Prepared in cooperation with the Texas State Soil and Water Conservation Board and the Upper Guadalupe River Authority

Simulation of Streamflow and the Effects of Brush Management on Water Yields in the Upper Guadalupe River Watershed, South-Central Texas, 1995–2010

Scientific Investigations Report 2012–5051

U.S. Department of the Interior
U.S. Geological Survey

Cover: North Fork Guadalupe River upstream from Highway 39, near Hunt, Texas, June 17, 2011.

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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)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	3.0689×10^{-6}	acre-foot
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the Texas Centric Mapping System–Albers Equal Area Projection, North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Simulation of Streamflow and the Effects of Brush Management on Water Yields in the Upper Guadalupe River Watershed, South-Central Texas, 1995–2010

By Johnathan R. Bumgarner and Florence E. Thompson

Abstract

The U.S. Geological Survey, in cooperation with the Texas State Soil and Water Conservation Board and the Upper Guadalupe River Authority, developed and calibrated a Soil and Water Assessment Tool watershed model of the upper Guadalupe River watershed in south-central Texas to simulate streamflow and the effects of brush management on water yields in the watershed and to Canyon Lake for 1995–2010. Model simulations were done to quantify the possible change in water yield of individual subbasins in the upper Guadalupe River watershed as a result of the replacement of ashe juniper (*Juniperus ashei*) with grasslands. The simulation results will serve as a tool for resource managers to guide their brush-management efforts.

Model hydrology was calibrated with streamflow data collected at the U.S. Geological Survey streamflow-gaging station 08167500 Guadalupe River near Spring Branch, Tex., for 1995–2010. Simulated monthly streamflow showed very good agreement with measured monthly streamflow: a percent bias of -5, a coefficient of determination of 0.91, and a Nash–Sutcliffe coefficient of model efficiency of 0.85.

Modified land-cover input datasets were generated for the model in order to simulate the replacement of ashe juniper with grasslands in 23 brush-management subbasins in the watershed. Each of the 23 simulations showed an increase in simulated water yields in the targeted subbasins and to Canyon Lake. The simulated increases in average annual water yields in the subbasins ranged from 6,370 to 119,000 gallons per acre of ashe juniper replaced with grasslands with an average of 38,900 gallons. The simulated increases in average annual water yields to Canyon Lake from upstream subbasins ranged from 6,640 to 72,700 gallons per acre of ashe juniper replaced with grasslands with an average of 34,700 gallons.

Introduction

The selective removal of woody (nonherbaceous or succulent) plants in an effort to increase water yields to downstream water resources is a brush-management conservation practice currently (2012) used in Texas (Natural Resources Conservation Service, 2009; Texas State Soil and Water Conservation Board, 2011). Generally, brush-management conservation practices (hereinafter referred to as “brush management”) include the removal of woody plants for the purpose of (1) creating desired plant communities, (2) controlling erosion, (3) improving water quality, (4) enhancing streamflow or water yield, (5) improving fish and wildlife habitat, (6) improving forage accessibility, and (7) managing fuel loads (Natural Resources Conservation Service, 2009). Woody plants have encroached into semiarid grasslands and savannas in Texas (Humphrey, 1958; Archer and others, 1988; Archer, 1989), and their potential to decrease groundwater recharge and streamflow via processes such as increased evapotranspiration, which reduces infiltration to the water table, and canopy interception of rainfall, which reduces both infiltration and streamflow, is well documented (Archer and others, 1995; Dugas and others, 1998; Van Auken, 2000; Wilcox, 2002; Huxman and others, 2005; Wilcox and Thurow, 2006; Musgrove and others, 2010). Ashe juniper (*Juniperus ashei*) is a woody plant species that has spread beyond its historical range in the understories of small stands of prairie oak (motte) and in sheltered canyons in Texas because of overgrazing and fire suppression (Smeins, 1980; Fuhlendorf, and others, 1996; Fuhlendorf and others, 1997). Studies of the water use of ashe juniper indicate that they might intercept and use more water than do native grasses (Young and others 1984; Thurow and others, 1987; Owens, 1996; Baxter, 2009; Saleh and others, 2009). As a result, the replacement of ashe juniper with grasslands is used in south-central Texas in an effort to increase water yields (Natural Resources Conservation Service, 2009; Texas State Soil and Water Conservation Board, 2011).

The Texas State Soil and Water Conservation Board (TSSWCB) Water Supply Enhancement Program (WSEP) provides funding for brush management in an effort to increase water yields to water bodies in Texas used for water supply (Texas State Soil and Water Conservation Board, 2011). Canyon Lake, a run-of-river reservoir (water is passed through the reservoir without being stored long term) in the upper Guadalupe River watershed in south-central Texas, is the water resource identified by the WSEP for this project that might receive more water as a result of brush management. In an effort to effectively manage brush in the upper Guadalupe River watershed and potentially increase water yields to Canyon Lake, the U.S. Geological Survey (USGS), in cooperation with the TSSWCB and the Upper Guadalupe River Authority (UGRA), developed a Soil and Water Assessment Tool (SWAT) (Arnold and others, 1998) watershed model of the upper Guadalupe River watershed to simulate the effects of the replacement of ashe juniper with grasslands and estimate the effects of brush management on water yields to the reservoir. Simulation results will be used as part of a WSEP feasibility study to quantify possible water-yield changes in subbasins in the upper Guadalupe River watershed as a result of brush management.

The use of watershed models, which are designed specifically to simulate surface and near-surface processes, has been applied previously to brush-management studies and can provide insights into the possible effects of brush management on water yields. SWAT was used previously in the TSSWCB brush-management feasibility studies of eight watersheds in Texas (Bednarz and others, 2000). The studies predicted average annual water-yield increases ranging from about 6,650 to about 172,000 gallons per acre of simulated brush management. Wu and others (2001) used the Simulation of Production and Utilization of Rangelands (SPUR–91) model to evaluate brush management in the Cusenbary Draw Basin in the Edwards Plateau in Texas. Their simulations showed increased water yields for a variety of brush-management scenarios. SWAT was used by Arrington and others (2002) to demonstrate the potential for brush management to increase water yields in conjunction with the retention of ecological value in rangelands. A USGS investigation of brush management in the Upper Seco Creek watershed using the Hydrological Simulation Program—FORTRAN (HSPF) demonstrated increased water yields immediately following brush management for several subbasins in the watershed (Brown and Raines, 2002). However, even though the study at Seco Creek showed that initial removal of brush led to increased water yields, 3 years later, after re-vegetation with native grasses, there was less aquifer recharge than on a control site that remained covered by ashe juniper. Lemberg and others (2002) interfaced SWAT with the hydrologic-based plant growth simulation model PHYGROW to assess the effects of brush management on water yields in the Frio River Basin, Tex. The simulations indicated that brush management would result in increased water yields but that brush management was not cost effective at that time. Finally, Afinowicz and others (2005) showed water-yield increases for multiple brush-management scenarios by using a SWAT model of the 140-square-mile (mi^2) North Fork Guadalupe River watershed in the western part of the upper Guadalupe River watershed.

Purpose and Scope

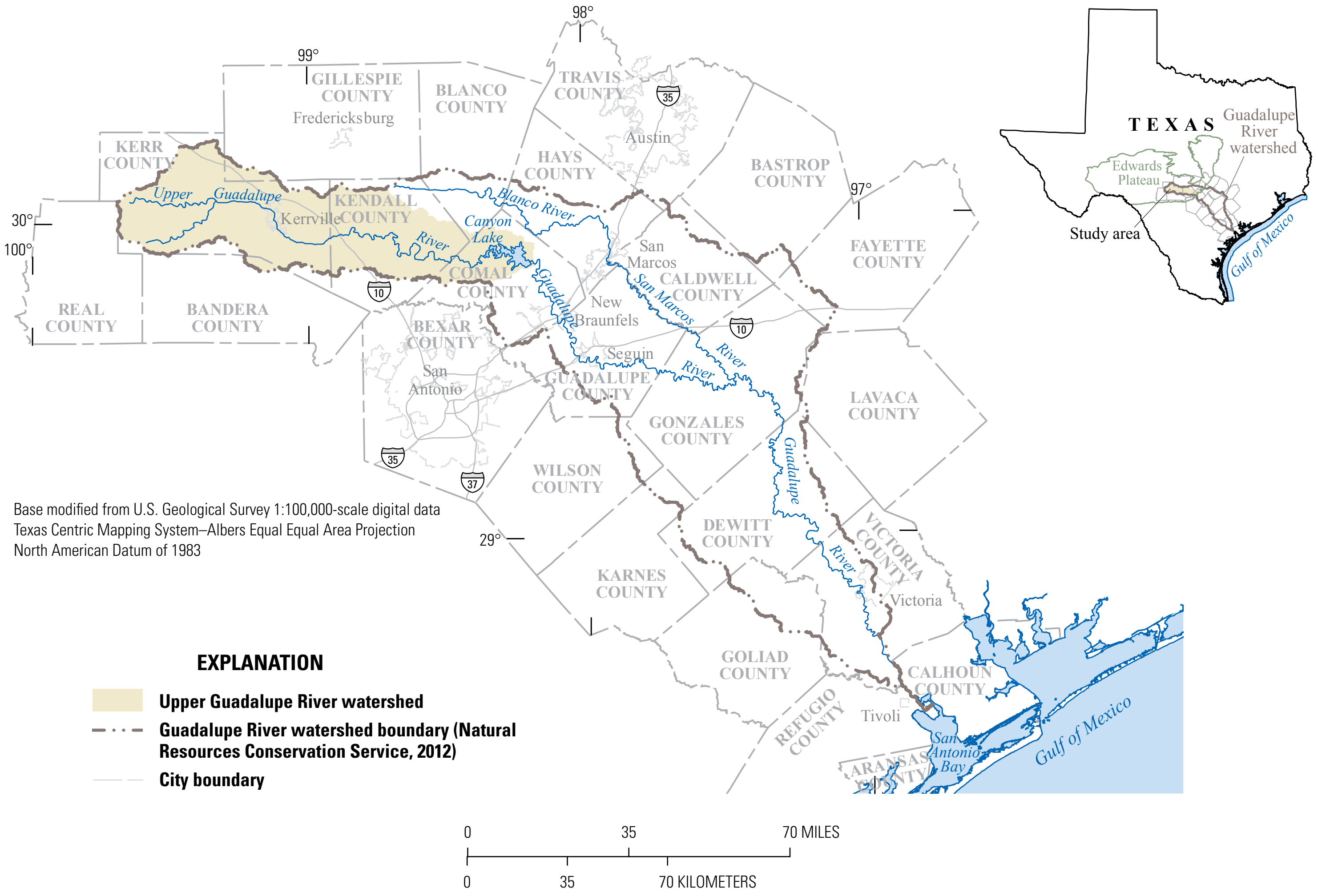
This report documents the development and calibration of a SWAT watershed model of the upper Guadalupe River watershed to simulate streamflow and the effects of brush management on water yields for 1995–2010. Model simulations were done to quantify the change in water yield of individual subbasins in the upper Guadalupe River watershed as a result of the replacement of ashe juniper with grasslands. Limitations of the model are described.

Description of the Upper Guadalupe River Watershed

The Guadalupe River extends about 230 miles (mi) from its headwaters in the Edwards Plateau in south-central Texas to San Antonio Bay near Tivoli, Tex., and has a drainage area of about 10,200 mi^2 (fig. 1). The upper Guadalupe River watershed study area is 1,432 mi^2 of the Guadalupe River Basin upstream from Canyon Dam in Comal County, Tex. Canyon Lake is a run-of-river reservoir formed by Canyon Dam that supplies water for municipal water supply, irrigation, and industrial uses, as well as for operation of several small hydroelectric plants. At conservation pool the lake has a capacity of about 382,000 acre-feet (acre-ft), a surface area of about 13 mi^2, and about 80 mi of shoreline (U.S. Army Corps of Engineers, 2011). The study area encompasses parts of Bandera, Blanco, Comal, Gillespie, Kendall, Kerr, and Real Counties in south-central Texas. The largest city in the study area is Kerrville, Tex., which had a human population of 22,347 in 2010 (U.S. Census Bureau, 2011).

