3 build 10 and WDMUtil 2.27. These programs are provided in BASINS 4.0 and are used to manage, display, transform, plot, and analyze time-series data stored in the WDM file and used in HSPF and other models. Time-series data are organized in the WDM database by dataset number (DSN). Each DSN has attribute information that describes the data type, time step, location, and other important characteristics of the data.

The HSPF users' manual provides detailed model documentation, underlying model theory, and model parameterization guidance (Bicknell and others, 2001). A watershed is represented in HSPF by a group of hydrologically similar areas referred to as hydrologic response units (HRUs) that drain to a stream reach or reservoir segment, referred to as a RCHRES (ReaCH REServoir). Each RCHRES has an associated drainage area partitioned into HRUs. HRUs are areas with similar land cover, surficial geology, and other factors deemed important to produce a similar hydrologic response to meteorological inputs. HRUs are categorized as pervious or impervious land segments, termed PERLNDs (PERvious LaND) or IMPLNDs (IMPervious LaND), respectively. A PERLND is represented conceptually within HSPF by three interconnected water-storage zones—an upper zone, a lower zone, and an active and inactive groundwater zone. Rainfall on a PERLND runs off the land surface or infiltrates a water storage zone where it can either evapotranspire, circulate back to the RCHRES, or recharge groundwater. Rainfall on an IMPLND runs off or directly evaporates from surface retention.

Direct rainfall, inflow from upstream, other inflows such as springflow and wastewater-treatment plant discharges, surface runoff from HRUs, interflow (shallow subsurface runoff), and groundwater inflow can contribute to the volume of water within a RCHRES. The volume-discharge relation in the RCHRES is described by its corresponding function table (FTABLE) in the input file. Streamflow losses from a RCHRES can include direct losses from evaporation, user-defined channel losses or surface-water withdrawals, and flow routed downstream. Streamflow losses can be applied by using a time series of constant or intermittent withdrawals or programmed into the RCHRES volume-discharge relation, which is established in the FTABLE. The remaining RCHRES outflow after all gains and losses are applied is the model-simulated streamflow that is routed to the next downstream RCHRES.

Water is moved through this network of HRUs and RCHRESs for each time step specified in the model while conserving water mass—that is, inflow equals outflow, plus or minus any change in storage. While maintaining the overall water balance, the model continuously simulates the interaction among subcomponents of the water-budget equation and variations of these subcomponents over time. The conceptualization of the complex hydrologic processes is depicted in figure 4. The hydrologic processes are described by empirical equations in the model software. Model parameters used in the empirical equations are estimated and then adjusted during the calibration of the model. Typical values and ranges of model parameters from Donigian and others (1984), as well as watershed characteristics, are used to develop initial values for model parameters and to guide calibration.

Primarily a surface-water model, HSPF has limited internal functionality for modeling groundwater and surface-water interactions. HSPF can be used to simulate groundwater inflow—base flow and interflow—that originates from infiltration of rainfall. The rainfall that percolates to the lower zone of a PERLND that is not evapotranspired and does not become active groundwater contributing to RCHRES flow becomes groundwater recharge. Other movement of water between the surface and the groundwater can be simulated by HSPF, such as groundwater discharging to the surface from springs or the effect of groundwater pumping on surface flow, but it must be simulated through the use of external time series developed by the user.

Model output can include time series of any of the simulated water-budget components at any designated outlet or HRU that has been defined by the user. HSPF is calibrated by adjusting the process-related model parameters for each HRU or RCHRES until there is acceptable correlation between measured data and model-simulated output. Generally, streamflow is the primary water-budget component considered for calibration because measured streamflow data are most readily available, compared to measured data of other components such as ET or recharge.

Model Development

The Frio model was developed by (1) defining stream and reservoir reaches (RCHRESs) and their associated drainage areas, called catchments, (2) defining HRUs on the basis of land cover and location of rainfall gages and determining their acreages within each RCHRES drainage area; (3) developing the input time series of meteorological and streamflow data; and (4) determining initial (uncalibrated) values of associated model parameters. Initial estimates of parameters were determined or estimated from default values, previous watershed studies in south-central Texas (Lizárraga and Ockerman, 2010; Ockerman, 2007), and available data.

Subwatershed and Stream Reach Delineations

Because of the large size of the study area, the lower Frio River watershed was divided into 12 smaller subwatersheds, and a separate model for each subwatershed was developed (fig. 5 and table 4). Each subwatershed model area

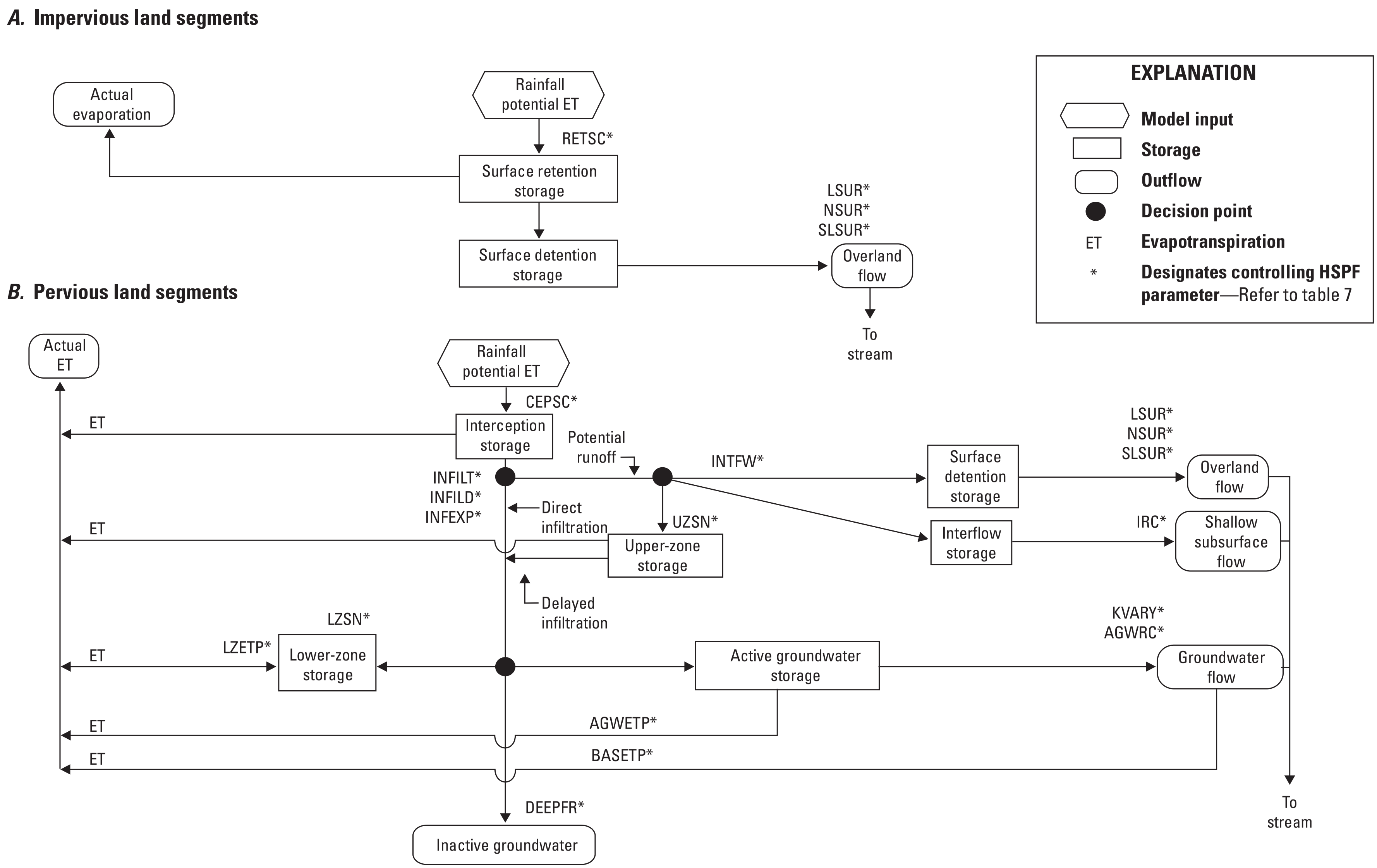

Figure 4. Hydrological Simulation Program—FORTRAN (HSPF) flowchart for hydrologic processes. *A*, Flowchart for impervious land segments. *B*, Flowchart for pervious land segments. (Modified from Berris, 1995, p. 14.)

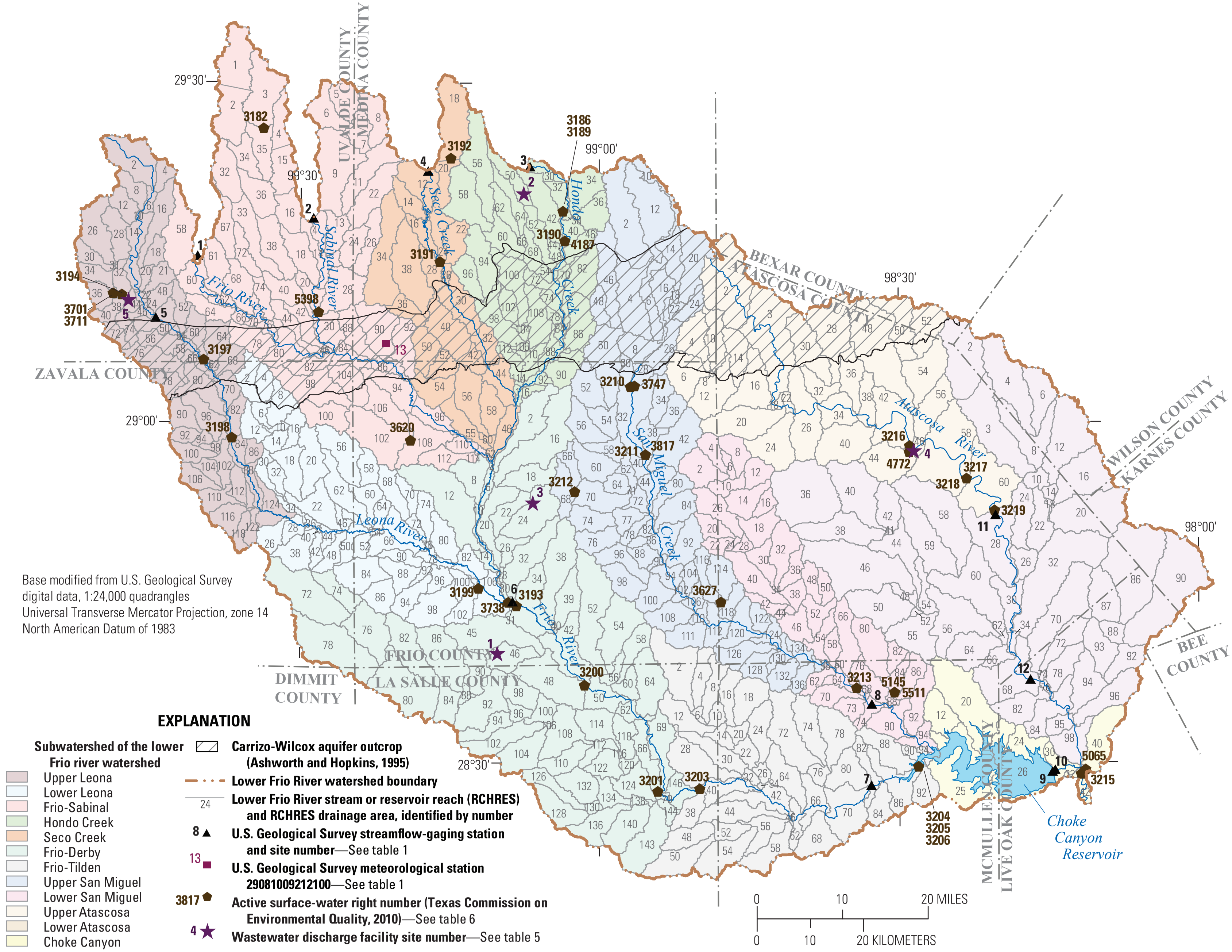

Figure 5. Subwatershed and stream or reservoir reach delineation for the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

Table 4. Subwatersheds of the Hydrological Simulation Program–FORTRAN model of the lower Frio River watershed, south Texas.

[mi^2, square miles; USGS, U.S. Geological Survey; --, not applicable; <, less than]

Subwatershed description	Subwatershed model name	Drainage area (mi^2)	Carrizo-Wilcox aquifer outcrop area (mi^2)
The drainage area of the upper Leona River from the headwaters to near Batesville, Tex.	Upper Leona	329	72
The drainage area of the lower Leona River near Batesville to the confluence with the Frio River	Lower Leona	343	15
The drainage area of the Frio and Sabinal Rivers downstream from USGS streamflow–gaging stations 08197500 and 08198500 (USGS sites 1 and 2, respectively; fig. 5, and table 1) to the confluence of the Frio River and Seco Creek	Frio-Sabinal	641	110
The drainage area contributing to Hondo Creek downstream from USGS streamflow–gaging station 08200720 (USGS site 3; fig. 5, and table 1) to the confluence of Hondo Creek with Seco Creek	Hondo Creek	291	112
The drainage area contributing to Seco Creek downstream from USGS streamflow-gaging station 08202700 (USGS site 4; fig. 5, and table 1) and downstream from the confluence of Hondo and Seco Creeks, to the confluence of the Frio River and Seco Creek	Seco Creek	255	58
The drainage area between the outlets of the Frio-Sabinal Rivers, Seco Creek, and Lower Leona subwatersheds contributing to a point downstream from USGS streamflow-gaging station 08205500 (USGS site 6; fig. 5, and table 1) near Derby, Tex.	Frio-Derby	814	--
The drainage area between the outlet of the Frio-Derby subwatershed to a point downstream from USGS streamflow-gaging station 08206600 Frio River at Tilden , Tex. (USGS site 7; fig. 5, and table 1) near an inlet of Choke Canyon Reservoir	Frio-Tilden	415	--
The drainage area contributing to the upper San Miguel Creek from its headwaters to a point upstream from USGS streamflow-gaging station 08206700 (USGS site 8; fig. 5, and table 1) near Tilden, Tex.	Upper San Miguel	580	124
The drainage area between the outlet of the upper San Miguel Creek model to an inlet of Choke Canyon Reservoir	Lower San Miguel	280	--
The drainage area of the Atascosa River from its headwaters to the USGS streamflow-gaging station 08207500 (USGS site 11; fig. 5, and table 1) near McCoy, Tex.	Upper Atascosa	509	179
The drainage area of the Atascosa River downstream from the outlet of the Upper Atascosa subwatershed to the confluence with the Frio River downstream from USGS streamflow-gaging station 08208000 (USGS site 12; fig. 5, and table 1) at Whitsett, Tex.	Lower Atascosa	884	<1
The drainage area contributing to the Frio River downstream from the outlets of the Frio-Tilden, Lower Atascosa, and Lower San Miguel subwatersheds, to the confluence of the Frio and Nueces River	Choke Canyon	146	--
Totals		5,490	669

is composed of stream reaches (RCHRESs), PERLNDs, and IMPLNDs. USGS 7.5-minute digital elevation models (U.S. Geological Survey, 2001) were used to delineate the RCHRES drainage areas and to calculate topographic information. Channel characteristics for each RCHRES were entered into HSPF FTABLES to establish the volume-discharge relations. For gaged stream reaches, these FTABLE parameters were based on discharge measurements made at USGS streamflow-gaging stations. FTABLE parameters for ungaged reaches were estimated on the basis of volume-discharge relations from nearby RCHRESs that used gaging station data. The 12 subwatersheds, their contributing drainage areas, and Carrizo-Wilcox aquifer outcrop areas are listed in table 4.

For the Choke Canyon Reservoir subwatershed (fig. 6), the main body of the reservoir is represented as two reaches with FTABLE values on the basis of previous volumetric survey (Texas Water Development Board, 2003). The upstream RCHRES 25 is modeled as 11 mi long. The downstream RCHRES 26 represents the deeper and wider part of the reservoir and is modeled as 6.5 mi long. Reservoir stage measured at USGS station 08206900 Choke Canyon Reservoir near Three Rivers (hereinafter station 08206900) (USGS site 9;

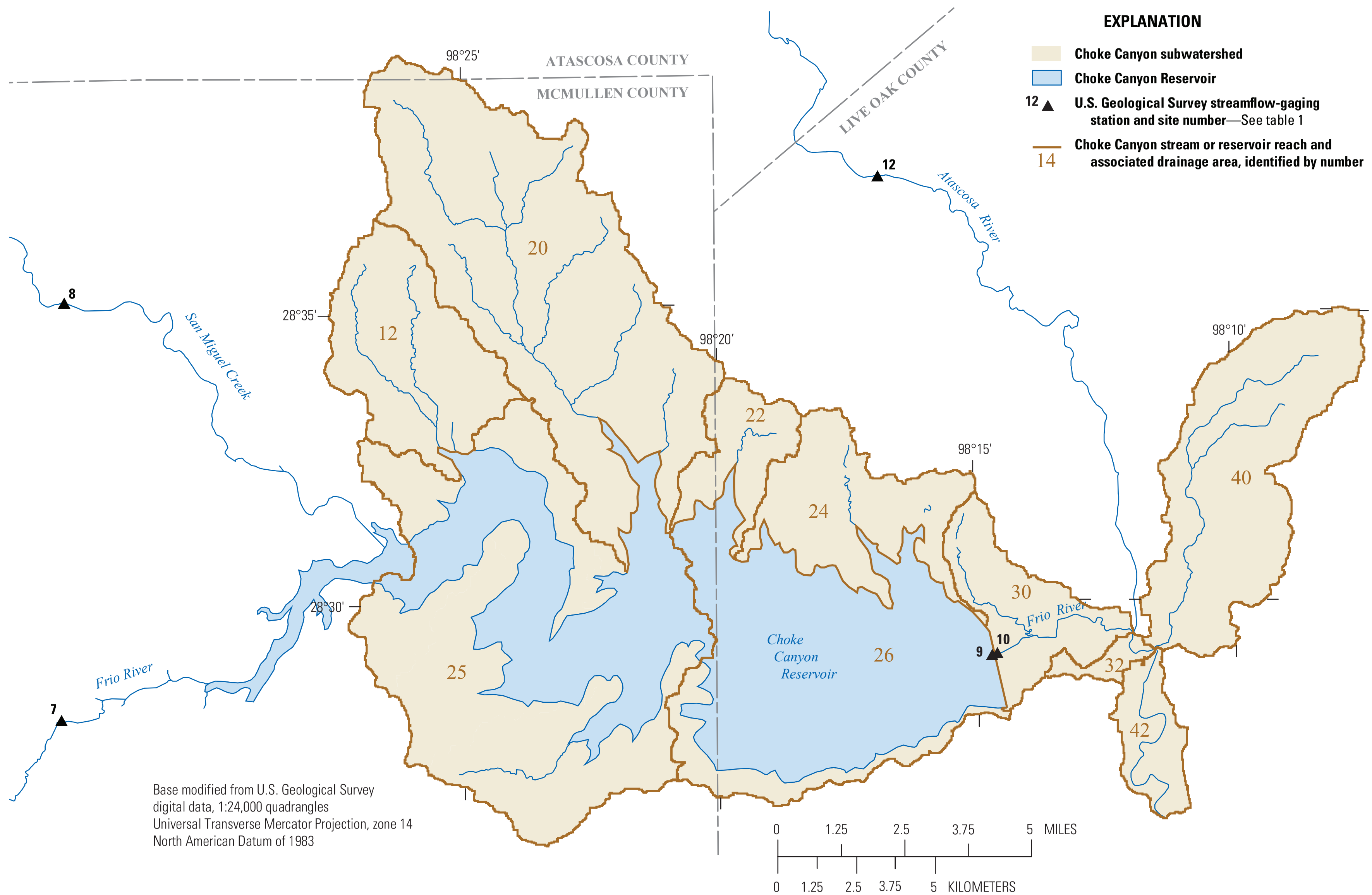

Figure 6. Streams or reservoir reaches and associated drainage areas for the Choke Canyon subwatershed used in the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

fig. 6 and table 1) is used to calibrate the reservoir volume. A partial record of releases from the reservoir, measured at station 08206910 (USGS site 10; fig. 6 and table 1), is modeled as direct withdrawals from RCHRES 26 and input to RCHRES 30. Flows over the spillway and from the tainter gates are modeled by using the RCHRES volume-discharge relations in the FTABLEs; as the combined volume RCHRES 25 and 26 approaches the full storage capacity of the reservoir, flood releases are routed to RCHRES 30.

Classification of HRUs and Variation of Model Parameters

Spatial information was compiled and analyzed by using the geographical information system software ArcGIS (ESRI, 2009). The pervious and impervious acreage of each PERLND and IMPLND were determined by using the 2001 land-cover data from the U.S. Environmental Protection Agency's Multi-Resolution Land Characteristics Consortium (Homer and others, 2004; Multi-Resolution Land Characteristics Consortium, 2010). Twenty percent of the developed land (fig. 3) was considered impervious. Impervious land in the study area was less than 1 percent of the total study area. The remaining developed land and all other categories were classified as pervious. Areas categorized as open water are not modeled as pervious or impervious area but as RCHRES surface area; the RCHRES surface area varies during model simulation on the basis of streamflow and channel dimensions in the FTABLEs.

Approximately 669 mi^2 of the Carrizo-Wilcox aquifer outcrop area, as defined by the Texas Water Development Board (Ashworth and Hopkins, 1995), are within the study area (fig. 5). A geographic information system was used to intersect the aquifer outcrop geodatabase with the pervious acreage, so that the Frio model could be used to generate output for the pervious areas (aquifer outcrops) in each subwatershed model (table 4).

County soil data from the Natural Resources Conservation Service (2010) were compiled for the study area (fig. 7). The permeability of the soils, as defined by the Natural Resources Conservation Service (2010), aided in the selection and gradation of initial and final estimates for PERLND parameters, such as the index to infiltration capacity of soil (INFILT).

Rainfall data from the 12 NWS meteorological stations (NWS sites 1–12; fig. 2 and table 2) were assigned areal significance by using the Thiessen method (Linsley and others, 1982). The Thiessen rainfall areas (fig. 8a) were used to apply the associated rainfall time-series data to the corresponding HRUs. Similarly, data from six NWS meteorological stations (NWS sites 1–6; fig. 2 and table 2) were assigned areal significance for the application of the time series of potential evapotranspiration (PEVT) rates (fig. 8b).

For modeling purposes the drainage area associated with each RCHRES was composed of one PERLND and one IMPLND. The pervious acreage within the drainage area of each RCHRES was considered to be a unique PERLND for the Frio model development and calibration. Differences in model parameters across PERLNDS largely were introduced from differences in aquifer outcrop area and relative soil infiltration rates (fig. 7). For the IMPLNDS, the number of sets of unique IMPLND parameters was limited to the number of rainfall gages used in each subwatershed model.

Time-Series Development

Streamflow data, meteorological data, wastewater-discharge information, springflow, and surface-water withdrawals are input to the Frio model as time-series data as described in this section. Streamflow data from USGS stations within the study area are used for calibration (2000–08) and testing (1991–99), and also are used as inputs to the model. These time-series data were compiled from national databases and local agencies by the BASINS 4.0 download features or manually and are stored with an associated DSN in the WDM file.

Streamflow

In addition to streamflow generated from rainfall events, streamflow was directly added to the model to account for upstream runoff, wastewater discharges, and surficial springflow from Leona Springs. Upstream runoff was measured at the northernmost USGS streamflow-gaging stations in the study area (USGS sites 1–4; fig. 2) (U.S. Geological Survey, 2010), and was estimated from Verde Creek model results. Mean daily wastewater-discharge estimates for five facilities, obtained from the U.S. Environmental Protection Agency (2004), were added to the relevant RCHRES for the entire simulation period, 1961–2008 (fig. 5; table 5).

Surficial springflow from Leona Springs was added to the Upper Leona subwatershed model. Flow measurements during 2003–08 at the Leona River near Uvalde station (USGS site 5; fig. 2 and table 1) were used to estimate the surficial component of the water discharged from Leona Springs (some of the spring discharge flows subsurface as underflow). Leona Springs discharges surficially at various locations upstream from the Leona River near Uvalde station. Also upstream from the Leona River near Uvalde station is the confluence of the Leona River with Cook's Slough (fig. 2); the flow in Cook's Slough is measured periodically by the USGS (U.S. Geological Survey, 2010). Surficial springflow from Leona Springs to the Leona River from 2003–08 was estimated by manually separating the base flow at the Leona River near Uvalde station and then subtracting the estimated base flow from Cook's Slough from the base flow at the Leona River near Uvalde station (Richard Slattery, U.S. Geological Survey, written commun., 2009).

In order to develop a complete time series (1961–2008) for the surficial component of springflow from Leona Springs, a relation was developed by using water-level altitudes measured in the nearby Uvalde J-27 index well (State well number YP-69-50-302) (Edwards Aquifer Authority, 2009) and the

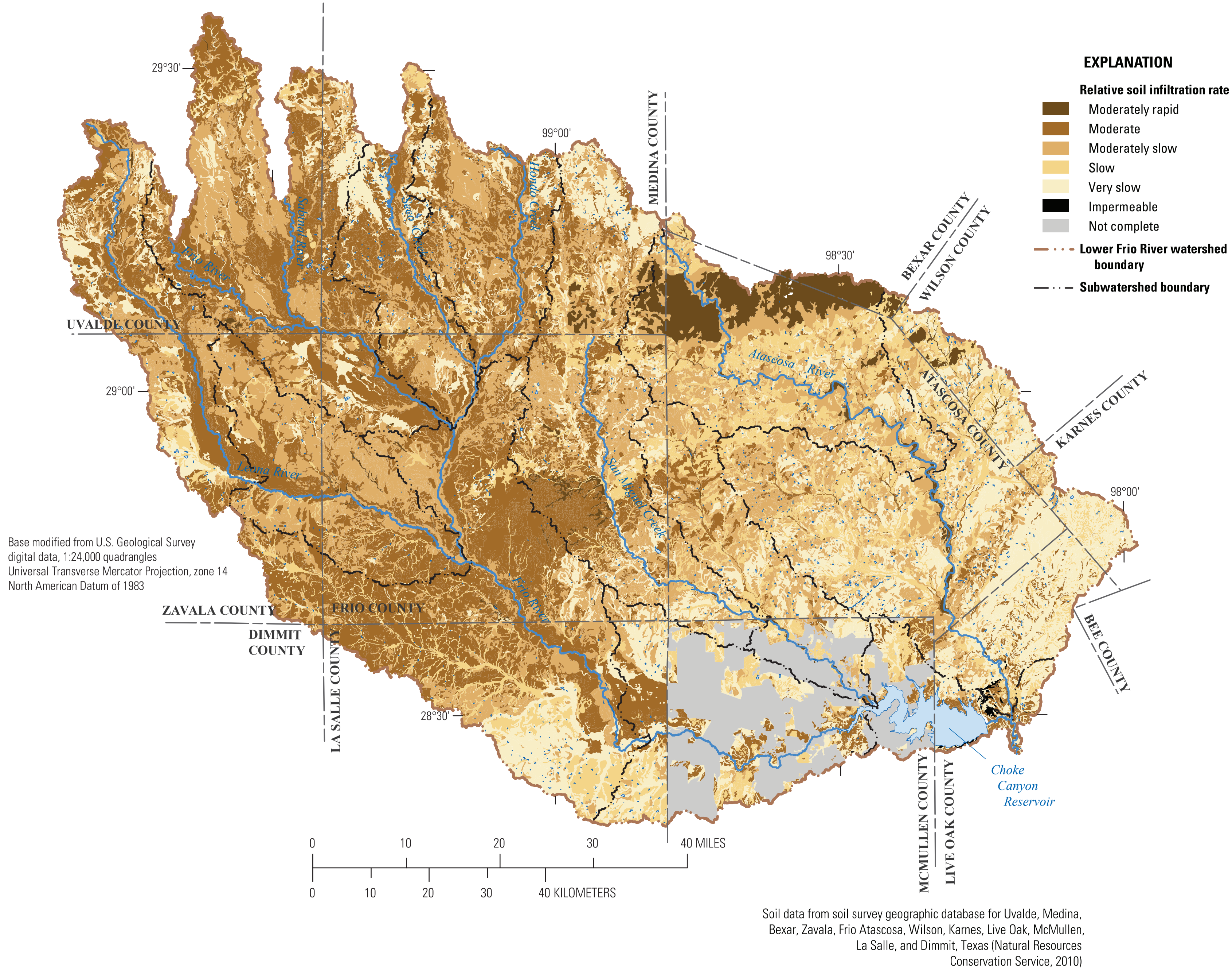

Figure 7. Relative soil infiltration rates in the lower Frio River watershed, south Texas.