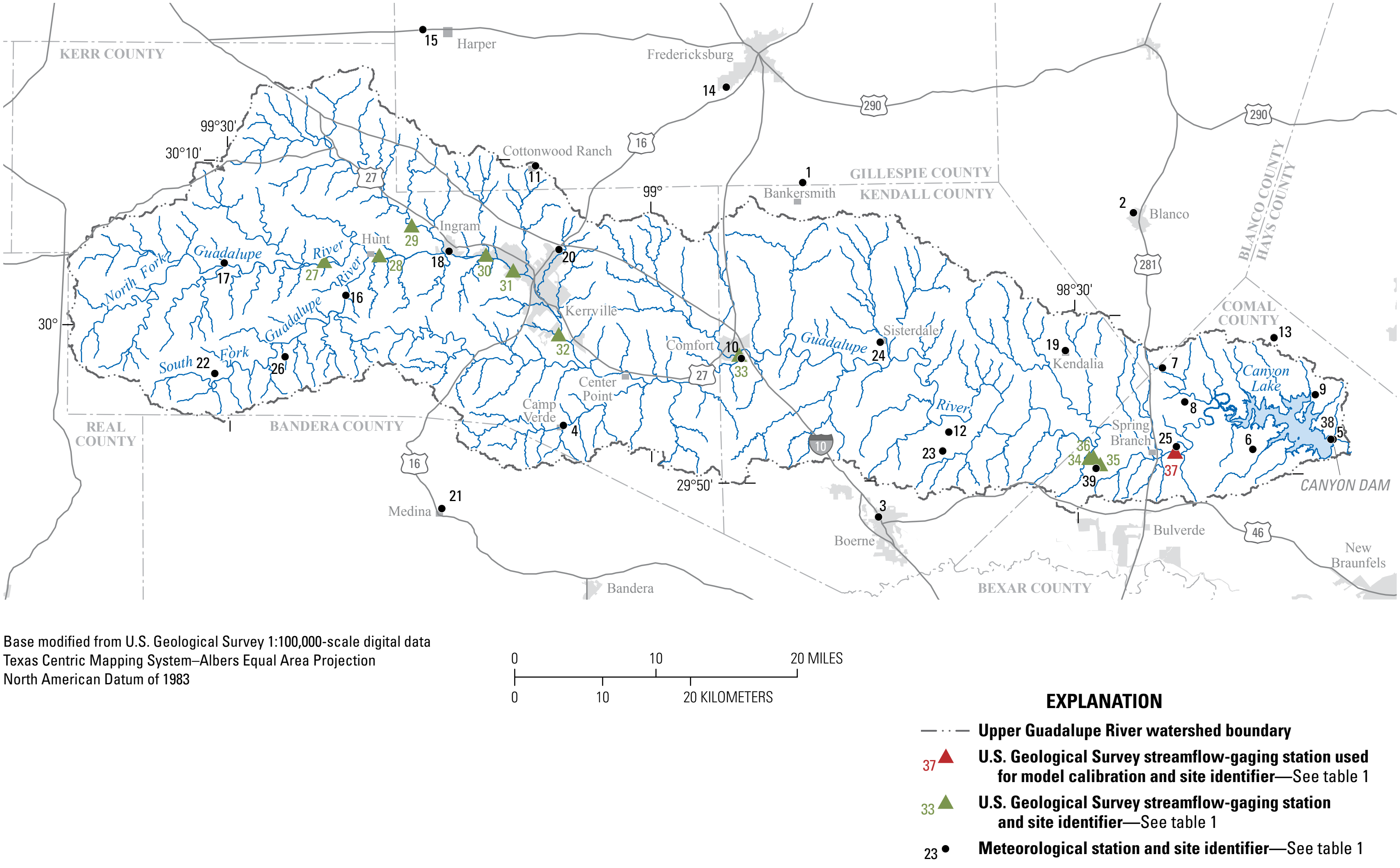
The study area has a subtropical, subhumid climate characterized by hot summers and mild winters (Larkin and Bomar, 1983). Average daily low temperatures for 1995–2010 ranged from 40 degrees Fahrenheit (ºF) in the month of January to 73ºF in August at the Canyon Dam National Weather Service (NWS) station (cooperative station identification [COOP ID] 411429) (site 5, fig. 2, table 1); average daily high temperatures ranged from 61ºF in January to 95ºF in August at that same station (National Climatic Data Center, 2011b). Average annual rainfall for 1995–2010 ranged from 27 inches at the Hunt 10 W NWS station (COOP ID 414375) (site 17, fig. 2, table 1) in the western part of the watershed to 39 inches at the Canyon Dam NWS station (COOP ID 411429) (site 5, fig. 2, table 1) in the eastern part of the watershed (National Climatic Data Center, 2011b). Daily rainfall equal to or greater than 1 inch for 1995–2010 occurred, on average, 40 days per year at the Hunt 10 W NWS station (COOP ID 414375) (site 17, fig. 2, table 1) and 53 days per year at the Canyon Dam NWS station (COOP ID 411429) (site 5, fig. 2, table 1; National Climatic Data Center, 2011a). Asquith and Roussel (2003) reported that daily rainfall equal to or greater than 1 inch occurs, on average, every 52 days at the western boundary of the watershed to every 36 days in the eastern part of the watershed. Although most rainfall occurs in spring, early summer, and fall, daily rainfall amounts greater than 1 inch occur anytime during the year (Larkin and Bomar, 1983).

The study area is located in a karst topographic region formed by the dissolution of Cretaceous-age carbonate rocks



Base modified from U.S. Geological Survey 1:100,000-scale digital data
Texas Centric Mapping System–Albers Equal Equal Area Projection
North American Datum of 1983

Figure 1. Location of the Guadalupe River watershed, including the upper Guadalupe River watershed study area, south-central Texas.



Base modified from U.S. Geological Survey 1:100,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

Figure 2. Locations of U.S. Geological Survey streamflow-gaging stations and the National Weather Service and U.S. Geological Survey meteorological stations providing data for the upper Guadalupe River watershed model, south-central Texas.

Table 1. Data-collection sites providing data for the upper Guadalupe River watershed model, south-central Texas.

[NWS, National Weather Service; COOP ID, cooperative station identification; no., number; max, maximum; min, minimum; temp, temperature; USGS, U.S. Geological Survey]

Site identifier (fig. 2)	Station name, number, and location	Latitude (decimal degrees)	Longitude (decimal degrees)	Type of data (period of record available)
1	NWS station COOP ID 410509, Bankersmith, Gillespie County, Tex.	30.14111	98.82000	Daily precipitation (1947–2010)
2	NWS station COOP ID 410832, Blanco, Blanco County, Tex.	30.10583	98.42861	Daily max and min air temp (1946–2010)
3	NWS station COOP ID 410902, Boerne, Kendall County, Tex.	29.79778	98.73473	Daily precipitation; daily max and min air temp (1946–2010)
4	NWS station COOP ID 411395, Camp Verde, Kerr County, Tex.	29.89472	99.10500	Daily precipitation (1961–2010)
5	NWS station COOP ID 411429, Canyon Dam, Comal County, Tex.	29.87056	98.19666	Daily precipitation; daily max and min air temp (1961–2010)
6	NWS station COOP ID 411431, Canyon Dam no. 1, Comal County, Tex.	29.86167	98.29195	Daily precipitation (1961–2002)
7	NWS station COOP ID 411433, Canyon Dam no. 3, Comal County, Tex.	29.94639	98.39694	Daily precipitation (1961–2010)
8	NWS station COOP ID 411434, Canyon Dam no. 4, Comal County, Tex.	29.91111	98.37139	Daily precipitation (1961–2010)
9	NWS station COOP ID 411438, Canyon Dam no. 7, Comal County, Tex.	29.91667	98.21667	Daily precipitation (1961–1993)
10	NWS station COOP ID 411920, Comfort 2, Kendall County, Tex.	29.96139	98.89472	Daily precipitation (1961–2010)
11	NWS station COOP ID 412040, Cottonwood, Gillespie County, Tex.	30.16055	99.13556	Daily precipitation (1946–2010)
12	NWS station COOP ID 412830, Northington Rch, Kendall County, Tex.	29.88333	98.65000	Daily precipitation (1963–2010)
13	NWS station COOP ID 413156, Fischers Store, Comal County, Tex.	29.97556	98.26472	Daily precipitation (1947–2010)
14	NWS station COOP ID 413329, Fredericksburg, Gillespie County, Tex.	30.23917	98.90889	Daily max and min air temp (1946–2010)
15	NWS station COOP ID 413954, Harper 1w, Gillespie County, Tex.	30.30111	99.26806	Daily precipitation; daily max and min air temp (1947–2010)
16	NWS station COOP ID 414374, Hunt 3 SW, Kerr County, Tex.	30.02944	99.36139	Daily precipitation (1947–2000)
17	NWS station COOP ID 414375, Hunt 10 W, Kerr County, Tex.	30.06278	99.50500	Daily precipitation; daily max and min air temp (1976–2010)
18	NWS station COOP ID 414458, Ingram no. 2, Kerr County, Tex.	30.07361	99.23861	Daily precipitation (1947–2010)
19	NWS station COOP ID 414757, Kendalia, Kendall County, Tex.	29.96583	98.51167	Daily precipitation (1961–2010)
20	NWS station COOP ID 414782, Kerrville 3 NNE, Kerr County, Tex.	30.07444	99.10861	Daily precipitation; daily max and min air temp (1974–2010)
21	NWS station COOP ID 415742, Medina 1ne, Bandera County, Tex.	29.81000	99.24973	Daily max and min air temp (1959–2010)
22	NWS station COOP ID 416257, Nelson Rch, Kerr County, Tex.	29.95000	99.51667	Daily precipitation (1962–1983)
23	NWS station COOP ID 416448, Northington Rch, Kendall County, Tex.	29.86417	98.65806	Daily precipitation (1963–2010)
24	NWS station COOP ID 418358, Sisterdale, Kendall County, Tex.	29.97667	98.73000	Daily precipitation (1961–2010)
25	NWS station COOP ID 418544, Spring Branch 2se, Comal County, Tex.	29.86555	98.38194	Daily precipitation (1956–2010)
26	NWS station COOP ID 419904, Worlds End Rch, Kerr County, Tex.	29.96667	99.43333	Daily precipitation (1947–1983)
27	USGS streamflow-gaging station 08165300 North Fork Guadalupe River near Hunt, Tex.	30.06410	99.38699	Streamflow (1967–2010)
28	USGS streamflow-gaging station 08165500 Guadalupe River at Hunt, Tex.	30.06993	99.32171	Streamflow (1941–2010)
29	USGS streamflow-gaging station 08166000 Johnson Creek near Ingram, Tex.	30.10021	99.28310	Streamflow (1941–2010)
30	USGS streamflow-gaging station 08166140 Guadalupe River above Bear Creek at Kerrville, Tex.	30.06965	99.19532	Streamflow (1978–2010)
31	USGS streamflow-gaging station 08166200 Guadalupe River at Kerrville, Tex.	30.05327	99.16338	Streamflow (1986–2010)

Table 1. Data-collection sites providing data for the upper Guadalupe River watershed model, south-central Texas.—Continued

[NWS, National Weather Service; COOP ID, cooperative station identification; no., number; max, maximum; min, minimum; temp, temperature; USGS, U.S. Geological Survey]

Site identifier (fig. 2)	Station name, number, and location	Latitude (decimal degrees)	Longitude (decimal degrees)	Type of data (period of record available)
32	USGS streamflow-gaging station 08166250 Guadalupe River near Center Point, Tex.	29.98778	99.11000	Streamflow (2008–2010)
33	USGS streamflow-gaging station 08167000 Guadalupe River at Comfort, Tex.	29.96524	98.89717	Streamflow (1939–2010)
34	USGS streamflow-gaging and meteorological station 08167347 Unnamed Tributary Honey Creek Site 1C near Spring Branch, Tex.	29.85531	98.48483	Streamflow (2000–2010); daily precipitation (2000–2010)
35	USGS streamflow-gaging and meteorological station 08167350 Unnamed Tributary Honey Creek Site 1T near Spring Branch, Tex.	29.85039	98.47289	Streamflow (1999–2010); daily precipitation (1999–2010)
36	USGS streamflow-gaging and meteorological station 08167353 Unnamed Tributary Honey Creek Site 2T near Spring Branch, Tex.	29.85624	98.48008	Streamflow (2000–2010); daily precipitation (2000–2010)
37	USGS streamflow-gaging station 08167500 Guadalupe River near Spring Branch, Tex.	29.86050	98.38363	Streamflow (1922–2010)
38	USGS meteorological station 08167700 Canyon Lake near New Braunfels, Tex.	29.86883	98.19890	Daily precipitation (1998–2010)
39	USGS meteorological station 295040098283701 Honey Creek Rain Gage No. 1, Tex.	29.84451	98.47699	Daily precipitation (1999–2010)

(U.S. Geological Survey, 2006). Karst systems are generally characterized by groundwater–surface-water connections, such as losing streams, sinkholes, springs, and fracture and conduit connections between surface water and groundwater (Katz and others, 1997; Winter and others, 1998). Land cover in the watershed is dominated by shrubland and evergreen forest (German and others, 2009). Soils generally are shallow, calcareous clay and clay loam with rocky outcrops (Natural Resources Conservation Service, 2011a). Elevation in the watershed ranges from about 900 to 2,400 feet (ft) (Gesch, 2007), and land slopes varied from 0 to greater than 60 percent.

Model Development

Functional Description of the Soil and Water Assessment Tool

The SWAT watershed model is a process-based, semi-distributed water balance model designed to predict the effects of management decisions on water, sediment, and agricultural chemical yields (Arnold and others, 1998). As summarized in part by Garcia (2009), in SWAT, a delineated watershed is divided into subbasins, each identified by a single reach. Each subbasin is further divided into hydrologic response units (HRUs) that consist of unique combinations of land cover, soil characteristics, land slope, and land-management criteria. Processes including, but not limited to, surface runoff, evapotranspiration, base flow, channel transmission losses, the life cycle of plants, nutrient cycling, and constituent transport can be simulated for each HRU and are determined by the process-related parameter values uniquely defined for each HRU. During model development, default values are assigned to the model parameters by the modeling software based on the unique HRU characteristics. The simulated water and constituent loads are aggregated within their corresponding subbasins, are allocated to the subbasin reach, and exit a subbasin via outlet points on the stream network that define the subbasin. The model accounts for in-stream processes while discharge and constituent fluxes are kinematically routed downstream from upstream subbasins to the watershed outlet. Model output includes streamflow for any subbasin outlet, including the delineated watershed outlet. The input data and user-specified parameters determine the model that is developed by delineating HRUs and assigning default and calibrated parameter values. A complete description of the SWAT model and its simulated processes can be found in Neitsch and others (2011a).