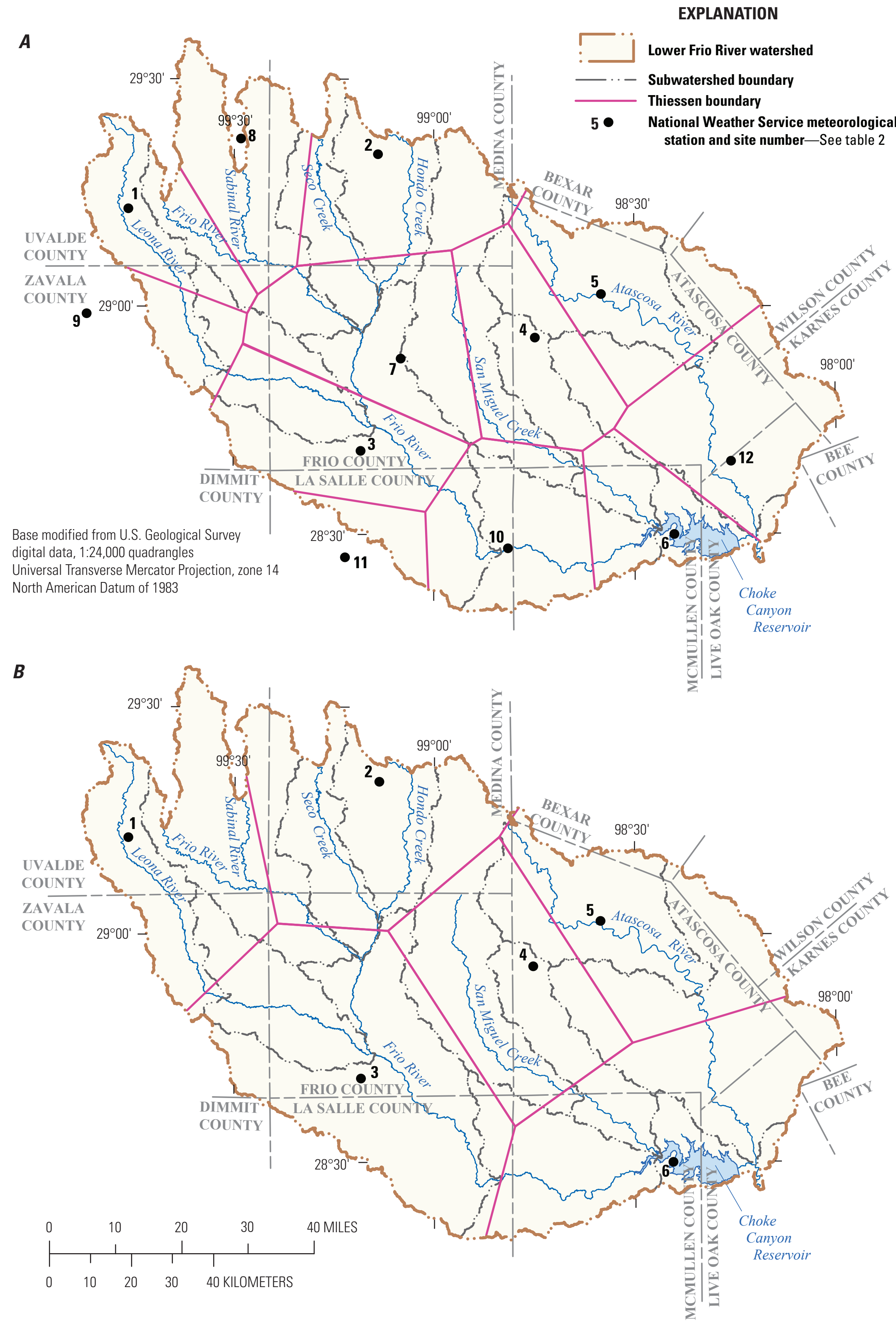

Figure 8. Location of National Weather Service meteorological stations and associated Thiessen areas. *A,* Stations and Thiessen areas for rainfall application. *B,* Stations and Thiessen areas for application of potential evapotranspiration rates in the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

Table 5. Wastewater discharges included in the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

[MGD, million gallons per day]

Facility site number (fig. 5)	Facility name	Subwatershed	Discharge (MGD)[1]
1	Dilley	Frio-Derby	0.42
2	Hondo	Hondo Creek	.98
3	Pearsall	Frio-Derby	.78
4	Pleasanton	Upper Atascosa	.75
5	Uvalde	Upper Leona	.98

[1] Discharge amounts are from the U.S. Environmental Protection Agency, 2004.

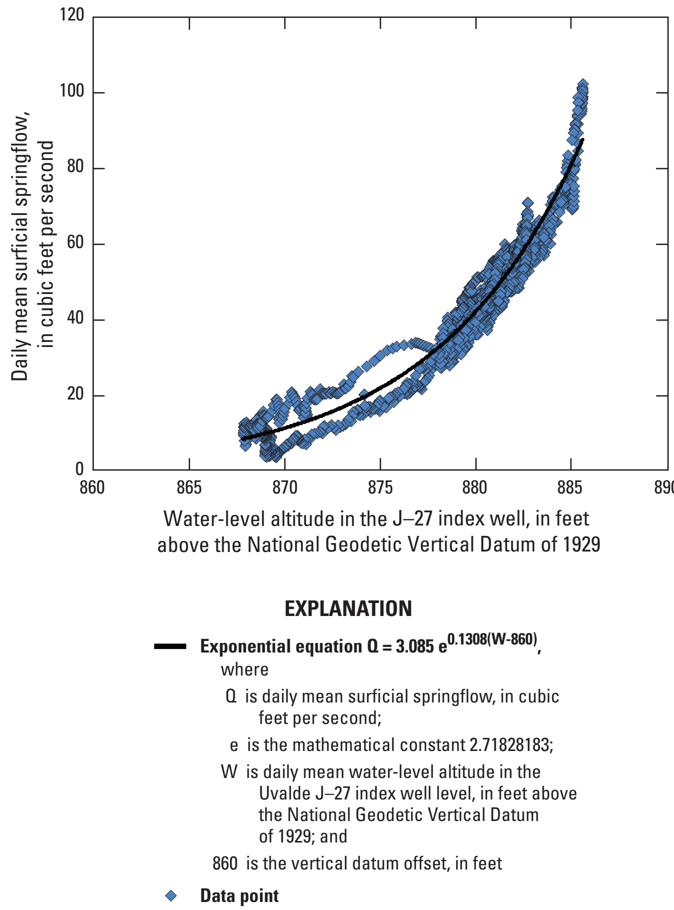

Figure 9. Water-level altitudes at the Uvalde J-27 index well (State well number YP-69-50-302) and estimated surficial springflow discharged from Leona Springs, lower Frio River watershed, south Texas, 2003–08.

2003–08 estimated surface discharge from Leona Springs (Richard Slattery, U.S. Geological Survey, written commun., 2009) (fig. 9).

The exponential function for estimating springflow from Leona Springs to the Leona River is:

$$Q = 3.085\ e^{0.1308(W-860)}, \qquad (1)$$

where

Q is the estimated daily mean surficial springflow to the Leona River, in cubic feet per second;
e is the mathematical constant 2.71828183;
W is the daily mean water-level altitude in the Uvalde J-27 index well level, in feet above the National Geodetic Vertical Datum of 1929; and
860 is the vertical datum offset, in feet.

The coefficient of determination (R^2) (Helsel and Hirsch, 2002) of the regression equation described in equation 1 is 0.92. The regression equation was used to generate surface springflow estimates for 1961–2003 by using measured Uvalde J-27 index well levels. To create an input springflow time series for 1961–2008, the estimated surface springflow estimates from Leona Springs for 2003–08 were appended to those from 1961–2003. The resulting time series simulated the inflow to RCHRES 46 in the Upper Leona subwatershed model (fig. 5).

In addition to flow lost from the model RCHRESs through evaporation, streamflow removed from the model RCHRESs included surface-water withdrawals and channel infiltration, including overbank (flood) losses. These withdrawals and losses would only be simulated during a model run if water was available in the given RCHRES. Any streamflow remaining in the RCHRES was routed downstream to the next RCHRES.

Surface-water withdrawals were simulated in all modeling time periods based on the active surface-water rights (permits) in the study area in December 2010 (fig. 5; table 6) (Texas Commission on Environmental Quality, 2010). The active surface-water right numbers are shown on figure 5. According to the Texas Commission on Environmental Quality (TCEQ) data, irrigation is the appropriated surface-water use for most of the surface-water rights in the study area (table 6, use code 3). In many cases, surface water for permitted uses is first captured in small ponds or lakes. Therefore, a combination of model-simulated channel storage and time series of withdrawals (based on the diversion amount in table 6) was used to estimate the appropriated water use for each permit. Permitted irrigation diversion amounts (table 6) were disaggregated into time series of equal daily amounts withdrawn from April through September (the months when irrigation withdrawals are considered most likely). Municipal-, industrial-, and mining-permitted diversion amounts (table 6, use codes 1, 2, and 4) were disaggregated into time series of equal daily amounts withdrawn over the entire year. Permits for domestic and livestock use and for storage use (table 6, use codes 11 and 13, respectively) do not list diversion amounts. For these permits, and for the permit for recharge located on

Table 6. Active surface-water rights included in the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas (Texas Commission on Environmental Quality, 2010).

[HSPF, Hydrological Simulation Program—FORTRAN; RCHRES, stream or reservoir reach; use code, indicates the appropriated use of water right (1, municipal; 2, industrial; 3, irrigation; 4, mining; 9, recharge; 11, domestic and livestock; 13, storage); --, no amount listed]

Surface-water right number (fig. 5)	Subwatershed	HSPF RCHRES location	Diversion amount (acre-feet per year)	Use code
3194	Upper Leona	32/38	99	3
3197	Upper Leona	58/62	828	3
3198	Upper Leona	82	150	3
3701	Upper Leona	36	28	3
3711	Upper Leona	36	56	3
3199	Lower Leona	102	50	3
3199	Lower Leona	102	--	13
3738	Lower Leona	106	124	3
3182	Frio-Sabinal	3	40	3
3620	Frio-Sabinal	102	--	11
5398	Frio-Sabinal	28	--	11
3186	Hondo Creek	32	84	3
3189	Hondo Creek	32	40	3
3190	Hondo Creek	40	80	3
4187	Hondo Creek	40	40	3
3191	Seco Creek	16	20	3
3192	Seco Creek	18	520	9
3193	Frio-Derby	31	--	3
3200	Frio-Derby	48	--	11
3201	Frio-Derby	66	649	3
3203	Frio-Derby	146	106	3
3204	Frio-Tilden	86	233	3
3205	Frio-Tilden	86	103	3
3206	Frio-Tilden	86	123	3
3210	Upper San Miguel	30	20	3
3211	Upper San Miguel	32	100	3
3212	Upper San Miguel	66/68	25	3
3627	Upper San Miguel	116	--	11
3747	Upper San Miguel	28	45	3
3817	Upper San Miguel	32	15	3
3213	Lower San Miguel	66	13	3
5145	Lower San Miguel	82/84	--	2
5511	Lower San Miguel	84	120	4
3216	Upper Atascosa	42	20	3
3217	Upper Atascosa	58	27	3
3218	Upper Atascosa	58	18	3
3219	Upper Atascosa	60	30	3
4772	Upper Atascosa	44	2	3
3215	Choke Canyon	32	700	1
3215	Choke Canyon	32	800	2
5065	Choke Canyon	40	1,121	3

Seco Creek (table 6, surface-water right number 3192, use code 9), channel storage was modeled, but time-series withdrawals were not included in the model.

Channel-infiltration losses (including overbank flood losses) were based on the channel dimensions and relations between the streamflow volume and discharge established in the RCHRES FTABLES. These losses were adjusted for each RCHRES during the streamflow calibration. Channel-infiltration losses were routed to active groundwater storage within the model. Water in active groundwater storage can evapotranspire, return to the stream channel, or recharge the groundwater (fig. 4).

Meteorological Data

BASINS 4.0 was used to download and process rainfall and air temperature data measured at NWS stations (table 2) into hourly time series of rainfall and PEVT rates. The algorithms in BASINS 4.0 (U.S. Environmental Protection Agency, 2007) download and process national datasets through 2006. To extend the record through 2008 for the Frio model, available rainfall and air temperature data from 2007 through 2008 from the same or nearby NWS sites were downloaded from the National Climatic Data Center (2009). These data were manually reviewed, processed, and appended to the hourly time series in the WDM files. The Hamon method (Bidlake, 2002), a subroutine available in the WDMUtil program of BASINS 4.0, was used on the 2007–08 maximum and minimum daily air temperature data to estimate computed PEVT during 2007–08. During simulation, HSPF uses BASINS 4.0-computed PEVT estimates with other model input (rainfall, storage, lower-zone parameters) to simulate actual ET.

Model Calibration and Model Testing

Model calibration is an inherently iterative process of parameter evaluation and adjustment. Initial estimates of model parameters are adjusted until the simulated streamflow and ET data compare favorably to measured data, and pre-defined calibration criteria are satisfied. Various acceptance criteria are used. Graphs and descriptive statistics facilitate comparisons between simulated and measured data. Model testing involves using a calibrated model to simulate data for a time period different from the one used for calibration; simulated data are compared with additional measured data that were not used in the initial calibration.

The Frio model parameters were manually adjusted to meet acceptance criteria for streamflow at various USGS streamflow-gaging stations in the watershed. Effort was also made to minimize the difference between simulated ET and measured ET from a land area, and simulated and measured evaporation from the Choke Canyon Reservoir. ET from the Carrizo-Wilcox aquifer outcrop (pervious area) in the Frio-Sabinal subwatershed model was calibrated by using the measured ET at USGS meteorological station 290810099212100 in southwest Medina County near D'Hanis, Tex. (hereinafter the Medina meteorological station) (USGS site 13; fig. 2 and table 1). Evaporation from the reservoir was calibrated by using estimated monthly evaporation from the reservoir computed from measured pan evaporation data at the reservoir dam (Nueces River Authority, 2010b; Susan Satterwhite, City of Corpus Christi, oral commun., 2010). As a result of the streamflow, reservoir storage, and ET and evaporation calibrations, a final set of model parameters was obtained for the Frio model; values for selected parameters are listed by subwatershed in table 7.

Streamflow and Reservoir Volume

A primary goal of model calibration is to adjust model-simulated streamflow to match streamflow measured at a nearby streamflow-gaging station. The Frio model was calibrated in accordance with guidelines by Donigian and others (1984) and Lumb and others (1994). These guidelines involved comparing measured and simulated streamflow data and minimizing the difference between the total volumes of streamflow, the highest 10 percent of streamflows, and the lowest 50 percent of streamflows. In addition, model-fit statistics and graphics generated by the software program GenScn (version 2.3 build 10) were used to examine the quality of the model fit on an annual, monthly, weekly, and daily basis. Model-fit statistics included the (1) coefficient of determination (R^2) of the linear regression between measured and simulated streamflow; (2) model-fit efficiency, which is a Nash-Sutcliffe (NS) model-fit efficiency coefficient (Nash and Sutcliffe, 1970); (3) mean absolute error (MAE); and (4) root mean square error (RMSE). The R^2 and NS are similar; each provides a measure of the variability in a dataset accounted for by the statistical model, in which a value of 1 indicates a perfect fit between measured and simulated values. The NS, however, provides a generally preferable evaluation of the fit quality because it measures the magnitude of the differences between measured and simulated values, whereas the R^2 measures the difference between mean values (Zarriello and Ries, 2000, p. 44). The MAE and RMSE statistics describe the difference between measured and simulated streamflow in original units (cubic feet per second).

Streamflow calibration began with the most upstream subwatersheds, by using available streamflow-gaging data to adjust the Frio model parameters. For example, data from the Leona River near Uvalde station (USGS site 5; fig. 2 and table 1) were used to calibrate streamflow for the drainage area upstream from the station (RCHRESs 2–46) in the Upper Leona subwatershed model. After calibration at the Uvalde station, the simulated (1961–2003) and measured (2003–08) flows at the station were routed along with other simulated flows—generated from the outlets of subwatersheds Frio-Sabinal, Seco Creek, and Hondo Creek, and RCHRES 1–31 of subwatershed Frio-Derby—to the next calibration point at USGS streamflow-gaging station 08205500 Frio River near Derby, Tex. (USGS site 6; fig. 5 and table 1). Similarly, the Upper Atascosa subwatershed was calibrated to the outlet, which was the location of the USGS streamflow-gaging station 08207500 Atascosa River near McCoy, Tex. (USGS site 11; fig. 5 and table 1). Measured flows during 2002–08 and simulated flows during 1961–2002 at the station near McCoy were combined as a time series and used as the boundary inflow to the Lower Atascosa subwatershed model. By routing measured streamflow data rather than simulated streamflow data downstream wherever possible, simulation errors (differences between measured and simulated streamflows) were not propagated downstream.

Data from four USGS streamflow-gaging stations (USGS sites 6, 7, 8, and 12; fig. 5 and table 1) in the lower Frio River watershed were used for model calibration (2000–08 data) and model testing (1991–99 data). Data from two USGS streamflow-gaging stations (USGS sites 5 and 11; fig. 5 and table 1) were used only for model calibration because of their shorter periods of record. Reservoir volume data from the USGS station 08206900 Choke Canyon Reservoir near Three Rivers, Tex. (USGS site 9; fig. 5 and table 1), ET data from the Medina meteorological station (USGS site 13; fig. 5 and table 1), and Choke Canyon Reservoir evaporation data (Nueces River Authority, 2010b) were used only for model calibration. Measured and simulated streamflows and model-fit statistics for the six USGS streamflow-gaging stations used in the calibration and testing process are listed in table 8.

Simulated streamflows and reservoir volumes also were evaluated graphically by comparing measured and simulated daily time series and exceedance-probability (flow-duration) curves (Chow, 1964). Graphs of weekly time series, exceedance-probability curves, and scatterplots of measured weekly mean and simulated weekly mean streamflow are shown for the 2000–08 calibration period at the following USGS streamflow-gaging stations:

- 08205500 Frio River near Derby, Tex. (USGS site 6; fig. 10 and table 1),
- 08206600 Frio River at Tilden, Tex. (hereinafter the Frio River at Tilden station) (USGS site 7; fig. 11 and table 1),
- 08206700 San Miguel Creek near Tilden, Tex. (hereinafter the San Miguel Creek near Tilden station) (USGS site 8; fig. 12 and table 1), and
- 08208000 Atascosa River at Whitsett, Tex. (hereinafter the Atascosa River at Whitsett station) (USGS site 12; fig. 13 and table 1).

General agreement between the measured and simulated exceedance-probability curves indicates good calibration over the range of flow conditions.

Donigian and others (1984) provide general guidelines for characterizing HSPF calibrations. For flow volumes, model calibration is considered very good when the error is less than 10 percent, good when the error is within 10 to 15 percent, fair when the error is within 15 to 25 percent, and poor when the error is greater than 25 percent. According to

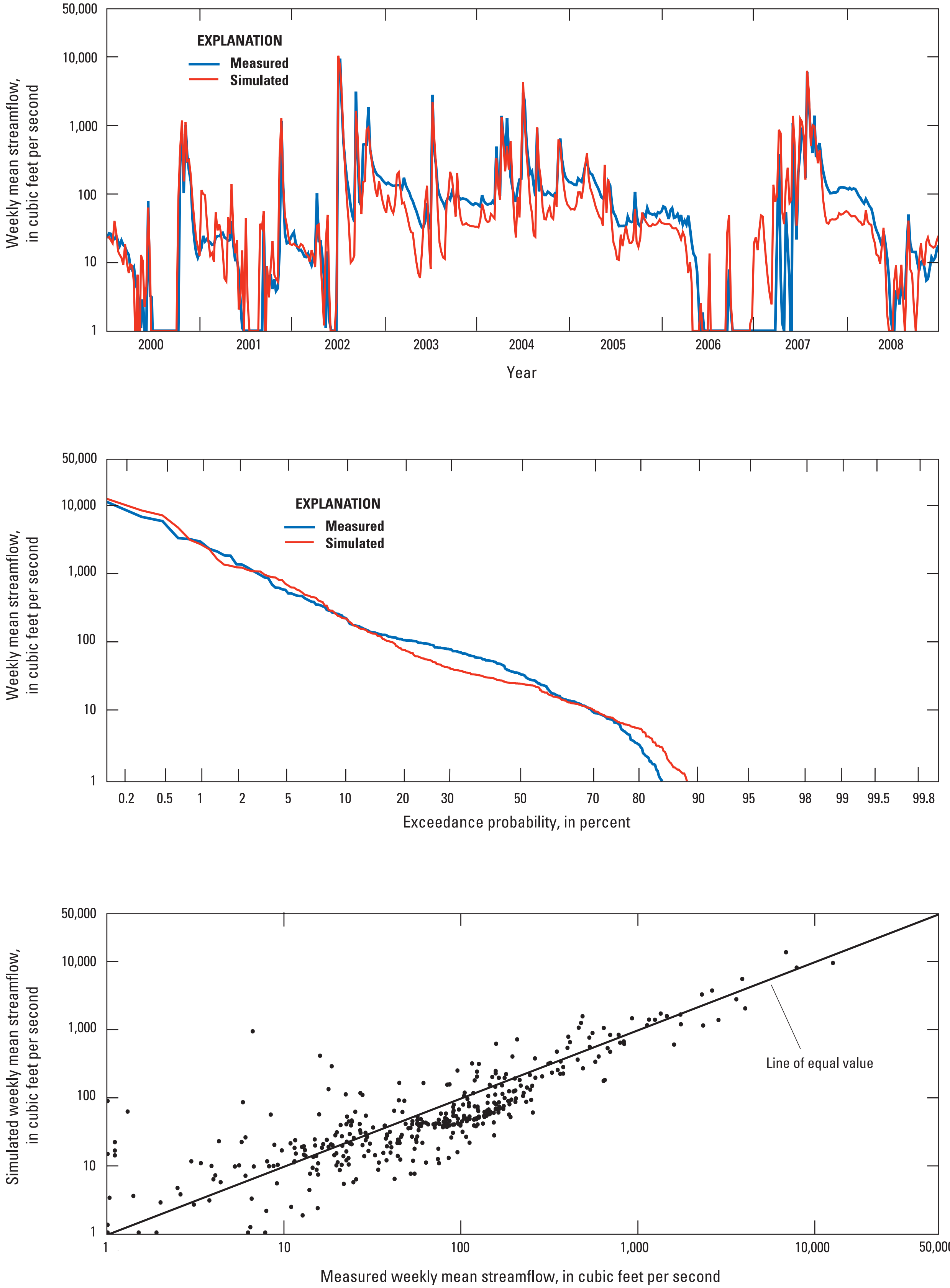

Figure 10. Measured and simulated weekly mean streamflow at streamflow-gaging station 08205500 Frio River near Derby, Texas, 2000–08.

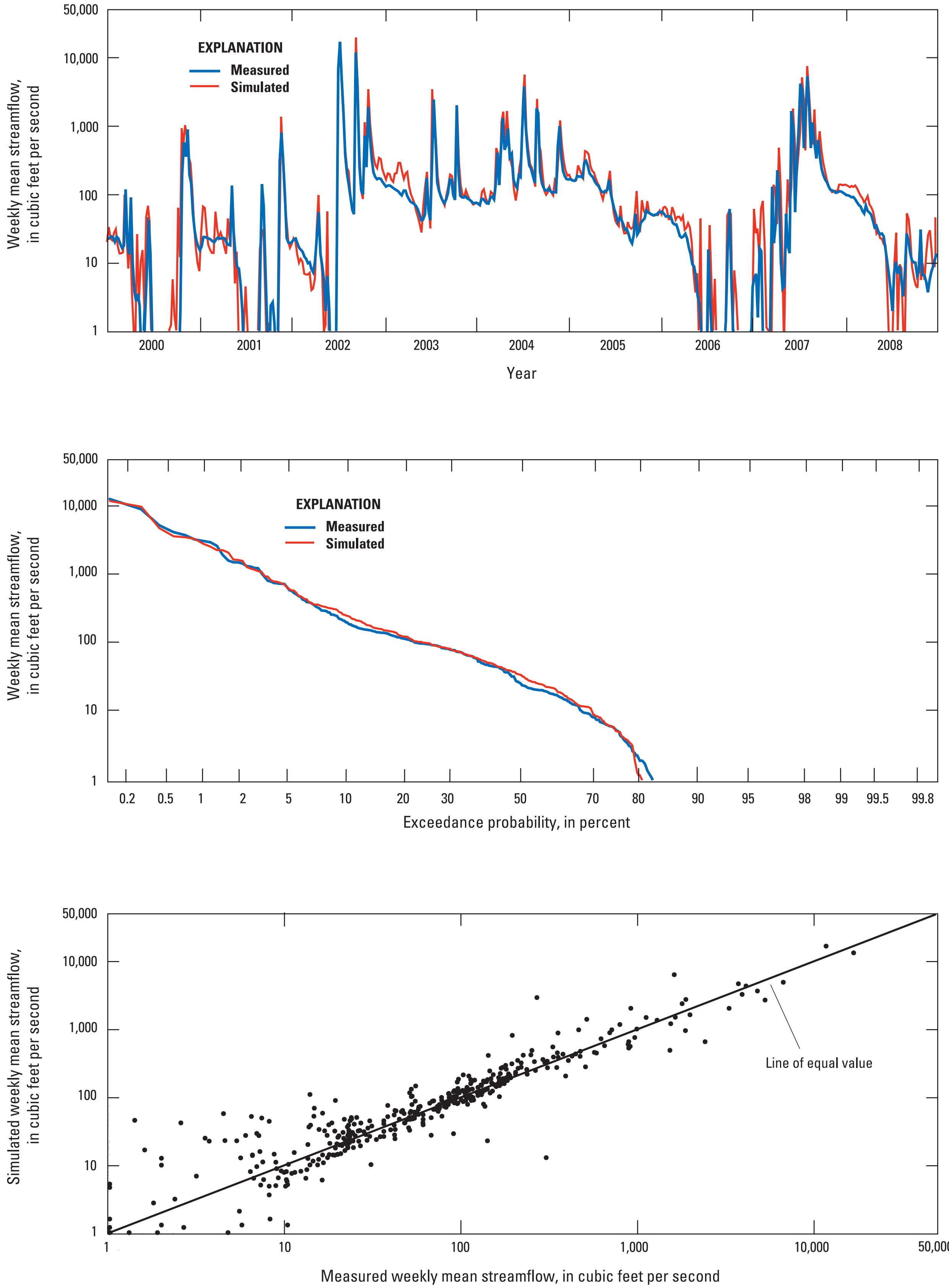

Figure 11. Measured and simulated weekly mean streamflow at streamflow-gaging station 08206600 Frio River at Tilden, Texas, 2000–08.

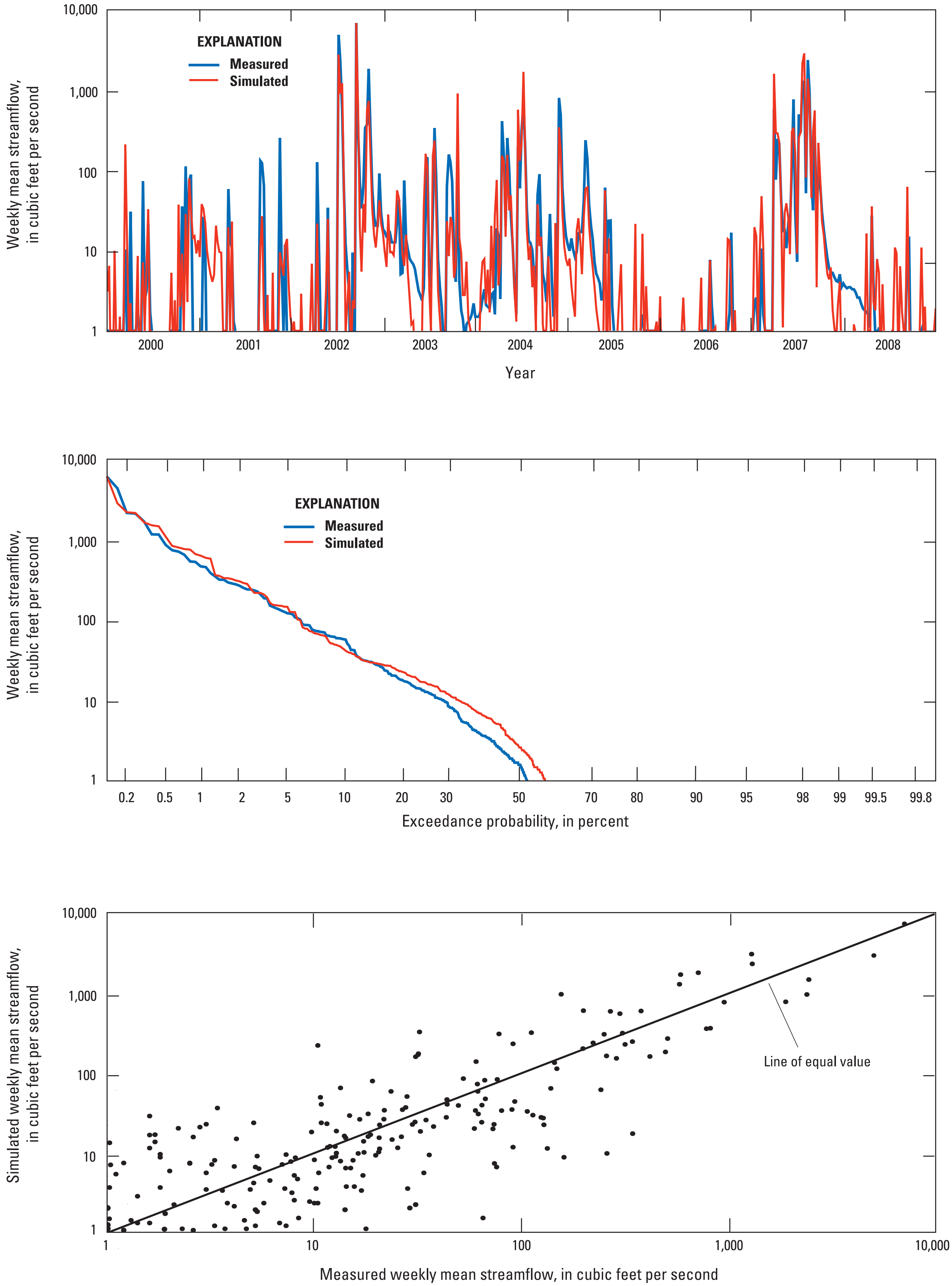

Figure 12. Measured and simulated weekly mean streamflow at streamflow-gaging station 08206700 San Miguel Creek near Tilden, Texas, 2000–08.