The hydrologic component of SWAT uses the Natural Resources Conservation Service (NRCS) runoff curve-number (CN) equation (Soil Conservation Service, 1986). The CN equation is empirically based and relates runoff potential to land-cover and soil characteristics. A high CN translates into greater runoff. For example, forested land cover, such as ashe juniper, has a lower CN than grasslands and produces less runoff (Soil Conservation Service, 1986). Daily CN values were calculated in the model as a function of plant evapotranspiration instead of the standard calculation, which is as a function of soil moisture (model parameter ICN=1) (Neitsch and others, 2011b). Daily CNs calculated as a function of soil moisture tended to overestimate runoff in watersheds with shallow soils (Neitsch and others, 2011b), and the upper Guadalupe River watershed generally has shallow soils (Natural Resources Conservation Service, 2011a).

The SWAT watershed model version used for this study was the SWAT2009.exe revision 445. The SWAT model can be executed from within a geographic information system (GIS), which incorporates spatially distributed data. For this study, ArcGIS 9.3.1 (Environmental Research Systems Institute, Inc., Redlands, Calif.) and the ArcGIS extension ArcSWAT version 2009.93.5 (Winchell and others, 2010) were used to execute SWAT. The model and simulations presented in this report can be replicated by following the model-development steps described in the ArcSWAT user's manual (Winchell and others, 2010) and the user input and calibration specifications described in this report.

Model Input Data

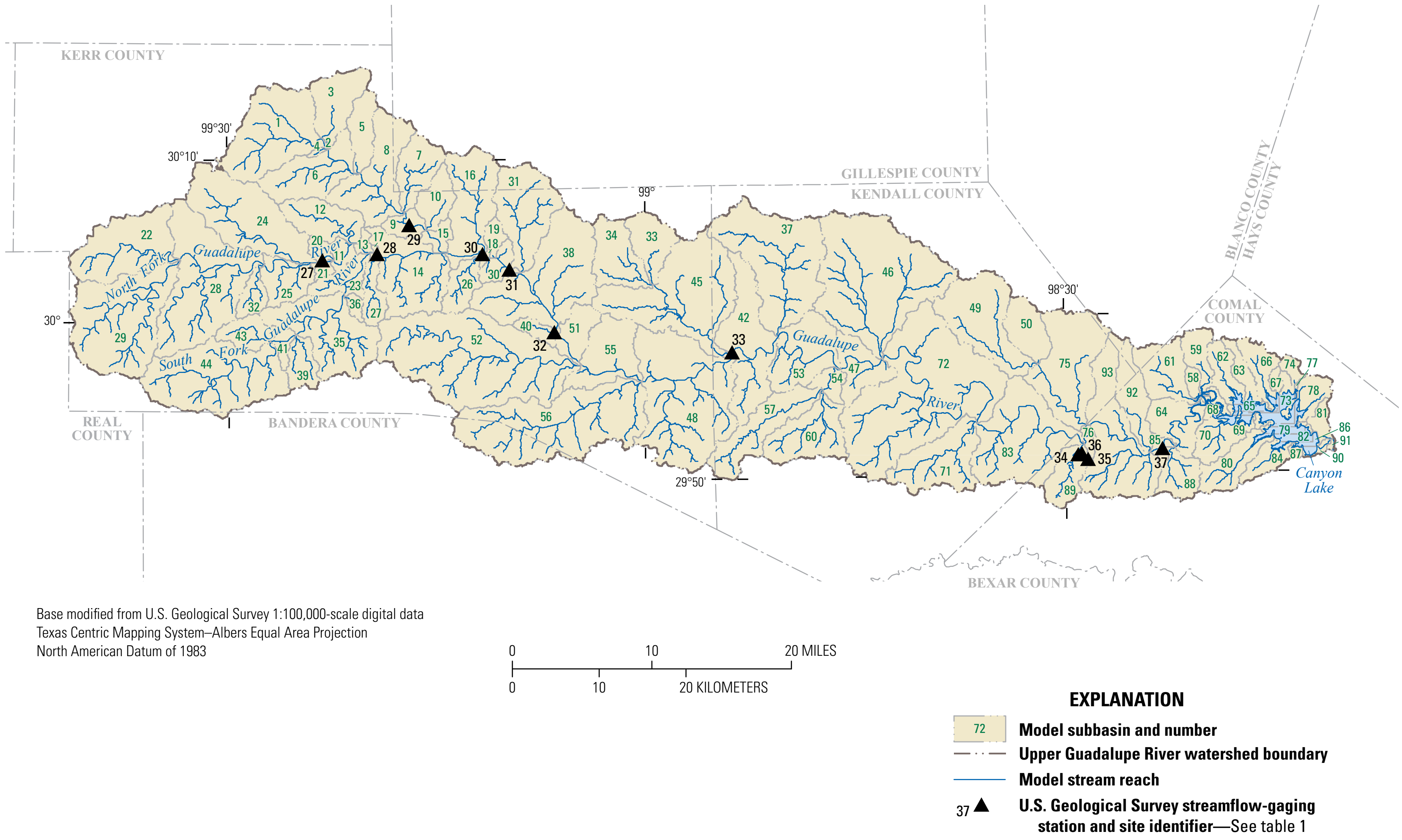
Input data for the upper Guadalupe River watershed model included spatial and temporal datasets. The spatial data consisted of elevation, soils, land cover, and locations of streamflow-gaging stations and meteorological stations. Temporal data consisted of streamflow, precipitation, and air temperature and were used for model calibration and model input.

Ten-meter (one elevation value derived for every 10-meter [m] by 10-m pixel) digital elevation models (DEMs) from the National Elevation Dataset were obtained to generate the topographic inputs for the model (Gesch and others, 2002; Gesch, 2007). Di Luzio and others (2005) and Cotter and others (2003) found that the resolution of the DEM was the most critical input parameter when developing a SWAT model. The study area watershed was delineated, and a stream network was created by using the DEM and a streamflow accumulation process in the ArcSWAT application. The 1,436-mi^2 domain of the SWAT watershed model extends about 2 mi downstream from Canyon Dam. Ninety-three subbasins were created by using the elevation data and the user-selected subbasin outlets on the stream network (fig. 3). The model subbasins define model output locations and are used to generate HRUs for model simulations and calibration. Many of the subbasin outlets were selected on the basis of their proximity to USGS streamflow-gaging stations and to the upper Guadalupe River inlet to Canyon Lake. A slope raster, which is used in HRU generation, also was created from the elevation models and classified into five categories: less than or equal to 5 percent, greater than 5 percent to 10 percent, greater than 10 percent to 30 percent, greater than 30 percent to 60 percent, and greater than 60 percent (fig. 4).

Soils data used for HRU generation were obtained from the Soil Survey Geographic (SSURGO) database (Natural Resources Conservation Service, 2011a). The SSURGO database was selected because it is the highest resolution soils product available that can be input to a SWAT model with minimal data processing. Some processing of the SSURGO data was required because ArcSWAT is developed for using the lower resolution State Soil and Geographic Survey (STATSGO) database (Natural Resources Conservation Service, 2011b). An ArcMap tool developed by Sheshukov and others (2009) was used to process the SSURGO database into a modified STATSGO format that is readable by ArcSWAT. The processing of the SSURGO data maintains the resolution of the data. One of the more important database attributes assigned to a soil by the NRCS is the hydrogroup, which is the infiltration rate of a soil (high, moderate, low, and very low) and is used to determine the CN of an HRU (fig. 5) (Natural Resources Conservation Service, 2011b).

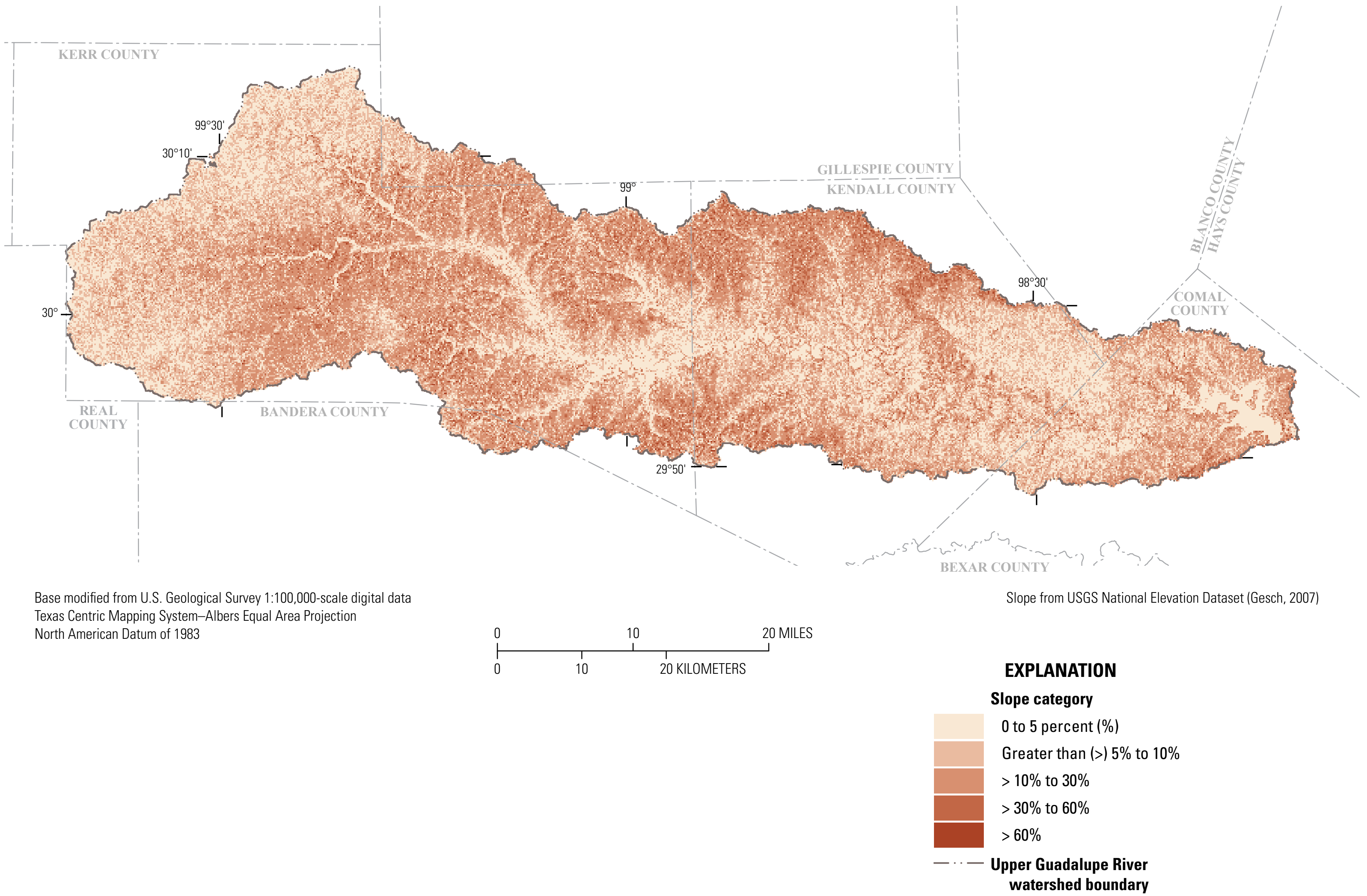
Land-cover data used to generate the HRUs were obtained from two sources: the National Land Cover Dataset (NLCD) 2006 (Fry and others, 2011) (fig. 6) and the Texas Ecological Systems Dataset (TESD) (German and others, 2009). The NLCD 2006 was selected because its land-cover classifications can be directly input to a SWAT model for HRU generation. The NLCD 2006 was used in the initial model runs to develop the HRUs and calibrate the model, and the TESD was used during the brush-management simulations to delineate areas where ashe juniper could be replaced with grasslands in the NLCD 2006. In general, the inherent model properties for forest land-cover categories, including those that might contain ashe juniper, account for less runoff, more canopy interception of rainfall, and more evapotranspiration than range categories. The parameter values associated with these model properties vary by HRU and are too numerous to reproduce in this report (on file at the USGS office in Austin, Tex., and available upon request). The model generated 6,357 HRUs as a result of intersecting the 93 model subbasins (fig. 3), 5 slope categories, soils data, and land-cover data.