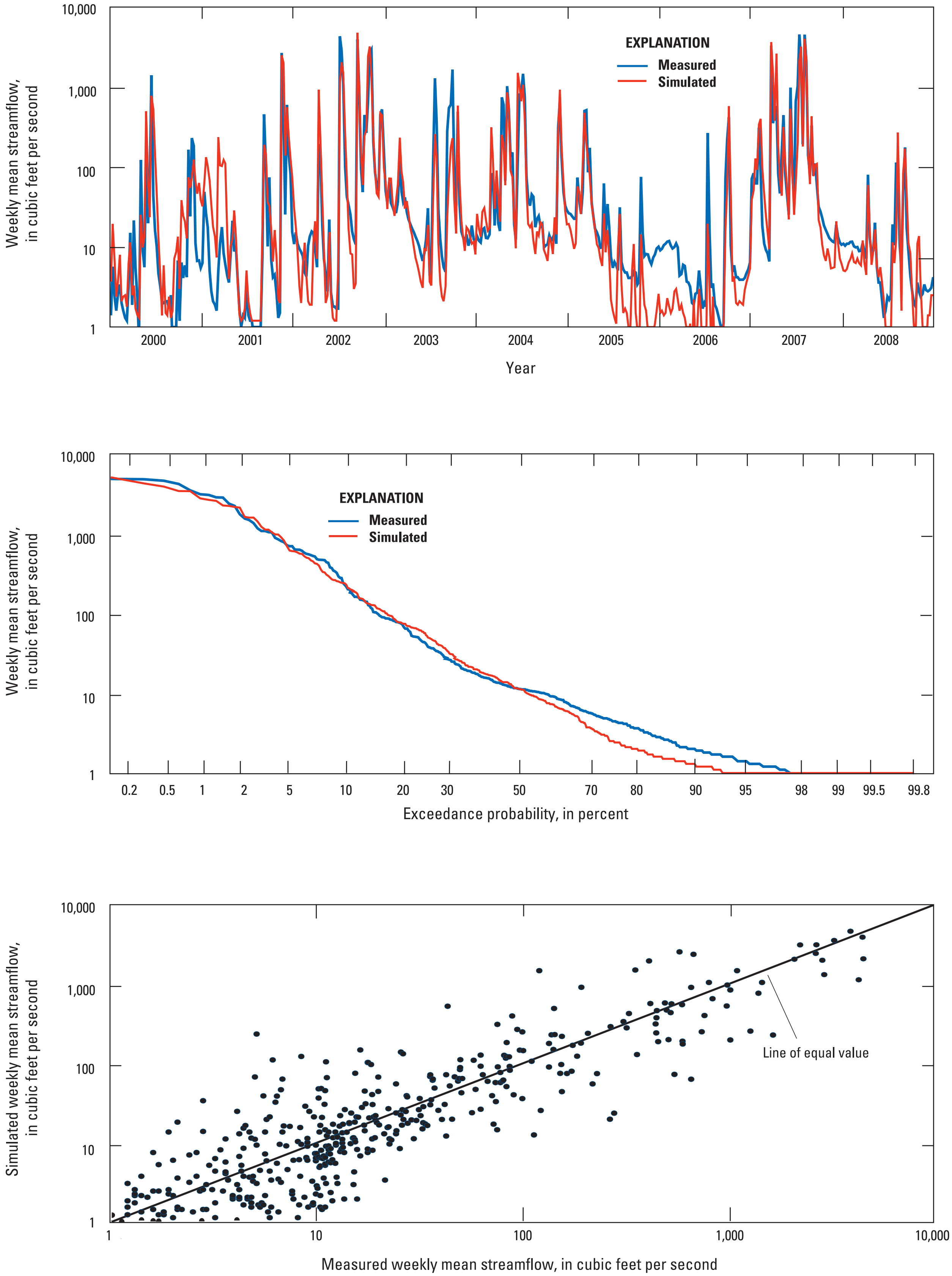

Figure 13. Measured and simulated weekly mean streamflow at streamflow-gaging station 08208000 Atascosa River at Whitsett, Texas, 2000–08.

Table 7. Calibrated values for selected model parameters, by subwatershed, for the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

Model parameter	Description	Units	Calibrated value by subwatershed											
			Upper Leona	Lower Leona	Frio-Sabinal	Hondo Creek	Seco Creek	Frio Derby	Frio Tilden	Upper San Miguel	Lower San Miguel	Upper Atas-cosa	Lower Atas-cosa	Choke Canyon
AGWETP	Fraction of remaining evapotrans-piration from groundwater	none	0.05	0.10	0.05	0.02	0.01–.05	0.05	0.03	0.02	0.02	0.05	0.01	0.01
AGWRC	Groundwater recession indexed to rate of drainage	1/day	.96	.96	.96	.96	.96	.94	.92	.85–.92	.95	.95	.93–.95	.95
BASETP	Fraction of remaining evapotrans-piration from baseflow	none	.01–.02	.03	.02	.02	.02–.05	.01–.10	.10	.05	.05	.05	.05	.05
CEPSC	Interception storage capacity	inches	.25	.25	.25	.35	.35	.35	.25	.01–.10	.01	.15–.25	.15	.1
DEEPFR	Fraction of groundwater inflow to deep recharge	none	.80	.80	.70–.85	.80	.80	.85	.8	.85	.85	.70–.80	.8	.85
INFILD	Ratio of max to mean infiltration rate of a pervious area	none	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
INFILT	Index to infiltration capacity of soil	inches/ hour	.2–.6	.65–.80	.45–.90	.60–.70	.60–.80	.65–.85	.45–.75	.15–.45	.10–.20	.25–.55	.10–.20	.20
INTFW	Interflow index	none	1	5	5	4	4	3–4	8.5	1.2	1	4.5	3	2
IRC	Interflow recession coefficient	1/day	.54	.54	.54	.54	.54	.54	.54	.54	.54	.54	.54	.54
KVARY	Variable groundwater recession	1/inch	1	1	1	1	1	1	1	1	1	1	1	1
LSUR	Length of assumed overland flow plane	feet	350	350	350	350	350	350	350	350	350	350	350	350
LZETP	Lower-zone evapotranspiration	none	.2–.9	.2–.9	.2–.9	.2–.9	.2–.9	.2–.9	.3–.8	.2–.8	.2–.8	.10–.80	.3–.8	.3–.8
LZSN	Lower-zone nominal storage	inches	12.5–13.5	12.5	13.5	11.0	12.0	8.0–9.0	8	7.5–9.5	6.5	8	6.5	6
NSUR	Manning's n for assumed over-land flow plane	none	.10–.15	.10–.31	.20–.31	.10–.31	.10–.31	.10–.31	.03–.31	.20–.31	.20–.31	.10–.31	.15–.31	.20–.31
RETSC	Impervious retention storage capacity	inches	.01	.1	.4	.4	.4	.2	.10	.01	.01	.25	.05	.25
SLSUR	Slope of assumed overland flow plane	feet	.03	.01–.03	.01–.03	.03	.03	.03	.03	.01	.01	.01–.03	.01–.03	.01
UZSN	Upper-zone nominal storage	inches	.50	.50	.50	.40	.40	.50	.20	.40	.35	.60	.15	.30

Table 8. Streamflow calibration and testing results, Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.

[acre-ft, acre-feet; ft^3/s, cubic feet per second; NS, Nash-Sutcliffe model-fit efficiency coefficient; R^2, coefficient of determination; NA, not able to be computed]

08205500 Frio River near Derby, Tex.

Calibration period 2000–08

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	1.512	1.522	0.61	10
Mean flow rate (ft^3/s)	232	233	.61	10
Total of highest 10 percent of daily flows, million acre-ft	1.152	1.253	8.7	10
Total of lowest 50 percent of daily flows, acre-ft	39,802	36,229	-9.0	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	9	108	469	3,288
Coefficient of determination (R^2)	.97	.95	.82	.44
Model-fit efficiency (NS)	.97	.93	.82	.39
Mean absolute error (ft^3/s)	37	81	107	166
Root mean square error (ft^3/s)	45	190	444	1,172

Testing period 1991–99

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	0.947	1.417	49.7	10
Mean flow rate (ft^3/s)	145	217	49.7	10
Total of highest 10 percent of daily flows, million acre-ft	.751	1.175	56.5	10
Total of lowest 50 percent of daily flows, acre-ft	22,482	28,364	26.2	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	9	108	469	3,287
Coefficient of determination (R^2)	.98	.94	.43	.25
Model-fit efficiency (NS)	.78	.84	.39	.14
Mean absolute error (ft^3/s)	72	88	123	133
Root mean square error (ft^3/s)	93	207	594	1,132

Simulation period 1961–2008

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	5.703	6.724	17.9	10
Mean flow rate (ft^3/s)	164	193	17.9	10
Total of highest 10 percent of daily flows, million acre-ft	4.473	5.537	23.8	10
Total of lowest 50 percent of daily flows, acre-ft	87,448	120,109	37.3	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	48	576	2,504	17,532
Coefficient of determination (R^2)	.91	.89	.75	.34
Model-fit efficiency (NS)	.88	.88	.74	.20
Mean absolute error (ft^3/s)	51	77	93	128
Root mean square error (ft^3/s)	76	209	448	1,044

Table 8. Streamflow calibration and testing results, Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.—Continued

[acre-ft, acre-feet; ft^3/s, cubic feet per second; NA, not able to be computed]

08206600 Frio River at Tilden, Tex.

Calibration period 2000–08

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	2.062	2.112	2.4	10
Mean flow rate (ft^3/s)	316	324	2.4	10
Total of highest 10 percent of daily flows, million acre-ft	1.677	1.671	-.3	10
Total of lowest 50 percent of daily flows, acre-ft	41,586	51,000	22.6	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	9	108	469	3,288
Coefficient of determination (R^2)	1.00	.94	.85	.60
Model-fit efficiency (NS)	.99	.93	.85	.58
Mean absolute error (ft^3/s)	17	67	121	193
Root mean square error (ft^3/s)	23	252	554	1,186

Testing period 1991–99

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	1.093	1.020	-6.7	10
Mean flow rate (ft^3/s)	168	157	-6.7	10
Total of highest 10 percent of daily flows, million acre-ft	.875	.790	-9.8	10
Total of lowest 50 percent of daily flows, acre-ft	20,418	19,164	-6.1	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	9	108	469	3,287
Coefficient of determination (R^2)	.96	.93	.89	.13
Model-fit efficiency (NS)	.92	.92	.88	-.12
Mean absolute error (ft^3/s)	29	40	59	118
Root mean square error (ft^3/s)	46	101	216	905

Simulation period July 14, 1978–Dec. 31, 2008

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	4.974	4.818	-3.1	10
Mean flow rate (ft^3/s)	225	218	-3.1	10
Total of highest 10 percent of daily flows, million acre-ft	4.053	3.815	-5.9	10
Total of lowest 50 percent of daily flows, acre-ft	96,784	97,927	1.2	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	30	365	1,589	11,129
Coefficient of determination (R^2)	.95	.93	.77	.49
Model-fit efficiency (NS)	.95	.91	.74	.42
Mean absolute error (ft^3/s)	35	57	102	146
Root mean square error (ft^3/s)	56	177	496	944

Table 8. Streamflow calibration and testing results, Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.—Continued

[acre-ft, acre-feet; ft³/s, cubic feet per second; NA, not able to be computed]

08206700 San Miguel Creek near Tilden, Tex.

Calibration period 2000–08

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, acre-ft	512,022	532,145	3.9	10
Mean flow rate (ft³/s)	78.5	81.6	3.9	10
Total of highest 10 percent of daily flows, acre-ft	483,131	492,871	2.0	10
Total of lowest 50 percent of daily flows, acre-ft	34	915	2,567	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	9	108	469	3,288
Coefficient of determination (R^2)	.87	.84	.79	.43
Model-fit efficiency (NS)	.85	.84	.76	.23
Mean absolute error (ft³/s)	24	36	49	69
Root mean square error (ft³/s)	43	112	213	510

Testing period 1991–99

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, acre-ft	191,696	233,111	21.6	10
Mean flow rate (ft³/s)	29.4	35.8	21.6	10
Total of highest 10 percent of daily flows, acre-ft	177,316	206,299	16.3	10
Total of lowest 50 percent of daily flows, acre-ft	0	474	NA	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	9	108	469	3,287
Coefficient of determination (R^2)	.93	.56	.50	.30
Model-fit efficiency (NS)	.84	.55	.46	.05
Mean absolute error (ft³/s)	11	19	23	29
Root mean square error (ft³/s)	17	61	96	195

Simulation period Feb. 1, 1964–Dec. 31, 2008

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	1.872	1.643	-12.2	10
Mean flow rate (ft³/s)	57.5	50.5	-12.2	10
Total of highest 10 percent of daily flows, million acre-ft	1.745	1.504	-13.8	10
Total of lowest 50 percent of daily flows, acre-ft	4,045	4,577	13.1	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	44	539	2,343	16,406
Coefficient of determination (R^2)	.77	.72	.63	.38
Model-fit efficiency (NS)	.75	.69	.58	.16
Mean absolute error (ft³/s)	23	32	40	52
Root mean square error (ft³/s)	32	98	186	393

Table 8. Streamflow calibration and testing results, Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.—Continued

[acre-ft, acre-feet; ft³/s, cubic feet per second; NA, not able to be computed]

08208000 Atascosa River at Whitsett, Tex.

Calibration period 2000–08

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	1.030	1.032	0.2	10
Mean flow rate (ft³/s)	158	158	.2	10
Total of highest 10 percent of daily flows, million acre-ft	.917	.888	-3.1	10
Total of lowest 50 percent of daily flows, acre-ft	16,221	11,783	-27.4	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	9	108	469	3,288
Coefficient of determination (R^2)	.97	.83	.70	.57
Model-fit efficiency (NS)	.97	.82	.67	.51
Mean absolute error (ft³/s)	23	69	84	110
Root mean square error (ft³/s)	31	162	311	553

Testing period 1991–99

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	0.640	0.950	48.4	10
Mean flow rate (ft³/s)	98	146	48.4	10
Total of highest 10 percent of daily flows, million acre-ft	.578	.839	45.2	10
Total of lowest 50 percent of daily flows, acre-ft	6,125	9,565	56.1	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	9	108	469	3,287
Coefficient of determination (R^2)	.78	.58	.39	.17
Model-fit efficiency (NS)	.62	.53	.38	.10
Mean absolute error (ft³/s)	63	87	107	127
Root mean square error (ft³/s)	82	254	419	764

Simulation period 1961–2008

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, million acre-ft	4.097	3.846	-6.1	10
Mean flow rate (ft³/s)	119	111	-6.1	10
Total of highest 10 percent of daily flows, million acre-ft	3.539	3.138	-11.3	10
Total of lowest 50 percent of daily flows, acre-ft	113,870	113,933	.1	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	48	576	2,504	17,532
Coefficient of determination (R^2)	.78	.73	.67	.37
Model-fit efficiency (NS)	.78	.71	.63	.14
Mean absolute error (ft³/s)	43	68	83	106
Root mean square error (ft³/s)	61	195	350	780

Table 8. Streamflow calibration and testing results, Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas.—Continued

[acre-ft, acre-feet; ft³/s, cubic feet per second; NA, not able to be computed]

08204005 Leona River near Uvalde, Tex.
Calibration period Mar. 1, 2003–June 30, 2007

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, acre-ft	117,029	123,597	5.6	10
Mean flow rate (ft³/s)	43.8	46.5	5.6	10
Total of highest 10 percent of daily flows, acre-ft	20,591	22,769	10.6	10
Total of lowest 50 percent of daily flows, acre-ft	45,945	47,446	3.3	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	2	34	148	1,037
Coefficient of determination (R^2)	1.00	.97	.93	.72
Model-fit efficiency (NS)	.98	.96	.91	.68
Mean absolute error (ft³/s)	2	3	4	4
Root mean square error (ft³/s)	3	5	7	15

08207500 Atascosa River near McCoy, Tex.
Calibration period Aug. 25, 2002–Dec. 31, 2008

Comparison of streamflow volumes	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Total flow volume, acre-ft	248,962	239,304	-3.9	10
Mean flow rate (ft³/s)	54.1	52.0	-3.9	10
Total of highest 10 percent of daily flows, acre-ft	215,123	199,197	-7.4	10
Total of lowest 50 percent of daily flows, acre-ft	5,586	4,719	-15.5	10

Model-fit statistics[3]	Annual	Monthly	Weekly	Daily
Number of years, months, weeks, or days	6	76	331	2,321
Coefficient of determination (R^2)	.94	.80	.63	.42
Model-fit efficiency (NS)	.93	.80	.60	.24
Mean absolute error (ft³/s)	10	21	33	42
Root mean square error (ft³/s)	13	59	128	230

[1] Error = [(simulated-measured)/measured] x100.