USGS streamflow-gaging station locations for the study area and mean daily streamflow data for 1995–2010 were obtained from the USGS National Water Information System (NWIS) Web interface (U.S. Geological Survey, 2011). There are 11 USGS streamflow-gaging stations in the study area that recorded streamflow during the simulation period (fig. 2, table 1). The upper Guadalupe River watershed model was calibrated with streamflow data recorded continuously at USGS streamflow-gaging station 08167500 Guadalupe River near Spring Branch, Tex. (hereinafter the Guadalupe River near Spring Branch gage) (site 37, fig. 2, table 1), for 1995–2010. The streamflow data collected at the Guadalupe River near Spring Branch station were chosen for model calibration because there are no structures or hydraulic modifications near the station—including, but not limited to, dams, flood-control structures, retention basins, and changes to channel



Base modified from U.S. Geological Survey 1:100,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

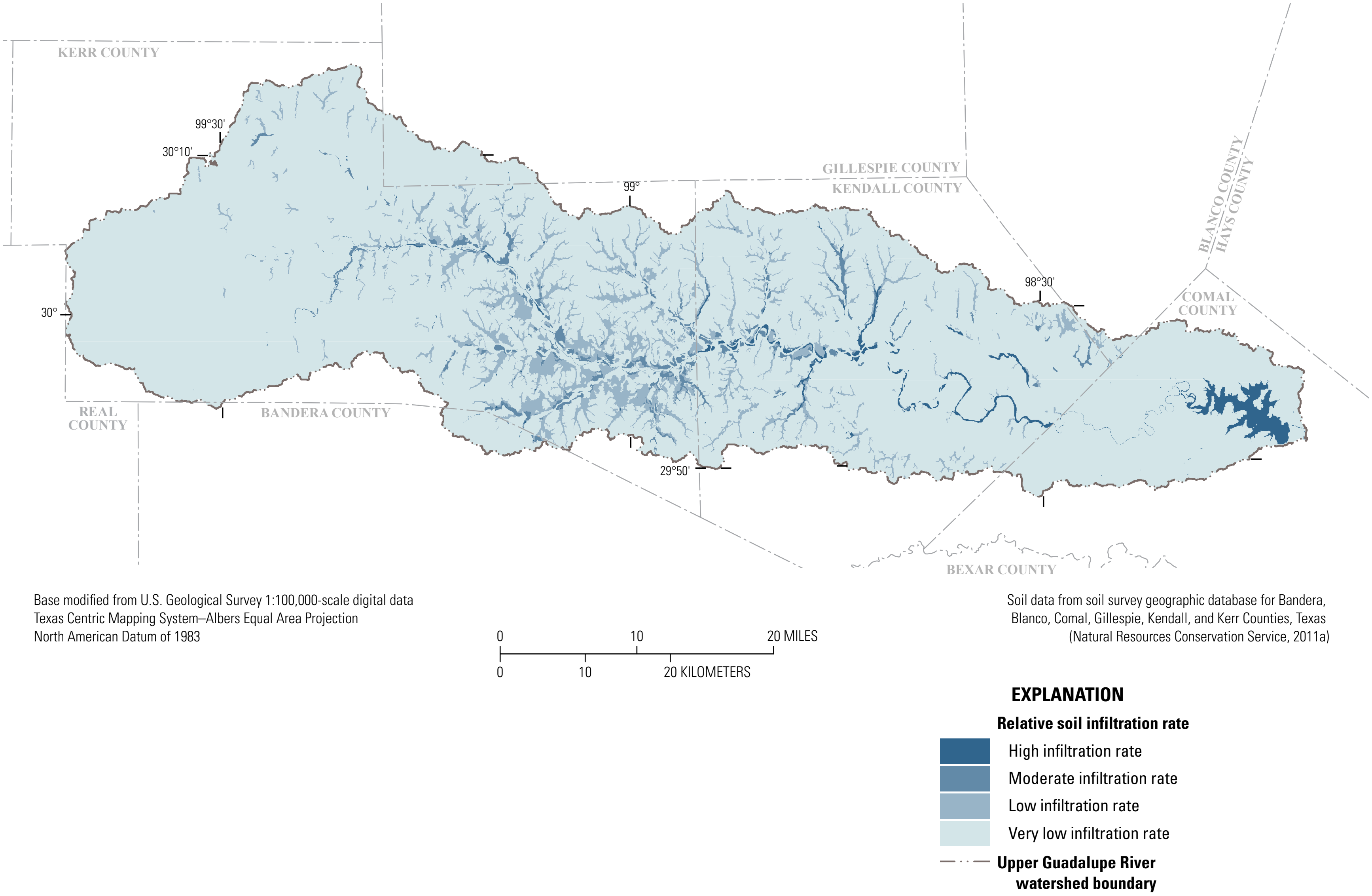
Figure 3. Subbasin delineation for the upper Guadalupe River watershed model, south-central Texas.



Base modified from U.S. Geological Survey 1:100,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

Slope from USGS National Elevation Dataset (Gesch, 2007)

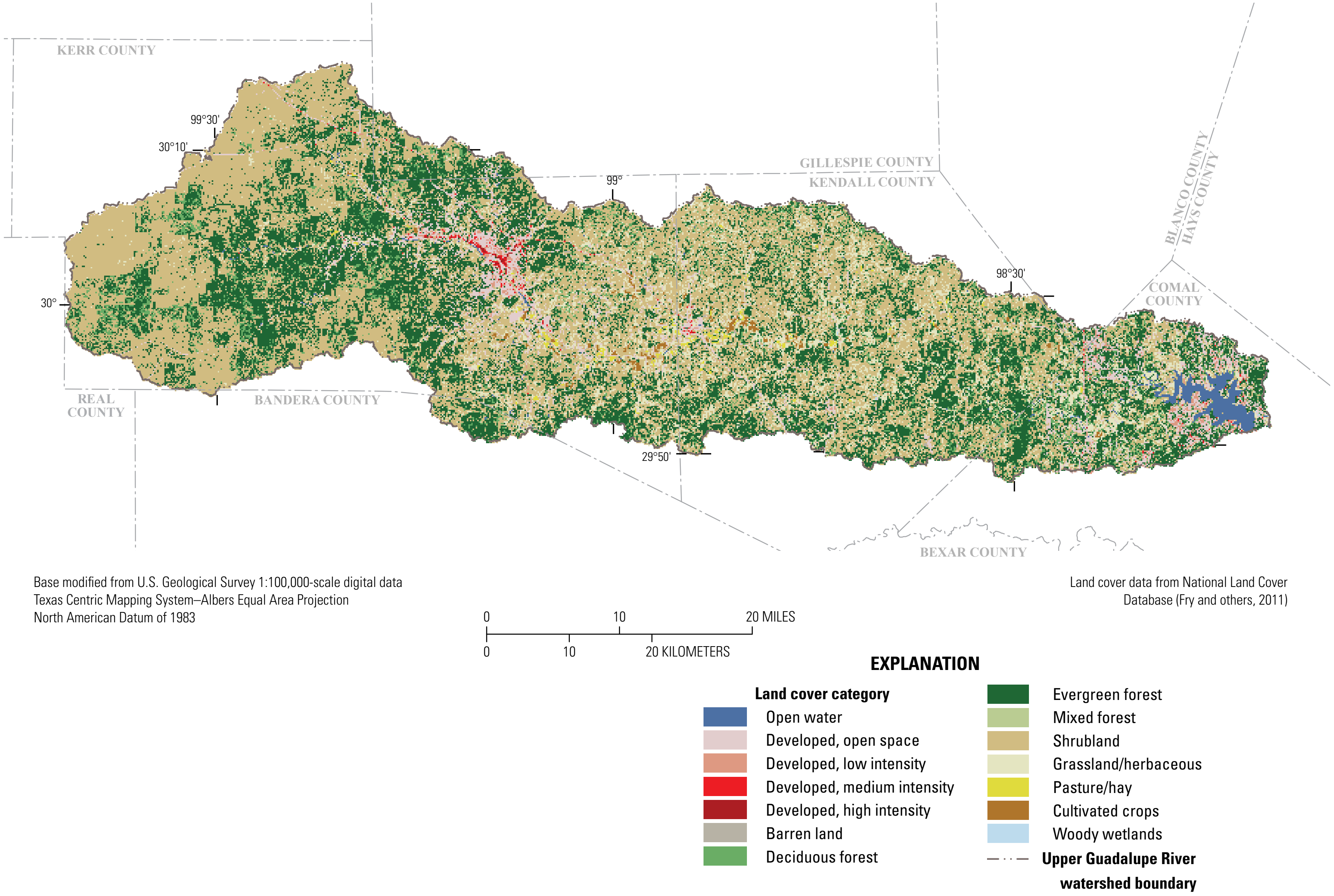
Figure 4. Slope categories used for the upper Guadalupe River watershed model, south-central Texas.



Base modified from U.S. Geological Survey 1:100,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

Soil data from soil survey geographic database for Bandera, Blanco, Comal, Gillespie, Kendall, and Kerr Counties, Texas (Natural Resources Conservation Service, 2011a)

Figure 5. Relative soil infiltration rates in the upper Guadalupe River watershed, south-central Texas.



Base modified from U.S. Geological Survey 1:100,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

Land cover data from National Land Cover Database (Fry and others, 2011)

Figure 6. National Land Cover Database 2006 land-cover categories in the upper Guadalupe River watershed, south-central Texas.

geometry—that might affect streamflows and the contributing drainage area (1,315 mi^2) of the station is more than 91 percent of the total watershed area. Minimum monthly streamflow at the Guadalupe River near Spring Branch station for 1995–2010 was 4.85 cubic feet per second (ft^3/s) in July 2009, maximum monthly streamflow was 10,534 ft^3/s in July 2002, mean monthly streamflow was 505 ft^3/s, and median monthly streamflow was 224 ft^3/s (U.S. Geological Survey, 2011).

National Weather Service (NWS) station locations and precipitation and air temperature data for 1980–2010 were obtained from the National Climatic Data Center (2011a, 2011b). The model was run using the 1980–1994 meteorological data and the ending conditions within the model (vegetation, soil moisture conditions, shallow groundwater levels, and so on) from that 15-year simulation were used as the initial conditions in the model for the 1995–2010 simulations. Total daily precipitation, daily maximum temperature, and daily minimum temperature were the data used to drive the model. Additional sites and precipitation data were obtained from the NWIS Web interface (U.S. Geological Survey, 2011). The SWAT watershed model automatically selected the 28 nearest rain gages and 8 temperature gages for use in the simulations (fig. 2, table 1).

Model Calibration

Hydrology of the upper Guadalupe River watershed model was manually calibrated. Manual hydrologic calibration of a SWAT model consisted of adjusting process-related parameter values to minimize the differences between simulated and measured streamflows at a USGS streamflow-gaging station. Parameter values can vary within a given uncertainty range defined in the SWAT tool input and output file documentation (Neitsch and others, 2011b). Model performance is evaluated with several criteria for goodness of fit (for example, calibration metrics): the percent bias (PBIAS) of simulated streamflow to measured streamflow, the coefficient of determination (R^2) of the linear regression, and the Nash–Sutcliffe coefficient of model efficiency (NSE) (Nash and Sutcliffe, 1970).

To evaluate the ability of a model to produce an unbiased estimate of the streamflow component of the mass balance for an entire simulation, the PBIAS statistic was used and is calculated by

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)} \qquad (1)$$

where

Y_i^{obs} is the measured streamflow at the i^{th} time step; and

Y_i^{sim} is the simulated streamflow at the i^{th} time step.

The total number of time steps is indicated by n. The PBIAS statistic can be positive or negative. The closer to 0 the PBIAS value is, the more equally balanced are the overpredictions and the underpredictions of streamflow for the period being evaluated. A negative PBIAS value indicates generally that a model is overpredicting streamflow, whereas a positive value indicates underprediction. PBIAS values between 0 and plus or minus (+/-) 10 percent indicate a “very good” model simulation, values between +/-10 and +/-15 percent indicate a “good” model simulation, and values between +/-15 and +/-25 percent indicate a “satisfactory” model simulation (Moriasi and others, 2007). These are the ranges that were used to evaluate the model calibration.

The R^2 value, which measures how well the simulated and measured regression lines approach an ideal linear regression, ranges from 0 to 1, with a value of 0 indicating no correlation and a value of 1 indicating that the simulated values equal the corresponding measured values. Gassman and others (2007) used 0.5 as a satisfactory fit for R^2 values for all time steps to compare results across various SWAT applications.

The NSE assesses the ability of a model to correctly simulate streamflow during periods when recorded streamflow deviates greatly from the measured mean monthly streamflow. The NSE is calculated by

$$\mathrm{NSE} = 1 - \left[\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2 / \sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2\right] \qquad (2)$$

where

Y^{mean} is the measured mean monthly streamflow (other variables were previously defined).

The NSE can range from negative infinity to 1. An NSE of 1 indicates a perfect fit between simulated and measured data. An NSE of 0 indicates that the model predictions are as accurate as the mean of the measured data, and an NSE of less than 0 indicates that the measured mean is a better predictor than the model (Nash and Sutcliffe, 1970).

A recent review of SWAT applications throughout the world, including many in Texas, shows monthly NSE values ranging from 0.30 to greater than 0.95 (Gassman and others, 2007). Moriasi and others (2007) proposed that the performance of a model is considered to be “very good” if the monthly NSE is greater than or equal to 0.75, “good” if the monthly NSE is greater than or equal to 0.65 and less than 0.75, “satisfactory” if the monthly NSE is greater than or equal to 0.5 and less than 0.65, and “unsatisfactory” if the monthly NSE is less than 0.5. Gassman and others (2007) used NSE values of greater than or equal to 0.5 as indicative of satisfactory fit for all time steps to compare results across various SWAT applications. The NSE model-performance criteria proposed by Moriasi and others (2007) were used to evaluate the model calibration.

Table 2 shows the process-related parameter values that were adjusted to calibrate the simulated watershed hydrology. The default parameter values, which are described in detail in Neitsch and others (2011a), were used for the remaining parameter values. Also, forest and range categories were

Table 2. Summary of the calibrated values for selected process-related parameters for the Soil and Water Assessment Tool watershed model of the upper Guadalupe River watershed, south-central Texas, 1995–2010.