[2] Default error criteria (Lumb and others, 1994).

[3] Model-fit statistics are generated from the GenScn software (version 2.3 build 10).

these guidelines, 2000–08 calibration results for streamflow at both the long-term and short-term calibration stations are considered good to very good for total flow volumes and for the flow volume of the highest 10 percent of daily flows. Calibration of flow volume of the lowest 50 percent of daily flows is not as accurate as the calibration of the flow volume of the highest 10 percent of daily flows and ranges from very good to poor. The flow volume of the lowest 50 percent of daily flows at the streamflow-gaging stations ranges from less than 1 to 2.6 percent of the total flow volume during calibration periods (table 8); an exception to this occurs at the Leona River near Uvalde station, where springflow contributes to flow on a continual basis, estimated as a minimum of about 3 ft³/s (exponential equation for springflow shown in fig. 9). At this station, the flow volume of the lowest 50 percent of daily flows is approximately 39 percent of the total flow volume, and the calibration is very good (table 8).

Model-fit statistics improve considerably for weekly and longer averaging of model output and measured streamflows. For the calibration period at all the streamflow-gaging stations, the NS for daily streamflows ranged from 0.23 to 0.68, and the RMSE ranged from 34 to 650 percent of the mean daily flow rate. The relatively small NS values (compared to the optimal value of 1.0) were caused by the difficulty in matching simulated to measured flows during periods of sudden, intense runoff as well as correctly simulating the timing of the flows routed from upstream from the study area. Weekly averaging improved the model statistics such that the NS ranged from 0.60 to 0.91, and the RMSE ranged from 16 to 271 percent of the mean flow rate. The streamflow calibrations at the Frio at Tilden station and the Leona River near Uvalde station had the highest (best) NS values; the streamflow calibrations at the Atascosa River stations (08207500 and 08208000) had the lowest NS values. The streamflow calibration at the Leona River near Uvalde station had the lowest (best) RMSE, and the San Miguel Creek near Tilden station had the highest RMSE as a percent of the mean flow rate.

Model testing was done by using 1991–99 streamflow data at the long-term gages. Less total flow volume was measured during the 9-year 1991–99 testing period than during the 9-year 2000–08 calibration period at the long-term gages (table 8). The simulated total flow volumes were larger than the measured total flow volumes during the testing period at the Frio River at Derby station, the San Miguel Creek near Tilden station, and the Atascosa River at Whitsett station. The simulated total flow volumes at those long-term gaging stations (table 8) exceeded the measured total flow volumes by approximately 22 to 50 percent. Simulated total flow volume during the testing period was within 7 percent of the measured total flow volume at the Frio River at Tilden station. For the entire 1961–2008 simulation period at the long-term stations (1978–2008 at the Frio River at Tilden station), simulated total flow volume was within about 3 to 18 percent of measured total flow volume. In comparison to the calibration period, and with the exception of the model-fit statistics at U.S. Geological Survey streamflow-gaging station 08206600 Frio River at Tilden, Tex., the model-fit statistics worsen (NS decreased, and the RMSE increased as a percentage of the mean flow rates) for the 1991–99 testing period and for the entire 1961–2008 simulation period.

A time series of daily mean reservoir volume during 1992–2008 was output from the Choke Canyon subwatershed model by using the combined volume of RCHRESs 25 and 26 (fig. 6). These volumes were compared with reservoir volumes measured by station 08206900 (USGS site 9; fig. 2 and table 1) and available online (U.S. Geological Survey, 2010). The mean daily reservoir volume over the entire period was 479,000 acre-ft. Simulated mean daily reservoir volume was within 1 percent of this measured volume, considered a very good calibration. Measured and simulated weekly mean reservoir volumes were graphically compared (fig. 14). The daily R^2 and NS for the daily comparison of simulated and measured storage volume were both 0.99, with a RMSE of less than 10 percent. From 2000–08, approximately 77 percent of the simulated inflow volume to the Choke Canyon Reservoir was from the Frio River, and 23 percent was from San Miguel Creek.

Evapotranspiration and Reservoir Evaporation

Besides accurate simulation of streamflow, another goal of the Frio model calibration was to accurately simulate the overall water budget in the watershed, including ET. The Medina meteorological station (fig. 5 and table 1) was installed in September 2006 on land with primarily shrub vegetation on the Carrizo-Wilcox aquifer outcrop. The daily ET at this meteorological station was computed by using the eddy covariance method (Slattery and others, 2010). The eddy covariance method is a statistical method that measures and calculates vertical turbulent fluxes within atmospheric boundary layers on the basis of measured micrometeorological data, including wind and scalar atmospheric data series, and produces values of fluxes for properties that are used to estimate ET (Bidlake, 2002).

The Frio-Sabinal subwatershed model calibration included comparing simulated ET from the Carrizo-Wilcox aquifer outcrop area of the subwatershed to ET computed from data collected at the Medina meteorological station from October 2006–December 2008 (fig. 15). Missing data at the gage were interpolated between the values measured during the nearest days. The total amount of ET measured at the station was 52.9 in. for this time period, and the total simulated ET from the Carrizo-Wilcox aquifer outcrop area in the Frio-Sabinal subwatershed was 51.6 in.; the simulated ET was 2.4 percent less than the measured ET. The total rainfall measured by tipping bucket at the ET tower from October 2006–December 2008 was 57.0 in. with 10 days of missing record (Richard Slattery, U.S. Geological Survey, written commun., 2010), while the rainfall recorded at the NWS rain gage at Sabinal, Tex. (NWS site 8; fig. 2 and table 2) and used in the model simulation was 54.7 in. Comparing measured ET to rainfall at the Medina meteorological station, and simulated ET to rainfall recorded at the NWS rain gage at Sabinal, approximately 93 to 94 percent of the rainfall during October 2006–December 2008 was evapotranspired.

Estimated monthly lake evaporation for Choke Canyon Reservoir since December 1999 is available online (Nueces River Authority, 2010b). Monthly estimates of lake evaporation are computed from daily pan evaporation data collected near Choke Canyon Dam and reservoir surface acreage estimated from reservoir stage (Susan Satterwhite, City of Corpus Christi, oral commun., 2010). From December 1999 to December 2008, monthly lake evaporation is reported to have varied from 1,994 acre-ft in January 2001 to 18,149 acre-ft in June 2008, with a mean annual evaporation during 2000–08 of 103,778 acre-ft. To calibrate the Choke Canyon subwatershed model to this evaporation data, the surface area-volume relation was increased for some of the reservoir stages in the FTABLES for RCHRESs 25 and 26, and the potential evaporation rate that BASINS estimates from the air temperature at the NWS station at Calliham, Tex. (NWS site 6; fig. 2) was multiplied by a factor of 1.05–1.10 for the reservoir surface evaporation in the lower reaches of the Frio Tilden subwatershed model and in RCHRES 25 and 26 of the Choke subwatershed model. After calibration, HSPF-simulated evaporation from RCHRES 25 and 26 of the Choke Canyon subwatershed was within 3 percent of the reported evaporation for Choke Canyon Reservoir from December 1999 to December 2008.

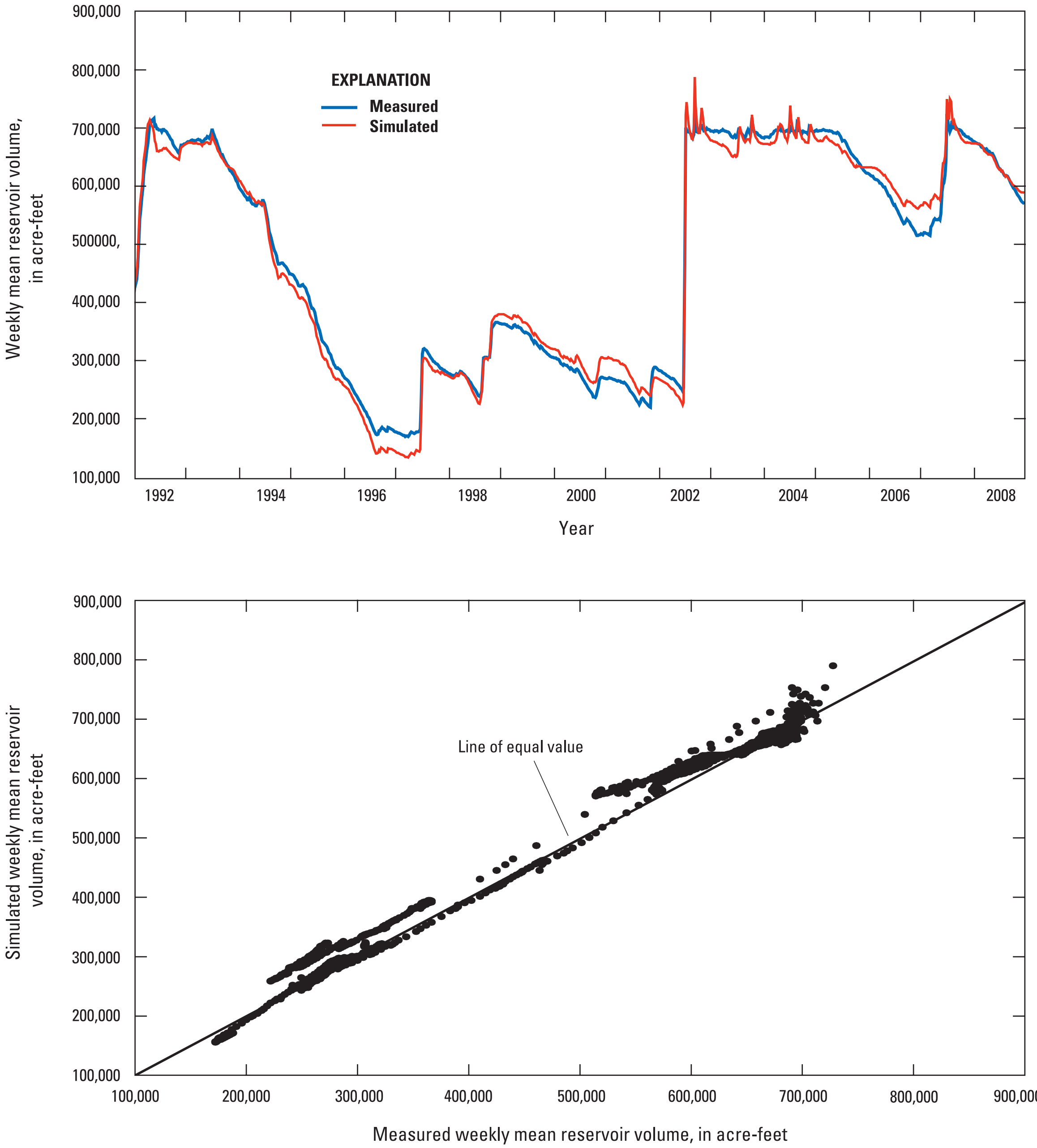

Figure 14. Measured and simulated weekly mean reservoir volume of Choke Canyon Reservoir, south Texas 1992–2008.

Simulated monthly lake evaporation varied from 2,630 acre-ft in January 2007 to 16,650 acre-ft in July 2005, with a mean annual evaporation during 2000–08 of 106,600 acre-ft.

Sensitivity Analysis

Calibrated values of selected HSPF-process-related parameters in the Upper San Miguel subwatershed were further evaluated by doing a sensitivity analysis. This analysis used the calibrated model parameters in the Upper San Miguel subwatershed (table 7) to determine the effects of systematic changes to the values of eight selected model parameters on simulated ET, groundwater recharge, and surface runoff from the PERLND areas in the outcrop of the Carrizo-Wilcox aquifer where it crosses the Upper San Miguel subwatershed (fig. 5). The calibrated model parameter set produced mean annual ET, groundwater recharge, and surface runoff estimates for 2000–08 of 23.4, 2.97, and 0.88 in., respectively. For each simulation, a selected model parameter of the Upper San Miguel subwatershed was changed by a hydrologically reasonable amount while keeping all other model parameters unchanged. The resulting changes in ET, groundwater recharge, and surface runoff for the Carrizo-Wilcox aquifer