[mm, millimeters; mm/hour, millimeters per hour; --, unitless value; SWAT, Soil and Water Assessment Tool; *, a variable model subbasin or HRU number is contained in input file name; **, value varies by HRU and was therefore increased or decreased by a percent or constant value; %, percent; calibration parameters for open-water land cover in .mgt and .hru files were not changed from default values]

Parameter	Description (units)	SWAT input file location	Calibrated parameter value	Default parameter value
ALPHA_BF	Base-flow recession constant (days)	*.gw	0.15	0.048
CANMX	Maximum canopy storage (mm)	*.hru	+20	**
CH_K2	Effective hydraulic conductivity in main channel alluvium (mm/hour)	*.rte	13	0
CN2	Initial SCS curve number (--)	*.mgt	All Range and Forest categories decreased by 7%	**
GW_DELAY	Groundwater delay time (days)	*.gw	15	30
GW_REVAP	Represents water movement from the shallow aquifer to the root zone (--)	*.gw	0.2	0.02
GWQMN	Threshold depth for water in the shallow aquifer for return flow to occur (mm)	*.gw	60	0
RCHRG_DP	Deep aquifer percolation factor (--)	*.gw	0.46	0
REVAPMN	Threshold depth for water in the shallow aquifer for percolation to the deep aquifer to occur (mm)	*.gw	0	1
SURLAG	Surface runoff lag coefficient (--)	.bsn	1	4

varied in an equitable way so as to maintain the relative parameter differences between the two categories. In other words, forest categories generally produced less runoff, had higher canopy interception of rainfall, and higher evapotranspiration rates than range categories in the model. Permitted surface-water withdrawals (water rights) (Texas Commission on Environmental Quality, 2012) and discharges for municipal, industrial, and agricultural purposes (U.S. Environmental Protection Agency, 2012) were evaluated but not included in the model calibration because they are each an order of magnitude less than the average annual flow volumes at the calibration gage. Current (2012) permitted annual withdrawals in the watershed upstream from Guadalupe River near Spring Branch gage used in the calibration (less than 30,000 acre-ft) are minimal compared to the average annual water yields at the calibration streamflow-gaging station (about 366,000 acre-ft for 1995–2010). The PBIAS for the monthly hydrologic calibration using data collected at the Guadalupe River near Spring Branch gage for 1995–2010 was -5 (overprediction), monthly R^2 was 0.91, and monthly NSE was 0.85 (fig. 7, table 3). These calibration metric values indicate a very good fit between the simulated and measured monthly streamflow values. Minimum simulated monthly streamflow was 11 ft^3/s in November 2008, maximum simulated monthly streamflow was 12,950 ft^3/s in July 2002, mean simulated monthly streamflow was 531 ft^3/s, and median simulated monthly streamflow was 171 ft^3/s. Finally, although the model performance was primarily evaluated on a monthly time step, the daily and annual calibration metrics were calculated as a secondary evaluation of model performance. As expected, there was variability in the NSE values based on temporal resolution. The daily NSE was 0.72, and the annual NSE was 0.90, which indicate a good fit and very good fit between the simulated and measured daily and annual streamflow values, respectively.

The calibration results of the upper Guadalupe River watershed model are similar to those of other SWAT watershed model applications in Texas watersheds of similar size. A study of an approximately 1,900-mi^2 part of the Trinity River watershed in north Texas (Srinivasan and others, 1998) reported monthly NSE values of 0.87 and 0.84. A modeling effort completed in the Bosque River watershed in central Texas obtained a monthly NSE value of 0.89 for an approximately 1,150-mi^2 watershed (Santhi and others, 2001). Moon and others (2004) reported monthly NSE values of 0.78 and 0.82 for the approximately 1,000-mi^2 Cedar Creek watershed in northeast Texas. A modeling effort in the approximately 1,750-mi^2 West Fork watershed of Trinity River watershed in northeast Texas obtained monthly NSE values of 0.12 and 0.72 (Santhi and others, 2006). A SWAT watershed model application to the approximately 1,750-mi^2 Lake Travis part of the Colorado River watershed in central Texas (Anchor QEA, LLC and Parsons Corporation, 2009) reported monthly NSE values of 0.47 and 0.82. Finally, Afinowicz and others (2005) reported a daily NSE of 0.05 and monthly NSE of 0.50 for a model of the approximately 140-mi^2 North Fork Guadalupe River watershed, which is in the western part of the upper Guadalupe River watershed in south-central Texas.

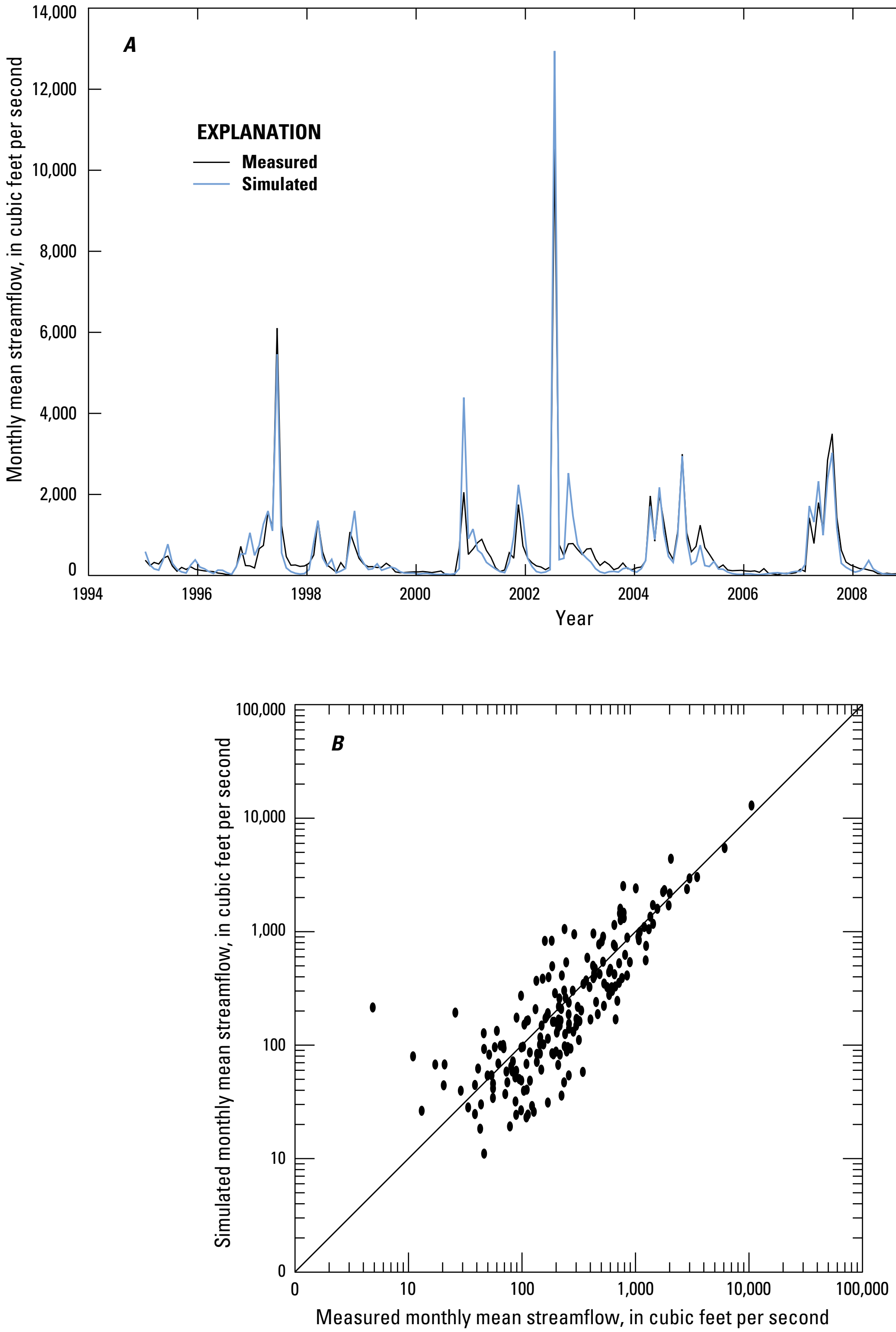


Figure 7. Calibration plots of the *A*, temporal distribution and *B*, relation of simulated monthly streamflow and measured monthly streamflow at U.S. Geological Survey streamflow-gaging station 08167500 Guadalupe River near Spring Branch, Texas, 1995–2010. Calibration metrics: Percent bias (PBIAS) of -5, monthly coefficient of determination (R^2) was 0.91, and monthly Nash–Sutcliffe coefficient of model efficiency (NSE) of 0.85.

Table 3. Hydrologic calibration results for the Soil and Water Assessment Tool watershed model of the upper Guadalupe River watershed at U.S. Geological Survey streamflow-gaging station 08167500 Guadalupe River near Spring Branch, Texas, 1995–2010.

[min, minimum; max, maximum; ft^3/s, cubic feet per second; calibration parameters for open-water land cover in .mgt and .hru files were not changed from default values]

Calibration time step	Percent bias (PBIAS)	Coefficient of determination (R^2)	Nash–Sutcliffe coefficient of model efficiency (NSE)	Simulation				Measured			
				Min streamflow (ft^3/s)	Max streamflow (ft^3/s)	Mean streamflow (ft^3/s)	Median streamflow (ft^3/s)	Min streamflow (ft^3/s)	Max streamflow (ft^3/s)	Mean streamflow (ft^3/s)	Median streamflow (ft^3/s)
Daily	-5%	0.83	0.72	8	87,227	531	161	0	69,400	506	197
Monthly	-5%	.91	.85	11	12,950	531	171	5	10,534	505	224
Annual	-5%	.91	.90	51	1,654	531	378	76	1,312	506	353

Model Limitations

Errors in the model calibration can be classified as systematic or measurement errors (Raines, 1996) and are represented in the model calibration metrics. Systematic errors are those that reflect the model's inability to perfectly represent the hydrologic processes of the watershed. As a result of these types of errors, there are limits to how well model parameters and equations can replicate the complex physical properties of streamflow processes, which can affect the accuracy of model calibration.

Measurement errors are those that are introduced as a result of inaccurate or missing data. The measurement errors that most likely affected the performance of the upper Guadalupe River watershed model were as follows: the spatial distribution of the land-cover data did not change over time; the model was calibrated by using data from one streamflow-gaging station; permitted water withdrawal amounts were not included; and point measurements of precipitation data were distributed in space across the model domain. The model simulations for this study did not consider changes in the spatial distribution of land cover over time, which might alter runoff calculations (Strauch and Linard, 2009). In an attempt to compensate, simulations were limited to a 16-year time period around the data compilation date of the NLCD 2006. The inherent assumption is that watershed land cover did not appreciably change during this period of time.

The model was calibrated to streamflow data collected at a single gage because the majority of the other gages in the watershed were near structures or hydraulic modifications that affected streamflows on a local level (for example, flood-control dams). As a result, there is more uncertainty related to subbasin streamflow than there would be if the watershed calibration included data collected at multiple streamflow-gaging stations. Because permitted withdrawals in the watershed upstream from the calibration streamflow-gaging station are only about 8 percent of average annual flow measured at the calibration streamflow-gaging station (Guadalupe River near Spring Branch gage), any uncertainty as a result of not including permitted withdrawals in the model is likely minimal.

In SWAT, precipitation data are used as direct input to subbasins from the closest precipitation gage instead of applying a gradient based on interpolation between gages, which might affect model calibration if gages are distributed unevenly throughout the basin (Strauch and Linard, 2009). There is an observed gradient of average annual precipitation increase from west to east in the watershed. Additionally, precipitation in the study area can be isolated to a small area surrounding a precipitation gage, and the model might overpredict the amount of rainfall-produced runoff from an HRU. Conversely, a substantially higher amount of precipitation might occur between gages than was recorded at the gages, and thus, the model might underpredict rainfall-produced runoff from an HRU. Finally, the trajectory and speed of a storm affect watershed response, and storm paths might not be represented by the recorded data, which may also affect model calibration.

Simulation of Streamflow and the Effects of Brush Management on Water Yields

The 93 model subbasins of the calibrated watershed model (fig. 3) were aggregated into 23 brush-management subbasins for the simulation of the effects of brush management on water yields (fig. 8). Twenty-three modified land-cover input datasets were created to estimate the potential for brush management in each of the 23 subbasins. HRUs were generated in the model by using the modified land-cover input datasets. Water-yield changes were calculated as the difference between the water-yield and streamflow outputs from the brush-management simulation and the water-yield and streamflow outputs from the unmodified model simulation.