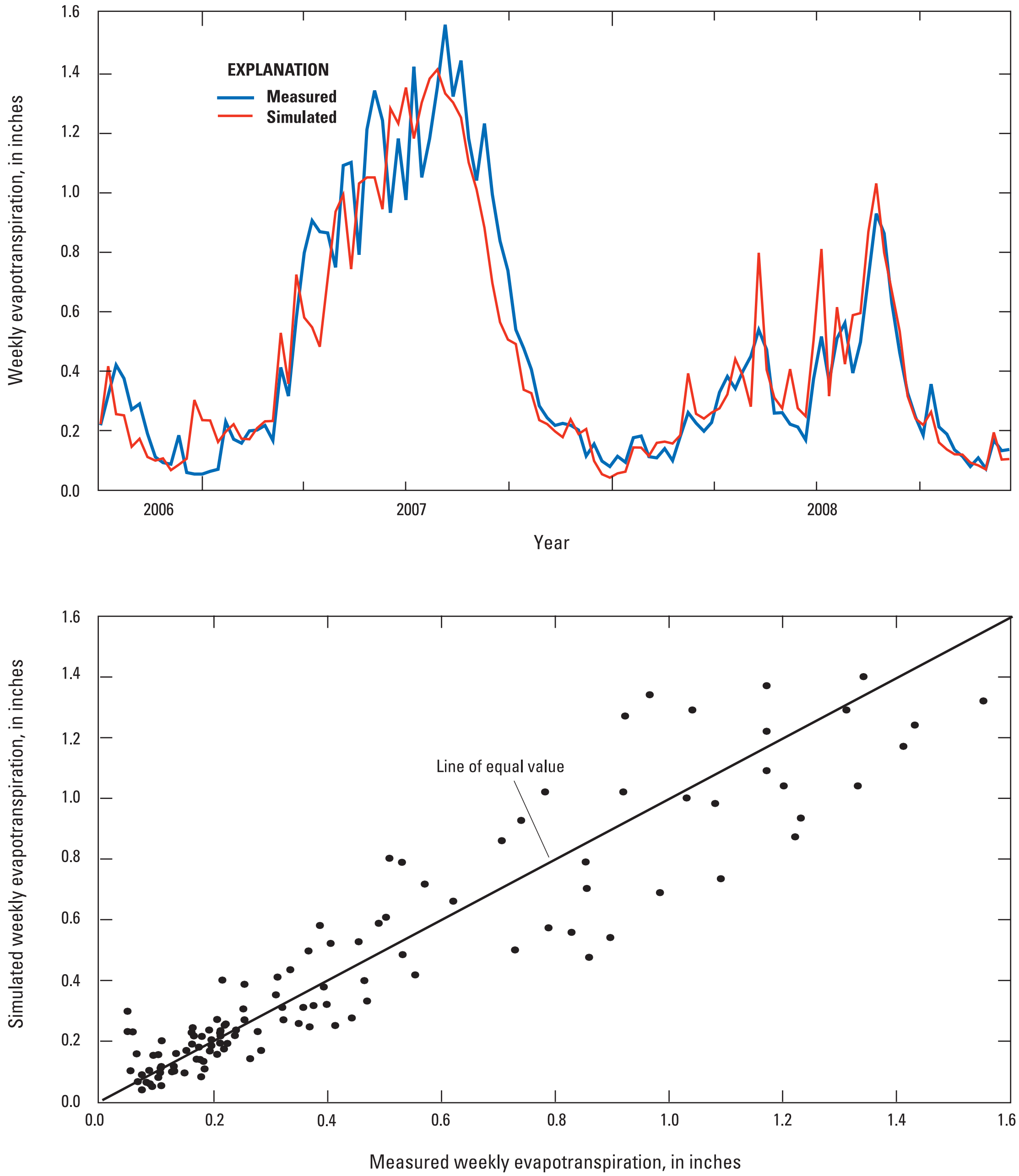

Figure 15. Measured weekly evapotranspiration at 290810099212100 southwest Medina County meteorological station near D'Hanis, Texas, and weekly evapotranspiration simulated by using the Hydrological Simulation Program—FORTRAN model for the Carrizo-Wilcox aquifer outcrop area in the Frio-Sabinal subwatershed of the lower Frio River watershed, south Texas, October 2006–December 2008.

outcrop in the Upper San Miguel subwatershed are listed in table 9.

The model parameters to which estimated recharge was most sensitive for the given model parameter changes were lower-zone ET (LZETP), the fraction of groundwater inflow to deep recharge (DEEPFR), and the interception storage capacity (CEPSC). Increasing the LZETP values by between 12.5 and 50 percent resulted in an increase in ET of 3 percent, a decrease in groundwater recharge of about 19 percent, and a decrease in surface runoff of about 19 percent. Reducing the DEEPFR values by about 12 percent resulted in an increase in ET of less than 1 percent, a decrease in groundwater recharge of 11 percent, and an increase in surface runoff of about 41 percent. Increasing the CEPSC values by 50–500 percent caused an increase in ET of about 1 percent, a decrease in groundwater recharge of about 9 percent, and a decrease in surface runoff of about 3 percent. Of these three parameters, the changes to the CEPSC values had the least effect on the surface runoff from the outcrop pervious area.

Table 9. Sensitivity of the estimated mean annual evapotranspiration, groundwater recharge, and surface runoff for the Carrizo-Wilcox aquifer outcrop to changes in selected model parameters of the Hydrological Simulation Program—FORTRAN model of the Upper San Miguel subwatershed, south Texas, 2000–08.

[ET, evaportranspiration; LZSN, lower-zone nominal storage; UZSN, upper-zone nominal storage; LZETP, lower-zone evapotranspiration; INFILT, index to infiltration capacity of soil; DEEPFR, fraction of groundwater inflow to deep recharge; AGWRC, groundwater recession indexed to rate of drainage; AGWETP, fraction of remaining evapotranspiration from groundwater; CEPSC, interception storage capacity]

Model parameter	Initial value	Unit	Adjusted value	Carrizo-Wilcox aquifer outcrop in Upper San Miguel subwatershed					
				ET (inches)	Change in ET (percent)[1]	Ground-water recharge (inches)	Change in groundwater recharge (percent)[1]	Surface runoff (inches)	Change in surface runoff (percent)[1]
LZSN	7.5–9.5	inches	Increase by 1.0	23.6	0.9	2.83	-4.7	0.82	-6.8
UZSN	.4	inches	Increase to 0.5	23.4	0	2.97	0	.81	-8.0
LZETP	.2–.8	none	Increase by 0.1 (0.3–0.9)	24.1	3.0	2.39	-19.5	.71	-19.3
INFILT	.15–.45	inches/hour	Increase by 0.05	23.3	-.4	3.10	4.4	.76	-13.6
DEEPFR	.85	none	Decrease by 0.1	23.5	.4	2.64	-11.1	1.24	40.9
AGWRC	.85–.92	1/day	Increase by 0.05	23.4	0	2.97	0	.84	-4.5
AGWETP	.02	none	Increase by 0.03	23.4	0	2.99	.7	.79	-10.8
CEPSC	.01–.10	inches	Increase by 0.05 (0.06–0.15)	23.7	1.3	2.70	-9.1	.85	-3.4

[1] Compared to the calibrated model, estimated amounts of mean annual ET, recharge, and surface runoff of 23.4, 2.97, and 0.88 inches, respectively.

Model Limitations

Model limitations include possible errors related to model conceptualization and parameter variability, lack of data to better quantify certain model inputs such as rainfall and irrigation, and measurement errors. HSPF is a complex watershed model that can handle multiple hydrologic scenarios; however, the model that was developed still represents a simplified understanding of the hydrologic processes of the lower Frio River watershed. Natural hydrologic processes are more complex than the simulations made possible by using empirical equations embedded in modeling software such as HSPF. The conceptualization of the watershed—FTABLES, stream dimensions, channel losses and surface withdrawals, and the imposed variation in model parameters—based on decisions as to which watershed factors drive the hydrologic responses of the watershed represents a simplification of the complex nature of the study watershed. HSPF distributes inflows and outflows to maintain a balanced water budget as process parameters are changed. The accuracy of the modeled distribution of water within the watershed depends on the adequacy of the measured data used to calibrate the model. Most of the rainfall in the study area evapotranspires, yet few measured ET data are available. The lack of measured ET data for different surficial geologic units, land covers, vegetative types, and seasons, could cause systematic errors in representing the hydrologic processes of the watershed.

Because large, isolated storms are common in south Texas, rainfall can vary greatly over a short distance. Uncertainty regarding the degree to which available rainfall data represents actual rainfall is potentially the most serious source of error for the Frio model. Hourly rainfall input to the model is disaggregated from measured daily rainfall at 12 NWS meteorological stations by using theoretical temporal distributions. Thiessen areas surrounding the 12 stations are determined, and the disaggregated rainfall amounts are applied evenly to these areas. The mean of the Thiessen areas is 458 mi^2. Because of the highly localized nature of rainfall in south Texas, the disaggregated rainfall time series applied by using Thiessen areas does not always accurately represent the rainfall duration or intensity in the study area. In addition, missing daily rainfall records at the 12 stations are estimated with nearby station data, which make the applied rainfall data less accurate (table 2).

The emphasis during calibration of most HSPF models is limited to the accurate simulation of streamflow. Streamflow accounts for a relatively small percentage of the water budget in the study area. Although an accurate calibration of streamflow relates to the accurate simulation of all the components of the water cycle, the accuracy of groundwater-recharge estimation also depends on accurate calibration of other water-budget components, especially ET. This is evidenced by the results of the sensitivity analysis; changes in some of the modeled parameters had an effect on the distribution of water between recharge and ET and a limited effect on the runoff. Fortunately, in addition to streamflow data on the outcrop of the Carrizo-Wilcox aquifer in Medina County (within the modeled outcrop area of the Frio-Sabinal subwatershed), October 2006–December 2008 ET data were available and could be used in model calibration. Differences between the measured and simulated weekly ET data were small, and the simulated ET data appear reasonable. In addition, simulated evaporation from Choke Canyon Reservoir was calibrated to computed reservoir evaporation from pan evaporation data. Simulations for other areas are less certain because of the lack of measured ET data for comparison purposes.

Irrigation represents the largest use of water in the study area, and groundwater has historically been the source of water for irrigation as well as other uses; surface-water withdrawals make up a small percentage of water needed for irrigation and other uses in the study area (Texas Water Development Board 2007, p. 150). However, with the exception of modeling surface-water irrigation diversion amounts (table 6) as a disaggregated time series of equal daily amounts during April through September of each year, other components of irrigation (including the application and distribution of water from groundwater sources) were not modeled in the study area. This greatly simplified the model development and data needs, but the exact timing and efficiency of irrigation processes could affect the modeling of recharge rates and surface-water runoff.

Streamflow Yields, 2000–08

The input and simulated output of the calibrated 2000–08 Frio model and the principles of the RCHRES water balance were utilized to quantify and compare the estimated streamflow production from each subwatershed. Watershed streamflow yields are often calculated to assess the production of surficial streamflow while normalizing for drainage area. Streamflow yield can vary substantially on an annual basis because of fluctuations in annual rainfall, but mean annual streamflow yield can be a useful measure for evaluating streamflow production and hydrologic differences between drainage areas. In addition, this quantification and comparison serves to help document the model calibration and also demonstrates another useful output from the model.

Measured or simulated mean annual streamflow volumes at the inflow boundaries and simulated mean annual streamflow volumes at the outlets of 11 of the 12 modeled subwatersheds were compiled for 2000–08 (table 10). Streamflow volumes were not compiled for the Choke Canyon subwatershed because there is a lack of calibration data for the high flow releases from the reservoir. For each subwatershed, the mean annual yield was calculated as the difference between the simulated mean annual streamflow volumes exiting and entering each subwatershed divided by the subwatershed drainage area, as illustrated in the following equation:

$$Y = \left(\left(Qout - Qin\right) / DA\right) \text{ x } F, \qquad (2)$$

where

Y is mean annual yield, in inches per year;

Qin and Qout are mean annual streamflow volumes entering and exiting the drainage area, respectively, in acre-feet;

DA is the drainage area, in square miles; and

F is a unit conversion factor (0.0187).

The difference between Qout and Qin equals the estimated overall gain or loss (negative value) in streamflow volume, in acre-feet, excluding gains from springflow and wastewater-treatment plants, but including losses due to surface-water withdrawals and channel infiltration. The majority of streamflow gain in the study area is estimated to occur in the Lower Atascosa subwatershed. A mean of 131,340 acre-ft per year is generated from 2000–08, which is more than one-third of the overall mean annual streamflow gain of 323,712 acre-ft per year from 11 of the 12 subwatersheds (excluding the Choke Canyon subwatershed) in the study area.

Model-estimated mean annual streamflow yields from the 11 subwatersheds ranged from -0.1 to 2.8 in/yr, with yields generally increasing from west to east and north to south. The lowest yields estimated were from the Frio-Sabinal (-0.1 in/yr) and Lower Leona (0.0 in/yr) subwatersheds. The highest yields were from the Lower San Miguel (2.7 in/yr) and Lower Atascosa (2.8 in/yr) subwatersheds. In addition to receiving more rainfall, the Lower San Miguel and Lower Atascosa subwatersheds had lower relative soil infiltration rates (fig. 7) represented in the model by lower values for the infiltration (INFILT) model parameter (table 7). The mean yield of the 11 subwatersheds is 1.1 in/yr for 2000–08, less than 5 percent of the mean annual rainfall (table 3).

Groundwater Recharge in the Carrizo-Wilcox Aquifer Outcrop, 1961–2008

Quantifying groundwater recharge in Texas is an important component of statewide water-resource planning. The Frio model was configured to output annual estimates of the groundwater recharge and other major water-budget components—rainfall, evapotranspiration, and runoff—for the part of the Carrizo-Wilcox aquifer outcrop in the study area. Selectively summarizing the model results in this

Table 10. Mean annual streamflow volumes and yields for subwatersheds in the Hydrological Simulation Program—FORTRAN model of the lower Frio River watershed, south Texas, 2000–08.

[--; not calculated]

Subwatershed name	Drainage area (square miles)	Qout, (mean annual streamflow volume exiting) (acre-feet)	Qin, (mean annual streamflow volume entering) (acre-feet)[1]	Qout-Qin (acre-feet)	Y, mean annual yield (inches)[2]
Upper Leona	329	33,058	26,662	6,396	0.4
Lower Leona	343	33,719	33,058	661	.0
Frio-Sabinal	641	67,878	70,303	-2,425	-.1
Hondo Creek	291	31,074	29,703	1,371	.1
Seco Creek	255	42,314	40,771	1,543	.1
Frio-Derby	814	200,770	145,254	55,516	1.3
Frio-Tilden	415	231,787	200,770	31,017	1.4
Upper San Miguel	580	28,043	0	28,043	.9
Lower San Miguel	280	67,788	28,043	39,745	2.7
Upper Atascosa	509	31,295	840	30,455	1.1
Lower Atascosa	884	163,525	32,135	131,390	2.8
Choke Canyon	146	--	--	--	--
Study area (exluding Choke Canyon subwatershed)	5,340	[3]463,100	[4]139,388	323,712	1.1

[1] Qin includes measured or simulated streamflow from upstream drainage area, springflow from Leona Springs, and wastewater treatment plant discharges (U.S. Environmental Protection Agency, 2004).

[2] $Y = ((Qout\text{-}Qin) / DA)) \times 0.01875$,

where

Qin and Qout = streamflow volumes entering and exiting the subwatershed, respectively, in acre-feet;

DA = subwatershed drainage area, in square miles; and

0.01875 = conversion factor.

[3] Qout = Qout from Frio-Tilden, Lower San Miguel, and Lower Atascosa subwatersheds = 231,787 + 67,788 + 163,525 = 463,100.

[4] Qin = Qin from Upper Leona, Frio-Sabinal, Hondo Creek, and Seco Creek subwatersheds (only 9,697 acre-feet inflow from Seco Creek subwatershed boundary, subtracting the nested inflow from Hondo Creek subwatershed) and additional wastewater treatment plant inflows of 3,023 acre-feet to Frio-Derby, Upper Atasacosa, and Lower Atascosa subwatersheds = 26,662 + 70,303 + 29,703 + 29,703 + 9,697 + 3,023 = 139,388.

manner demonstrates one use of the calibrated model for water-resource planning. Future scenarios, such as increased impervious land cover in the watershed or decreased rainfall, could be simulated to project changes to the recharge rates to this part of the outcrop.

The annual estimates of the water-budget components from seven subwatersheds with streams flowing across part of the Carrizo-Wilcox aquifer outcrop area (fig. 5) were areally weighted to determine the estimated inches of annual rainfall, ET, recharge, and runoff for the Carrizo-Wilcox aquifer outcrop during 1961–2008 (table 11). The mean annual rainfall on the outcrop during the 1961–2008 simulation period was 26.5 in. Of this rainfall, a mean of 24.3 in. (about 92 percent) was simulated as evapotranspiration; 1.8 in. (less than 7 percent) was simulated as groundwater recharge; and 0.5 in. (less than 2 percent) was simulated as runoff. Estimated annual groundwater recharge in the aquifer outcrop area varied from 0.1 to 7.1 in. depending on the amount of rainfall. Mean annual recharge for 1961–2008 across the seven subwatersheds varied from 1.0 to 2.7 in/yr, with recharge generally increasing from west to east (fig. 16). These recharge estimates are consistent with recharge values compiled from the literature (Scanlon and others, 2003; Kelley and others, 2004).

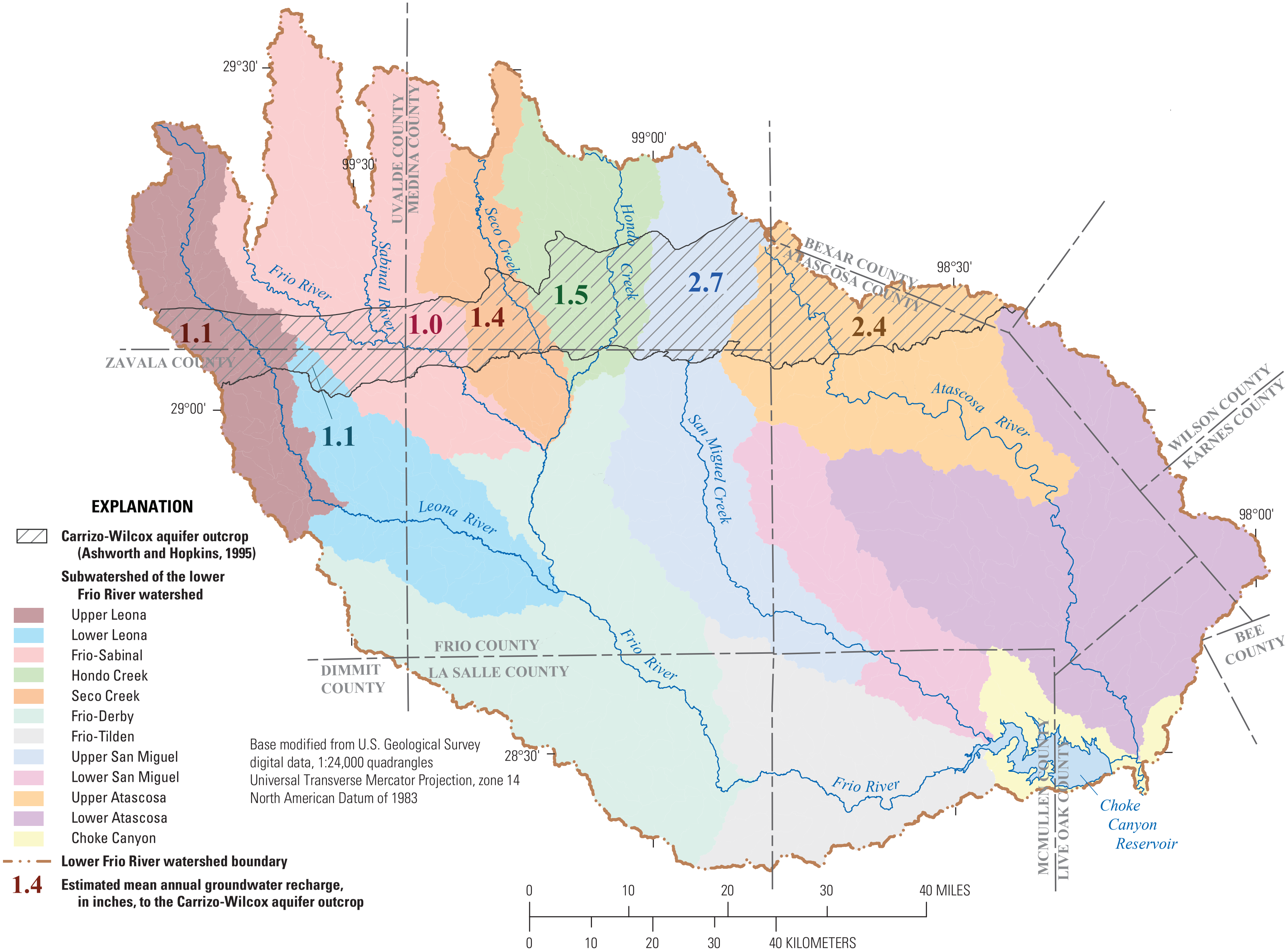

Figure 16. Estimated mean annual groundwater recharge, in inches, to the Carrizo-Wilcox aquifer outcrop in subwatersheds of the lower Frio River watershed, south Texas, 1961–2008.

Table 11. Estimated annual rainfall, evapotranspiration, groundwater recharge, and surface runoff for the Carrizo-Wilcox aquifer outcrop in the lower Frio River watershed, south Texas, 1961–2008.

[ET, evapotranspiration]

Year or period	Rainfall (inches)[1]	ET (inches)	Groundwater recharge (inches)	Surface runoff (inches)
1961	25.7	22.8	0.7	0.2
1962	14.3	17.1	.1	0
1963	18.0	16.7	.2	0
1964	22.0	19.9	.4	.1
1965	29.1	26.1	1.4	.2
1966	21.4	24.7	.8	.1
1967	24.7	17.2	1.2	.6
1968	35.0	31.0	4.9	1.7
1969	31.5	25.4	2.2	.5
1970	21.4	25.9	1.6	.3
1971	29.8	22.6	1.7	.5
1972	21.6	25.0	.7	.1
1973	39.0	31.6	3.5	.9
1974	34.0	27.4	2.7	1.0
1975	29.2	31.4	3.1	.6
1976	42.9	30.5	4.5	.9
1977	20.4	26.4	2.5	.8
1978	22.8	19.9	.4	0
1979	29.4	28.1	2.6	1.3
1980	24.9	21.2	.7	.2
1981	28.7	28.2	1.5	.4
1982	23.7	22.7	.7	.1
1983	23.2	24.5	.6	.1
1984	22.1	17.2	.6	.1
1985	29.0	27.0	1.7	.4
1986	34.0	27.4	2.7	.5
1987	35.5	32.1	7.1	2.7
1988	12.4	16.1	.1	0
1989	17.0	14.4	.1	0
1990	26.5	25.3	.9	.1
1991	32.0	25.4	1.8	.6
1992	39.4	32.4	7.0	2.1
1993	23.2	24.9	1.7	1.3
1994	28.2	24.6	1.0	.1
1995	22.9	23.4	.5	.1
1996	14.9	15.0	.1	0
1997	32.6	28.6	1.7	.6
1998	30.9	25.1	2.3	.6
1999	18.9	25.0	.9	.1
2000	26.0	19.9	.9	.2
2001	23.4	23.5	1.2	.2
2002	38.2	27.9	4.1	1.5
2003	23.4	28.7	1.6	.2
2004	38.8	31.7	3.1	1.0
2005	19.3	23.5	1.2	.2
2006	12.0	10.8	.1	0
2007	42.0	33.0	5.6	1.7
2008	15.8	18.7	.3	0
1961–2008	26.5	24.3	1.8	.5

[1] Because some water is simulated as stored in the unsaturated zone, the average annual rainfall does not always equal the sum of the simulated annual ET, groundwater recharge, and surface runoff amounts.

Summary

The U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers, Fort Worth District; the city of Corpus Christi; the Guadalupe-Blanco River Authority; the San Antonio River Authority; and the San Antonio Water System configured, calibrated, and tested a Hydrological Simulation Program—FORTRAN (HSPF) watershed model for the lower Frio River watershed in the Nueces River Basin. The lower Frio River watershed is approximately 5,490 square miles (mi^2), and includes all or parts of the following 12 counties in south Texas: Atascosa, Bexar, Dimmit, Frio, Karnes, La Salle, Live Oak, McMullen, Medina, Uvalde, Wilson, and Zavala. The modeled watershed area begins near the southern boundary of the Edwards aquifer outcrop and extends to the Frio River and Nueces River confluence downstream from Choke Canyon Reservoir.

Because of the large size of the study area, the lower Frio River watershed was divided into 12 subwatersheds, and separate HSPF models were developed for each subwatershed. The subwatershed models are referred to collectively as the Frio model. The Frio model was configured to simulate streamflow at locations where there is existing gage information and subwatershed outlets, reservoir volume at Choke Canyon Reservoir, and evapotranspiration (ET) and groundwater recharge for the Carrizo-Wilcox aquifer outcrop in the study area.

Rainfall data used as input for the Frio model were obtained from 12 National Weather Service (NWS) meteorological stations in or near the study area. Air temperature data from six of the NWS stations were used to estimate potential ET. Rainfall and potential ET rates were applied as time-series to land area in the model by using Theissen polygons. Other time-series datasets for the Frio model were developed for wastewater discharges, surface-water withdrawals, and surficial springflow from Leona Springs.

The model was calibrated and tested by using streamflow data obtained from six USGS streamflow-gaging stations in the study area. Additionally, for the Choke Canyon subwatershed, reservoir volume was calibrated by using reservoir stage measurements and evaporation data. Model calibration also included comparing simulated ET from the Carrizo-Wilcox aquifer outcrop area of the Frio-Sabinal subwatershed to ET measured at USGS meteorological station 290810099212100 in southwest Medina County near D'Hanis, Tex. (Medina meteorological station) during October 2006–December 2008.

Model calibration of streamflow volume is considered very good when the error is less than 10 percent, good when the error is within 10 to 15 percent, fair when the error is within 15 to 25 percent, and poor when the error is greater than 25 percent. Total flow volumes and flow volume of the highest 10 percent of flows at the six streamflow gages calibrated to within about 10 percent of the measured streamflow volumes by using 2000–08 data, which is considered a "very good" calibration. Simulated flows and storage also were evaluated graphically by comparing measured and simulated daily time series and exceedance-probability (flow-duration) curves. General agreement between the measured and simulated exceedance-probability curves indicates adequate calibration over the range of flow conditions during the calibration period. With the exception of simulated total flow volumes at USGS streamflow-gaging station 08206600 Frio River at Tilden, Tex., simulated total flow volumes were larger than measured total flow volumes during the testing periods at the long-term stations.

Various additional model-fit statistics were used to examine the quality of the streamflow model fit on an annual, monthly, weekly, and daily basis, including the Nash Sutcliffe model-fit efficiency (NS) and root mean square error (RMSE). Weekly averaging improved the model statistics such that the NS ranged from 0.60 to 0.91, and the RMSE ranged from 16 to 271 percent of the mean flow rate. With the exception of the model-fit statistics at USGS streamflow-gaging station 08206600 Frio River at Tilden, Tex., the model-fit statistics worsened for the 1991–99 testing period and for the entire 1961–2008 simulation period.

Measured ET data were available for calibration of HSPF-simulated ET. The total measured ET at the Medina meteorological station during October 2006–December 2008 was 52.9 inches (in.), and simulated ET from the outcrop within the Frio-Sabinal subwatershed for this same time period was 51.6 in., a difference of -2.4 percent. Estimates of Choke Canyon reservoir evaporation are computed by using pan evaporation data and reservoir stage, and monthly estimates are reported by the Nueces River Authority. Model-simulated evaporation from the two reaches representing Choke Canyon reservoir in the Choke Canyon subwatershed was within 3 percent of the evaporation reported by the Nueces River Authority for 1999–2008.

A sensitivity analysis was performed for the Upper San Miguel subwatershed model to show the effect of changes to model parameter values on the estimated mean recharge, ET, and surface runoff from that part of the Carrizo-Wilcox aquifer outcrop. Simulated recharge was most sensitive to the changes in the parameter values of lower-zone ET (LZETP), the fraction of groundwater inflow to deep recharge (DEEPFR), and the interception storage capacity (CEPSC). Of these three model parameters, the changes to the CEPSC values had the least effect on the surface runoff from the outcrop pervious area.

Model limitations include possible errors related to model conceptualization and parameter variability, lack of data to quantify certain model inputs, and measurement errors. The conceptualization of the watershed and the variation in model parameters among water-storage zones, as well as decisions as to which watershed factors drive the hydrologic responses of the watershed, represent a simplification of the complex hydrologic processes of the study watershed.

Uncertainty regarding the degree to which available rainfall data are used to represent actual rainfall is potentially the most serious source of measurement error in the model. Hourly rainfall input to the model is disaggregated from measured daily rainfall at 12 NWS meteorological stations by using theoretical temporal distributions. Thiessen areas surrounding the 12 stations are determined, and the disaggregated rainfall amounts are applied evenly to these areas. The mean of the Thiessen areas is 458 mi^2. Because of the highly localized nature of rainfall in south Texas, the disaggregated rainfall time series applied by using Thiessen areas does not always accurately represent the rainfall duration or intensity in the study area.

Streamflow volumes for 11 of the 12 subwatersheds were compiled from the model input and simulated results, and streamflow yields were determined. Yields were not estimated for the Choke Canyon subwatershed because there is a lack of calibration data for the high flow releases from the reservoir. Model-estimated mean annual streamflow yields from the 11 subwatersheds ranged from -0.1 to 2.8 inches per year (in/yr), with yields generally increasing from west to east and north to south. The lowest yields estimated from the model results were from the Frio-Sabinal (-0.1 in/yr) and Lower Leona (0.0 in/yr) subwatersheds. The highest yields were from the Lower San Miguel (2.7 in/yr) and Lower Atascosa (2.8 in/yr) subwatersheds. In addition to receiving higher rainfall, the Lower San Miguel and Lower Atascosa subwatersheds had lower relative soil infiltration rates represented in the model by lower values for the infiltration (INFILT) model parameter. The mean yield of the 11 subwatersheds was 1.1 in/yr for 2000–08, less than 5 percent of the mean annual rainfall.

The Frio model was used to estimate groundwater recharge for the Carrizo-Wilcox aquifer outcrop. The mean annual rainfall on the outcrop during the 1961–2008 simulation period was 26.5 in. Of this rainfall, a mean of 24.3 in. (about 92 percent) was simulated as evapotranspiration, 1.8 in. (less than 7 percent) was simulated as groundwater recharge, and 0.5 in. (less than 2 percent) was simulated as runoff. Estimated annual groundwater recharge in the aquifer outcrop area varied from 0.1 to 7.1 in. depending on the amount of rainfall. Mean annual recharge for 1961–2008 across the seven subwatersheds varied from 1.0 to 2.7 in/yr, with recharge generally increasing from west to east.

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