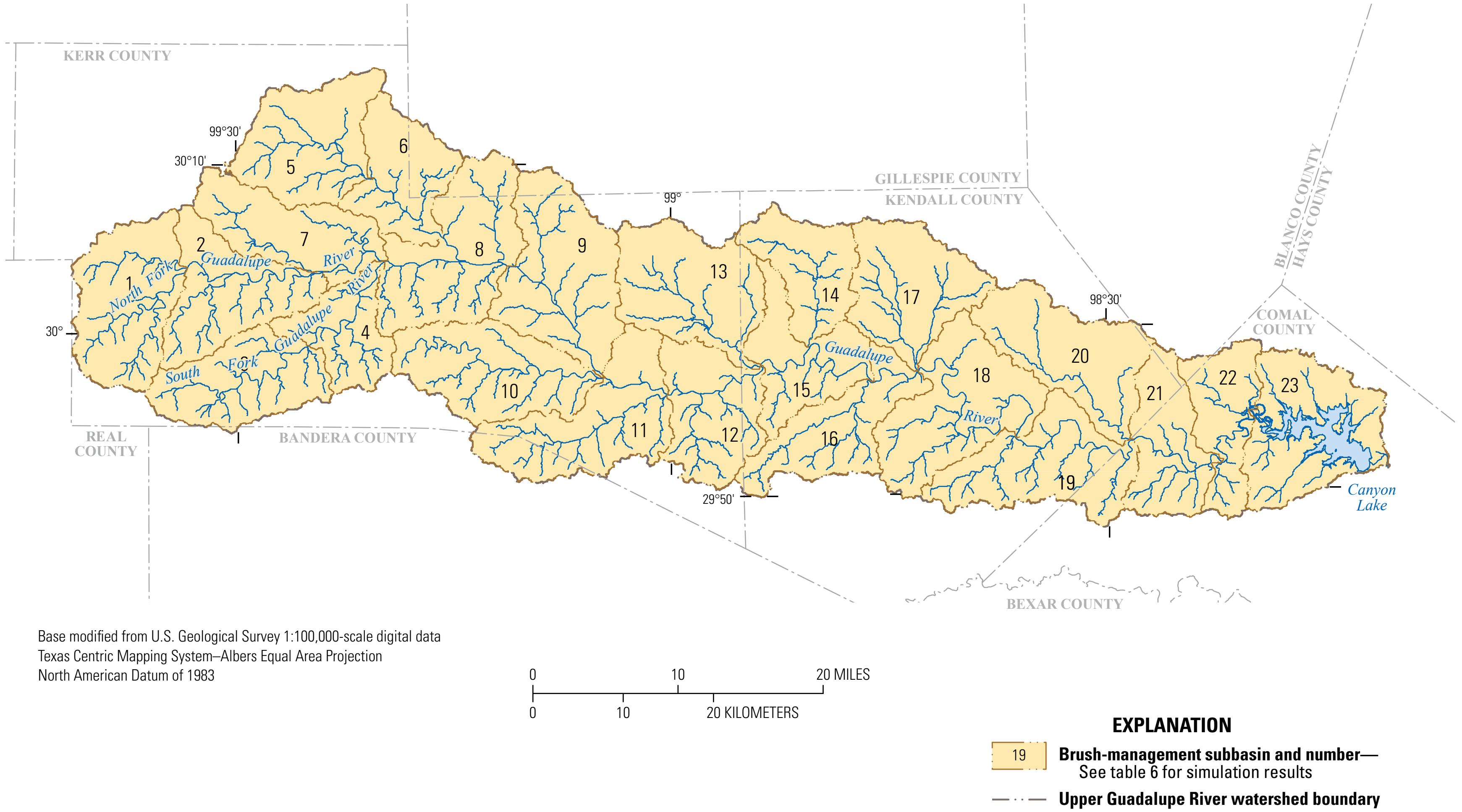


Figure 8. Delineation of the brush-management subbasins for the upper Guadalupe River watershed model brush-management simulations, south-central Texas.

Simulation Methods

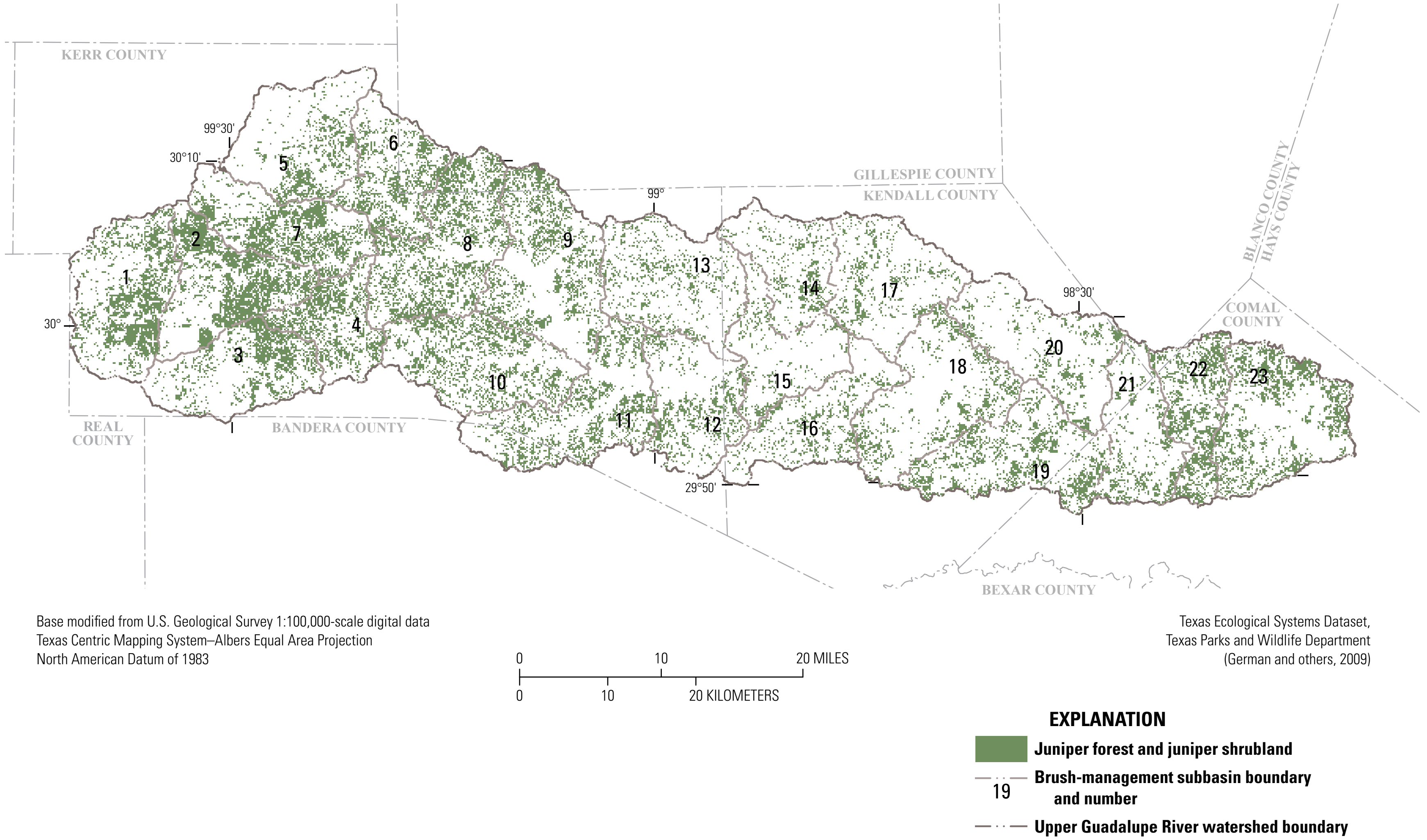
The NLCD 2006 was modified to simulate ashe juniper replacement with grasslands in each of the 23 brush-management subbasins. The NLCD 2006 categories chosen to represent areas that might contain ashe juniper were Deciduous Forest, Evergreen Forest, Mixed Forest, and Shrubland. Because the NLCD 2006 categories do not explicitly identify vegetation types, a second dataset with more detailed categories of vegetation was required to isolate ashe juniper in each subbasin. The TESD was selected for this task because it has 43 ecological-system categories in the study area, and ashe juniper was identified as present in 13 of them (German and others, 2009). The 13 categories with ashe juniper were evaluated on the basis of the TESD ecological-system descriptions. Categories in which ashe juniper was listed as one of the dominant vegetation types in the category description, except those that were also classified as riparian zone or steep slope, were selected for use in the brush-management simulations. The categories dominated by ashe juniper that were also classified as riparian zone or steep slope were not removed for the brush-management simulations because, as explained by Afinowicz and others (2005), field applications are unlikely to replace ashe juniper with grasslands in these areas. Ultimately, there were three TESD categories chosen to represent the location of ashe juniper to be replaced with grassland for the brush-management simulations. The “common names” for the TESD categories are Edwards Plateau: Ashe Juniper Motte and Woodland; Edwards Plateau: Ashe Juniper and Live Oak Shrubland; and Native Invasive: Ashe Juniper Shrubland. The two TESD land-cover class names for these categories are Juniper Forest and Juniper Shrubland, and they are in about 23 percent of the upper Guadalupe River watershed study area (fig. 9; German and others, 2009).

To simulate removal of the ashe juniper, the raster calculator in ArcMap 9.3.1 was used to change the NLCD 2006 values from Deciduous Forest, Evergreen Forest, Mixed Forest, and Shrubland to Grassland/Herbaceous if the cells in the NLCD 2006 raster intersected cells in the TESD raster that represented Juniper Forest and Juniper Shrubland. This method is similar to the removal methods used in the previous Texas State Soil and Water Conservation Board (TSSWCB) feasibility studies (Bednarz and others, 2000) and the maximum removal scenarios used by Afinowicz and others (2005). Twenty-three modified land-cover input datasets were created, each with the ashe juniper removed from just one subbasin. Table 4 shows the areal coverage of unmodified NLCD 2006 land-cover categories for each brush-management subbasin in the upper Guadalupe River watershed. Table 5 shows the areal coverage of the NLCD land-cover categories after modification of the NLCD 2006 for each brush-management subbasin that was used in the 23 brush-management simulations.

For each of the 23 brush-management simulations, the HRUs were generated in the model by using the modified land-cover input dataset that corresponded with the simulated subbasin, and the model parameters associated with land cover were automatically modified by the modeling software accordingly (Neitsch and others, 2011b). Following each brush-management simulation, the model output was compared to the unmodified model simulation output to calculate the change in water yield per acre of ashe juniper replaced with grasslands. Change in water yield was calculated in two ways: (1) as the difference in annual water yield to the reach in a given brush-management subbasin (calculated by using the model output parameter WYLD in the output.sub file, which is the net amount of water that leaves a given subbasin and contributes to streamflow in the reach via surface runoff, lateral flow, and groundwater discharge over a given time step) and (2) as the difference in annual water yield from the subbasin to Canyon Lake based on the difference in annual streamflow at the combined subbasin outlets of model subbasins 58 and 59 (brush-management subbasin 22; calculated by using the model output parameter FLOW_OUT in the output.rch file, which is the average streamflow out of a reach over a given time step) (figs. 3 and 9). The difference in annual streamflow (the second method) represents the simulated change in water yield to Canyon Lake for each of the brush-management subbasins except subbasin 23. Subbasin 23 is downstream from subbasin 22, and water yield in subbasin 23 (the first method) was considered direct drainage to Canyon Lake.

Simulation Results

Annual water yields increased in each of the 23 brush-management simulations (table 6). The increases in average annual water yields in the subbasins ranged from 6,370 to 119,000 gallons per acre of ashe juniper replaced with grasslands with an average of 38,800 gallons per acre of ashe juniper replaced with grasslands. The increases in average annual water yields from upstream subbasins to Canyon Lake ranged from 6,640 to 72,700 gallons per acre of ashe juniper replaced with grasslands with an average of 34,700 gallons per acre of ashe juniper replaced with grasslands. These values are within the range of water-yield increases calculated for the eight previous TSSWCB brush-management feasibility studies (Bednarz and others, 2000). In some cases, the increase in streamflow volume was less than the increase in water yield because of simulated stream-channel transmission losses that occurred between each subbasin and Canyon Lake. There is uncertainty in the absolute values of water-yield increases from brush-management practices that is represented by the calculated uncertainty within the model (the calibration metrics). Given the distributed approach to model calibration (unique HRU parameter values were treated equally regardless of the location of the HRU in the watershed), there is probably less uncertainty in the relative differences in subbasin sensitivities to simulated brush management than the absolute values. Finally, simulations did not consider potential ashe juniper re-growth as this was beyond the scope of the study.



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Texas Ecological Systems Dataset,
Texas Parks and Wildlife Department
(German and others, 2009)

Figure 9. Texas Ecological Systems Dataset land-cover classes used for brush-management simulations for the upper Guadalupe River watershed model, south-central Texas.

Table 4. Percent areal coverage of unmodified National Land Cover Database 2006 land-cover categories for the brush-management subbasins used for the upper Guadalupe River watershed model brush-management simulations, south-central Texas.

[Because of rounding differences, percent areal coverages for a subbasin might not add to 100 percent]

Brush-management subbasin (fig. 8)	Subbasin area (acres)	Open water (percent)	Developed, open space (percent)	Developed, low intensity (percent)	Developed, medium intensity (percent)	Developed, high intensity (percent)	Barren land (percent)	Deciduous forest (percent)
1	45,369	0	0.243	0.022	0.015	0	0.012	9.62
2	42,270	.243	.029	.028	.005	0	0	10.3
3	45,138	.024	1.01	.004	0	0	0	6.28
4	37,717	.320	2.46	.096	.006	.004	0	7.15
5	50,379	.065	1.67	.345	.103	0	0	2.90
6	49,977	.175	4.02	.473	.182	0	.010	6.83
7	44,312	.054	.482	.034	.004	0	0	5.99
8	45,287	.442	9.48	1.35	.540	.142	0	8.55
9	27,095	.559	18.7	3.99	1.81	.861	.056	2.89
10	39,486	.224	6.02	.250	.044	0	.004	3.56
11	31,697	.434	5.81	.194	.057	.015	.096	5.57
12	36,106	.090	4.86	.047	0	0	.027	4.10
13	50,332	.099	5.15	.458	.125	0	.102	6.26
14	41,192	.038	.663	.013	0	0	.028	6.20
15	52,853	.047	5.58	.561	.180	.063	.242	3.48
16	46,664	.068	2.97	.052	.005	0	.139	5.57
17	47,758	.113	1.16	.006	.003	0	.107	7.40
18	35,501	.054	2.08	.071	0	0	0	5.53
19	30,848	.210	1.12	.085	.020	.002	.162	10.4
20	34,697	.019	.833	.019	0	0	.037	8.77
21	28,626	.286	9.04	1.47	.190	.018	.045	13.6
22	30,873	.673	13.2	2.66	.131	.004	.040	12.7
23	24,614	16.5	15.3	5.44	.462	.090	.306	7.65

Brush-management subbasin (fig. 8)	Evergreen forest (percent)	Mixed forest (percent)	Shrubland (percent)	Grassland or herbaceous (percent)	Pasture or hay (percent)	Cultivated crops (percent)	Woody wetlands (percent)
1	17.6	0.006	72.0	0.404	0	0	0
2	34.3	.038	53.5	1.53	0	0	.004
3	31.2	.067	61.0	.379	0	0	.006
4	47.0	.051	41.4	1.55	0	0	.007
5	14.7	.023	78.9	1.19	.054	0	.007
6	34.3	.003	51.2	2.58	.073	.160	.008
7	32.7	.020	58.5	2.07	.185	.000	.009
8	46.7	.019	28.9	3.71	.151	.094	.007
9	31.6	0	32.3	6.32	.677	.230	.035
10	34.8	.047	48.3	6.01	.121	.550	.002
11	30.9	.031	44.3	11.1	.856	.621	.045
12	28.5	.005	42.2	16.4	1.349	2.41	.013
13	15.6	.007	56.9	13.9	.490	.834	.043
14	19.5	0	58.2	14.7	.337	.262	.015
15	19.7	0	46.4	18.7	2.04	3.04	.059
16	37.5	.012	37.5	15.3	.381	.453	.033
17	22.4	.007	50.1	18.2	.320	.177	.040
18	30.9	.017	44.4	16.7	.169	.109	.026
19	39.6	.005	37.6	10.8	.000	.000	.061
20	27.7	0	48.0	13.8	.441	.347	.054
21	27.5	0	29.3	17.7	.114	.633	.238
22	35.7	0	23.5	11.2	.060	0	.199
23	28.6	0	16.0	9.50	.029	0	.149

Table 5. Percent areal coverage of modified National Land Cover Database 2006 land-cover categories for the brush-management subbasins used for the upper Guadalupe River watershed model brush-management simulations, south-central Texas.

[Because of rounding differences, percent areal coverages for a subbasin might not add to 100 percent]

Brush-management subbasin (fig. 8)	Subbasin area (acres)	Open water	Developed, open space (percent)	Developed, low intensity (percent)	Developed, medium intensity (percent)	Developed, high intensity (percent)	Barren land (percent)	Deciduous forest (percent)
1	45,369	0	0.243	0.022	0.015	0	0.012	4.17
2	42,270	.243	.029	.028	.005	0	0	3.75
3	45,138	.024	1.01	.004	0	0	0	3.18
4	37,717	.320	2.46	.096	.006	.004	0	3.95
5	50,379	.065	1.67	.345	.103	0	0	1.52
6	49,977	.175	4.02	.473	.182	0	.010	3.32
7	44,312	.054	.482	.034	.004	0	0	2.15
8	45,287	.442	9.48	1.35	.540	.142	0	4.82
9	27,095	.559	18.7	3.99	1.81	.861	.056	1.82
10	39,486	.224	6.02	.250	.044	0	.004	1.81
11	31,697	.434	5.81	.194	.057	.015	.096	3.56
12	36,106	.090	4.86	.047	.000	0	.027	2.94
13	50,332	.099	5.15	.458	.125	0	.102	5.65
14	41,192	.038	.663	.013	0	0	.028	5.63
15	52,853	.047	5.58	.561	.180	.063	.242	3.00
16	46,664	.068	2.97	.052	.005	0	.139	4.44
17	47,758	.113	1.16	.006	.003	0	.107	6.59
18	35,501	.054	2.08	.071	0	0	0	4.43
19	30,848	.210	1.12	.085	.020	.002	.162	7.34
20	34,697	.019	.833	.019	.000	0	.037	7.44
21	28,626	.286	9.04	1.47	.190	.018	.045	10.9
22	30,873	.673	13.2	2.66	.131	.004	.040	6.34
23	24,614	16.5	15.3	5.44	.462	.090	.306	4.50

Brush-management subbasin (fig. 8)	Evergreen forest (percent)	Mixed forest (percent)	Shrubland (percent)	Grassland or herbaceous (percent)	Pasture or hay (percent)	Cultivated crops (percent)	Woody wetlands (percent)
1	8.13	0.005	57.3	30.1	0	0	0
2	12.4	.024	41.7	41.8	0	0	.004
3	17.5	.058	53.5	24.7	0	0	.006
4	24.5	.037	31.3	37.4	0	0	.007
5	8.83	.018	71.2	16.2	.054	0	.007
6	20.0	.002	41.2	30.4	.073	.160	.008
7	14.3	.019	45.9	36.8	.185	0	.009
8	27.3	.016	20.3	35.4	.151	.094	.007
9	20.2	0	24.4	26.7	.677	.230	.035
10	23.8	.043	37.1	30.0	.121	.550	.002
11	20.9	.023	34.2	33.2	.856	.621	.045
12	21.1	.005	33.5	33.8	1.35	2.41	.013
13	12.9	.007	48.9	25.3	.490	.834	.043
14	16.1	0	49.8	27.2	.337	.262	.015
15	16.6	0	41.5	27.1	2.04	3.04	.059
16	30.8	.011	31.7	29.0	.381	.453	.033
17	18.2	.007	44.0	29.3	.320	.177	.040
18	23.5	.015	39.6	29.9	.169	.109	.026
19	24.9	.003	31.0	35.1	0	0	.061
20	21.8	0	44.1	25.0	.441	.347	.054
21	18.4	0	25.3	33.3	.114	.633	.238
22	16.3	0	15.1	45.4	.060	0	.199
23	14.6	0	11.9	30.7	.029	0	.149

Table 6. Effects of brush management on water yields simulated by the Soil and Water Assessment Tool watershed model of the upper Guadalupe River watershed, south-central Texas, 1995–2010.

[gal, gallons; --, value is not applicable because the flow from the subbasin is direct drainage to the lake]

Brush-management subbasin (fig. 8)	Subbasin area (acres)	Total area modified for brush management simulation (acres)	Percent of subbasin modified	Increased average annual water yield to the subbasin reach per acre of ashe juniper replaced with grasslands (gal)[1]	Increased average annual water yield to Canyon Lake per acre of ashe juniper replaced with grasslands from each subbasin (gal)[2]
1	45,369	13,475	30	21,000	18,200
2	42,270	17,035	40	29,200	28,500
3	45,138	10,969	24	20,600	18,600
4	37,717	13,540	36	20,600	19,800
5	50,379	7,557	15	17,800	17,600
6	49,977	13,894	28	20,200	19,900
7	44,312	15,376	35	22,800	22,500
8	45,287	14,356	32	42,100	41,600
9	27,095	5,527	20	71,500	70,600
10	39,486	9,477	24	45,800	45,700
11	31,697	7,005	22	6,370	6,640
12	36,106	6,282	17	61,900	60,800
13	50,332	5,738	11	27,400	27,300
14	41,192	5,149	13	15,200	15,000
15	52,853	4,493	9	18,700	19,100
16	46,664	6,393	14	33,200	33,200
17	47,758	5,301	11	29,300	29,200
18	35,501	4,686	13	56,000	54,700
19	30,848	7,496	24	73,300	72,700
20	34,697	3,886	11	58,500	58,500
21	28,626	4,494	16	45,400	44,700
22	30,873	10,558	34	38,100	38,100
23	24,614	5,218	21	119,000	--

[1] The difference in annual water yield to the reach in a given brush-management subbasin is calculated by using the model output parameter WYLD in the output.sub file, which is the net amount of water that leaves a given subbasin and contributes to streamflow in the reach via surface runoff, lateral flow, and groundwater discharge over a given time step.

[2] The difference in annual water yield from the brush-management subbasin to Canyon Lake, based on the difference in annual streamflow to Canyon Lake, which is calculated by using the model output parameter FLOW_OUT in the output.rch file for the combined subbasin outlets of model subbasins 58 and 59 (brush-management subbasin 22); FLOW_OUT is the average streamflow at a subbasin outlet over a given time step.

In general, the highest water-yield increases were calculated for the brush-management subbasins in the eastern half of the watershed (7 of the top 10), which is the part of the watershed that receives the most precipitation. Previous studies indicated that brush management had the greatest effect on water yields in areas that received at least 18 inches of annual precipitation (Thurow, 1998); Bednarz and others (2000) reported a correlation between water-yield increase and precipitation ($R^2 = 0.75$). Investigation of the correlation between the amount of precipitation and watershed response to brush management is beyond the scope of this study. Future studies are needed to determine if there are correlations between water-yield increases and precipitation, watershed attributes, or simulation methodology.

Summary

The U.S. Geological Survey (USGS), in cooperation with the Texas State Soil and Water Conservation Board (TSSWCB) and the Upper Guadalupe River Authority (UGRA), developed a Soil and Water Assessment Tool (SWAT) watershed model of the upper Guadalupe River watershed in south-central Texas to simulate the effects of brush management on water yields in the watershed for 1995–2010. In general, brush management is the removal of woody plants for the purpose of (1) creating desired plant communities, (2) controlling erosion, (3) improving water quality, (4) enhancing streamflow or water yield, (5) improving fish and wildlife habitat, (6) improving forage accessibility, and (7) managing fuel loads. Ashe juniper (*Juniperus ashei*) is a woody plant species that has spread beyond its historical range in the understories of small stands of prairie oak (motte) and in sheltered canyons in Texas because of overgrazing and fire suppression, and studies of the water use of ashe juniper indicate that they might intercept and use more water than do native grasses. As a result, the replacement of ashe juniper with grasslands is used in south-central Texas in an effort to increase water yields.

The SWAT watershed model simulations were done to quantify the possible change in water yield of individual subbasins in the upper Guadalupe River watershed as a result of the replacement of ashe juniper with grasslands. The evaluation of possible reductions in water-yield increases as ashe juniper re-growth occurs was beyond the scope of the study. Resource managers, such as TSSWCB and UGRA, plan to use the model results as a tool to guide brush management in the upper Guadalupe River watershed.

A monthly calibration of the SWAT model, which consisted of adjusting process-related parameter values to minimize the differences between simulated and measured streamflows, was done by using streamflow data collected at the USGS streamflow-gaging station 08167500 Guadalupe River near Spring Branch, Tex., for 1995–2010. Forest categories generally produced less runoff, had higher canopy interception of rainfall, and higher evapotranspiration rates than range categories in the model. Simulated monthly streamflow was a “very good” fit to measured monthly data (percent bias of -5, coefficient of determination of 0.91, and a Nash–Sutcliffe coefficient of model efficiency of 0.85). Model calibration was limited by systematic and measurement errors, which are represented in the model calibration metrics. These errors included, but were not limited to, the spatial distribution of the land-cover data did not change over time; the model was calibrated by using data from one streamflow-gaging station; permitted water withdrawal amounts were not included; and point measurements of precipitation data were distributed in space across the model domain.

The calibrated SWAT watershed model was used to complete brush-management simulations. The National Land Cover Dataset 2006, which was the land-cover dataset used to develop the watershed model, was modified to simulate ashe juniper replacement with grasslands in each of the 23 brush-management subbasins, and the model parameters associated with land cover were automatically modified by the modeling software accordingly. A simulation was completed for each of the 23 brush-management subbasins, and the results indicated that brush management in the watershed would increase water yields. The simulated increases in average annual water yields in the subbasins (calculated by using the model output parameter WYLD in the output.sub file, which is the net amount of water that leaves a given subbasin and contributes to streamflow in the reach via surface runoff, lateral flow, and groundwater discharge over a given time step) ranged from 6,370 to 119,000 gallons per acre of ashe juniper replaced with grasslands with an average of 38,800 gallons per acre. The simulated increases in average annual water yields from upstream subbasins to Canyon Lake (calculated by using the model output parameter FLOW_OUT in the output.rch file, which is the average streamflow out of a reach over a given time step) ranged from 6,640 to 72,700 gallons per acre of ashe juniper replaced with grasslands with an average of 34,700 gallons. The highest simulated water-yield increases occurred in the eastern half of the watershed, which receives more rainfall than does the western half of the watershed. Future studies are needed to determine if there are correlations between water-yield increases and precipitation, watershed attributes, or simulation methodology.

References Cited

Afinowicz, J.D., Munster, C.L., and Wilcox, B.P., 2005, Modeling effects of brush management on the rangeland water budget—Edwards Plateau, Texas: Journal of the American Water Resources Association, v. 41, no. 1, p. 181–193.

Anchor QEA, LLC, and Parsons Corporation, 2009, Colorado River environmental models phase 2—Lake Travis final report: Lower Colorado River Authority report, 973 p., accessed February 21, 2012, at http://www.lcra.org/water/quality/models.html.

Archer, Steve, 1989, Have southern Texas savannas been converted to woodlands in recent history: The American Naturalist, v. 134, no. 4, p. 545–561.

Archer, Steve, Schimel, D.S., and Holland, E.A., 1995, Mechanisms of shrubland expansion—Land use, climate or CO2?: Climate Change, v. 29, no. 1, p. 91–99.

Archer, Steve, Scifres, Charles, Bassham, C.R., and Maggio, Robert, 1988, Autogenic succession in a subtropical savanna—Conversion of grassland to thorn woodland: Ecological Monographs, v. 58, no. 2, p. 111–127.

Arnold, J.G., Srinivasan, Raghavan, Muttiah, R.S., and Williams, J.R., 1998, Large area hydrologic modeling and assessment part I—Model development: Journal of the American Water Resources Association, v. 34, no. 1, p. 73–89.

Arrington, D.A., Conner, Richard, Dugas, William, Hejl, Sallie, Magness, Dawn, Muttiah, Ranjan, Olenick, Keith, Rosenthal, Wes, Srinivasan, Raghavan, Winemiller, K.O., Zinn, Michele, Wilkins, Neal, Amonett, Carl, Bednarz, Steve, Dybala, Tim, Griffith, Rebecca, and Jarboe, Hank, 2002, Ecosystem and wildlife implications of brush—Management systems designed to improve water yield: Texas Water Resources Institute Report TR–201, 320 p.

Asquith, W.H., and Roussel, M.C., 2003, Atlas of interoccurrence intervals of selected thresholds of daily precipitation in Texas: U.S. Geological Survey Water-Resources Investigations Report 03–4281, 204 p. (Also available at http://pubs.usgs.gov/wri/wri03-4281/.)

Baxter, David, 2009, Selah, Bamberger Ranch Preserve—Leopold/Lone Star Land Steward Award: Texas Wildlife Magazine, accessed April 9, 2011, at http://brp-journal.blogspot.com/2009/09/selah-bamberger-ranch-preserve.html.

Bednarz, S.T., Dybala, Tim, Muttiah, R.S., Rosenthal, Wes, and Dugas, W.A., 2000, Brush management/water yield feasibility studies for eight watersheds in Texas: Texas Water Resources Institute Report TR–182, p. 1–21.

Brown, D.S., and Raines, T.H., 2002, Simulation of flow and effects of best-management practices in the Upper Seco Creek Basin, south-central Texas, 1991–98: U.S. Geological Survey Water-Resources Investigations Report 02–4249, 22 p. (Also available at http://pubs.usgs.gov/wri/wri02-4249/.)

Cotter, A.S., Chaubey, Indrajeet, Costello, T.A., Soerens, T.S., and Nelson, M.A., 2003, Water quality model output uncertainty as affected by spatial resolution of input data: Journal of the American Water Resources Association, v. 39, no. 4, p. 977–986.

Di Luzio, Mauro, Arnold, J.G., and Srinivasan, Raghavan, 2005, Effect of GIS data quality on small watershed streamflow and sediment simulations: Hydrological Processes, v. 19, no. 3, p. 629–650.

Dugas, W.A., Hicks, R.A., and Wright, Phillip, 1998, Effect of removal of *Juniperus ashei* on evapo-transpiration and runoff in the Seco Creek watershed: Water Resources Research, v. 34, no. 6, p. 1499–1506.

Fry, J.A., Xian, George, Jin, Suming, Dewitz, J.A., Homer, C.G., Yang, Limin, Barnes, C.A., Herold, N.D., and Wickham, J.D., 2011, Completion of the 2006 National Land Cover Database for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 77, no. 9, p. 858–864.

Fuhlendorf, S.D., Smeins, F.E., and Grant, W.E., 1996, Simulation of a fire-sensitive ecological threshold—A case study of Ashe juniper on the Edwards Plateau of Texas, USA: Ecological Modelling, v. 90, no. 3, p. 245–255.

Fuhlendorf, S.D., Smeins, F.E., and Taylor, C.A., Jr., 1997, Browsing and tree size influences on Ashe juniper understory: Journal of Range Management, v. 50, p. 507–512.

Garcia, A.M., 2009, Simulation of water quality in the Tull Creek and West Neck Creek watersheds, Currituck Sound Basin, North Carolina and Virginia: U.S. Geological Survey Scientific Investigations Report 2008–5226, 22 p.

Gassman, P.W., Reyes, M.R., Green, C.H., and Arnold, J.G., 2007, The Soil and Water Assessment Tool—Historical development, applications, and future research directions: Transactions of the American Society of Agricultural and Biological Engineers, v. 50, no. 4, p. 1211–1250.

German, Duane, Diamond, D.D., Elliott, L.F., Treuer–Kuehn, Amie, Ludeke, Kim, and Scott, Jim, 2009, Texas Ecological Systems project phase 1 interpretive booklet: Austin, Texas Parks and Wildlife Department, accessed February 10, 2011, at http://www.tpwd.state.tx.us/landwater/land/maps/gis/tescp/index.phtml.

Gesch, Dean, 2007, The National Elevation Dataset, *in* Maune, David, ed., Digital elevation model technologies and applications—The DEM users manual (2d ed.): Bethesda, Md., American Society for Photogrammetry and Remote Sensing, p. 99–118.

Gesch, Dean, Oimoen, Michael, Greenlee, Susan, Nelson, Charles, Steuck, Michael, and Tyler, Dean, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, p. 5–11.

Humphrey, R.R., 1958, The desert grassland—A history of vegetational change and an analysis of causes: The Botanical Review, v. 24, no. 4, p. 193–252.

Huxman, T.E., Wilcox, B.P., Breshears, D.D., Scott, R.L., Snyder, K.A., Small, E.E., Hultine, Kevin, Pockman, W.T., and Jackson, R.B., 2005, Ecological implications of woody plant encroachment: Ecology, v. 86, p. 308–319.

Katz, B.G., DeHan, R.S., Hirten, J.J., and Catches, J.S., 1997, Interactions between ground water and surface water in the Suwanee River Basin, Florida: Journal of the American Water Resources Association, v. 33, p. 1237–1254.

Larkin, T.J., and Bomar, G.W., 1983, Climatic atlas of Texas: Texas Department of Water Resources, Limited Printing Report LP–192, 151 p.

Lemberg, B.J., Mjelde, J.W., Conner, J.R., Griffin, R.C., Rosenthal, W.D., and Stuth, J.W., 2002, An interdisciplinary approach to valuing water from brush control: Journal of the American Water Resources Association, v. 38, p. 409–422.

Moon, Jongpil, Srinivasan, Raghavan, and Jacobs, J.H., 2004, Stream flow estimation using spatially distributed rainfall in the Trinity River Basin, Texas: Transactions of the American Society of Agricultural Engineering, v. 47, no. 5, p. 1445–1451.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Binger, R.L., Harmel, R.D., and Veith., T.L., 2007, Model evaluation guidelines for systematic quantification of accuracy in watershed simulations: Transactions of the American Society of Agricultural and Biological Engineers, v. 50, no. 3, p. 885–900.

Musgrove, MaryLynn, Stern, L.A., and Banner, J.L., 2010, Springwater geochemistry at Honey Creek State Natural Area, central Texas—Implications for surface water and groundwater interaction in a karst aquifer: Journal of Hydrology, v. 388, p. 144–156.

Nash, J.E., and Sutcliffe, J.V., 1970, River flow forecasting through conceptual models, part I—A discussion of principles: Journal of Hydrology, v. 10, no. 3, p. 282–290.

National Climatic Data Center, 2011a, Cooperative Stations Index: National Oceanic and Atmospheric Administration, National Environmental Satellite, Data and Information Service, accessed January 12, 2011, at http://www.ncdc.noaa.gov/oa/climate/surfaceinventories.html.

National Climatic Data Center, 2011b, Daily Surface Data: National Oceanic and Atmospheric Administration, National Environmental Satellite, Data and Information Service, accessed January 13, 2011, at http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter?datasetabbv=SOD&countryabbv=&georegionabbv=.

Natural Resources Conservation Service, 2009, National Conservation Practice Standard Code 314: U.S. Department of Agriculture, 4 p.

Natural Resources Conservation Service, 2011a, Soil Survey Geographic (SSURGO) Database for Texas: accessed January 10, 2011, at http://datagateway.nrcs.usda.gov.

Natural Resources Conservation Service, 2011b, State Soil and Geographic Survey (STATSGO) Database for Texas: accessed January 10, 2011, at http://datagateway.nrcs.usda.gov.

Natural Resources Conservation Service, 2012, Watershed boundary dataset: U.S. Department of Agriculture, accessed February 17, 2012, at http://www.ncgc.nrcs.usda.gov/products/datasets/Watershed/.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., and Williams, J.R., 2011a, Soil and Water Assessment Tool theoretical documentation, version 2009: Temple, Tex., Grassland, Soil and Water Research Laboratory, Agricultural Research Service. (Also available at http://twri.tamu.edu/reports/2011/tr406.pdf.)

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., and Williams, J.R., 2011b, Soil and Water Assessment Tool input/output file documentation, version 2009: Temple, Tex., Grassland, Soil and Water Research Laboratory, Agricultural Research Service. (Also available at http://ssl.tamu.edu/media/19754/swat-io-2009.pdf.)

Owens, M.K., 1996, The roll of leaf and canopy-level gas exchange in the replacement of *Quercus virginiana* (Fagaceae) by *Juniperus ashei* (Cupressaceae) in semiarid savannas: American Journal of Botany, v. 83, p. 617–623.

Raines, T.H., 1996, Simulation of storm peaks and storm volumes for selected subbasins in the West Fork Trinity River Basin, Texas, water years 1993–94: U.S. Geological Survey Water-Resources Investigations Report 96–4110, 41 p.

Saleh, Ali, Wu, Hong, Brown, C.S., Teagarden, F.M., McWilliams, S.M., Hauck, L.M., and Millican, J.S., 2009, Effect of brush control on evapotranspiration in the North Concho River watershed using the eddy covariance technique: Journal of Soil and Water Conservation, v. 64, no. 5, p. 336–349.

Santhi, Chinnasamy, Arnold, J.G., Williams, J.R., Dugas, W.A., Srinivasan, Raghavan, and Hauck, L.M., 2001, Validation of the SWAT model on a large river basin with point and nonpoint sources: Journal of the American Water Resources Association, v. 37, no. 5, p. 1169–1188.

Santhi, Chinnasamy, Srinivasan, Raghavan, Arnold, J.G., and Williams, J.R., 2006, A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas: Environmental Modeling and Software, v. 21, p. 1141–1157.

Sheshukov, A.Y., Daggupati, Prasad, Lee, M.C., and Douglas–Mankin, Kyle, 2009, ArcMap tool for pre-processing the SSURGO Soil Database for ArcSWAT, in Proceedings of the 5th International SWAT Conference: Texas Water Resources Institute Report TR–356, p. 116–123.

Smeins, F.E., 1980, Natural role of fire on the Edwards Plateau, *in* Proceedings, Prescribed Burning of the Edwards Plateau, College Station, Tex.: Texas Agriculture Extension Service, p. 4–16.

Soil Conservation Service, 1986, Urban hydrology for small watersheds: U.S. Department of Agriculture, Conservation Engineering Division, Technical Release 55 [variously paged].

Srinivasan, Raghavan, Ramanarayanan, T.S., Arnold, J.G., and Bednarz, S.T., 1998, Large area hydrologic modeling and assessment, part II—Model application: Journal of the American Water Resources Association, v. 34, no. 1, p. 91–101.

Strauch, K.R., and Linard, J.I., 2009, Streamflow simulations and percolation estimates using the Soil and Water Assessment Tool for selected basins in north-central Nebraska, 1940–2005: U.S. Geological Survey, Scientific Investigations Report 2009–5075, 20 p.

Texas Commission on Environmental Quality, 2012, Water Rights Database: accessed March 2011 at http://www.tceq.texas.gov/permitting/water_supply/water_rights/wr_databases.html.

Texas State Soil and Water Conservation Board, 2011, Water Supply Enhancement Program: accessed January 15, 2011, at http://www.tsswcb.texas.gov/en/brushcontrol.

Thurow, T.L., 1998, Assessment of brush management as a strategy for enhancing water yield, *in* Proceedings of the 25th Water for Texas Conference: College Station, Tex., Texas Water Resources Institute, Texas A&M University System, p. 191–198.

Thurow, T.L., Blackburn, W.H., Warren, S.D., and Taylor, C.A., 1987, Rainfall interception by midgrass, shortgrass, and live oak mottes: Journal of Range Management, v. 40, no. 5, p. 455–460.

U.S. Army Corps of Engineers, 2011, Canyon Lake home page: accessed September 12, 2011, at http://www.swf-wc.usace.army.mil/canyon/index.asp.

U.S. Census Bureau, 2011, 2010 population finder: accessed September 12, 2011, at http://www.census.gov/popfinder/.

U.S. Environmental Protection Agency, 2012, Permit compliance system: accessed March 2011 at http://www.epa.gov/enviro/facts/pcs/index.html.

U.S. Geological Survey, 2006, Geologic database of Texas: accessed February 10, 2011, at http://tin.er.usgs.gov/geology/state/state.php.

U.S. Geological Survey, 2011, USGS water data for Texas: National Water Information System Web interface: accessed January 31, 2011, at http://waterdata.usgs.gov/tx/nwis/nwis.

Van Auken, O.W., 2000, Shrub invasions of North American semiarid grasslands: Annual Review of Ecology and Systematics, v. 31, p. 197–215.

Wilcox, B.P., 2002, Shrub control and streamflow on rangelands—A process-based viewpoint: Journal of Range Management, v. 55, p. 318–326.

Wilcox, B.P., and Thurow, T.L., 2006, Emerging issues in rangeland ecohydrology—Vegetation change and the water cycle: Rangeland Ecology and Management, v. 59, p. 220–224.

Winchell, Michael, Srinivasan, Raghavan, Di Luzio, Mauro, and Arnold, Jeffrey, 2010, ArcSWAT interface for SWAT2009 user's guide: Temple, Tex., Blackland Research Center, Texas Agricultural Experiment Station. (Also available at http://swatmodel.tamu.edu/software/arcswat.)

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water—A single resource: U.S. Geological Survey Circular 1139, 79 p.

Wu, X.B., Redeker, E.J., and Thurow, T.L., 2001, Vegetation and water yield dynamics in an Edwards Plateau watershed: Journal of Range Management, v. 54, p. 98–105.

Young, J.A., Evans, R.A., and East, D.A., 1984, Stem flow on western juniper (*Juniperus occidentalis*) trees: Weed Science, v. 32, p. 320–327.

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