Prepared in cooperation with the City of Lubbock and the Texas State Soil and Water Conservation Board

Simulation of Streamflow and the Effects of Brush Management on Water Yields in the Double Mountain Fork Brazos River Watershed, Western Texas, 1994–2013

Scientific Investigations Report 2016–5032

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

Front cover:

Background, Location is about 3 miles downstream from U.S. Highway 84 bridge over Double Mountain Fork Brazos River near Justiceburg, Texas, in Garza County.

Top, Location is about 5 miles downstream from Farm to Market Road 669 bridge over Double Mountain Fork Brazos River near Justiceburg, Texas, in Garza County.

Bottom, Location is about 11 miles downstream from Farm to Market Road 669 bridge over Double Mountain Fork Brazos River near Justiceburg, Texas, in Garza County.

Back cover:

Top, Location is about 9 miles downstream from Farm to Market Road 669 bridge over Double Mountain Fork Brazos River near Justiceburg, Texas, in Garza County.

Bottom, Location is about 8 miles downstream from Farm to Market Road 669 bridge over Double Mountain Fork Brazos River near Justiceburg, Texas, in Garza County.

All photographs were taken on August 4, 2015, by Neil Weems, City of Lubbock Water Utilities.

Simulation of Streamflow and the Effects of Brush Management on Water Yields in the Double Mountain Fork Brazos River Watershed, Western Texas, 1994–2013

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

Inch/Pound to International System of Units

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)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
acre-foot (acre-ft)	1,233	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)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to either the National Geodetic Vertical Datum of 1929 (NGVD 1929) or 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).

Elevation, as used in this report, refers to distance above the NAVD 88 except where noted.

Abbreviations

CN	Curve number
DEM	Digital elevation model
EMST	Ecological Mapping Systems of Texas
GIS	Geographic information system
HRU	Hydrologic response unit
NLCD	National Land Cover Database
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe coefficient of model efficiency
PBIAS	Percentage bias
R^2	Coefficient of determination
SWAT	Soil and Water Assessment Tool
TSSWCB	Texas State Soil and Water Conservation Board
USGS	U.S. Geological Survey
WSEP	Water Supply Enhancement Program

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Abstract

The U.S. Geological Survey, in cooperation with the City of Lubbock and the Texas State Soil and Water Conservation Board, developed and calibrated a Soil and Water Assessment Tool watershed model of the Double Mountain Fork Brazos River watershed in western Texas to simulate monthly mean streamflow and to evaluate the effects of brush management on water yields in the watershed, particularly to Lake Alan Henry, for calendar years 1994–2013. Model simulations were done to quantify the possible change in water yield of individual subbasins in the Double Mountain Fork Brazos River watershed as a result of the replacement of shrubland (brush) with grassland. The simulation results will serve as a tool for resource managers to guide brush-management efforts.

The model was calibrated from 1994 through 2008 and validated from 2009 through 2013 with streamflow data collected at the U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas (hereinafter referred to as the “Justiceburg gage”). Simulated monthly mean streamflow showed agreement with measured monthly mean streamflow for the 1994–2013 study period: the percentage bias was +6, the coefficient of determination was 0.73, and the Nash–Sutcliffe coefficient of model efficiency was 0.71.

The calibrated watershed model was used to perform brush-management simulations. The National Land Cover Database 2006, which was the land-cover data used to develop the watershed model, was modified to simulate shrubland replacement with grassland in each of the 35 model subbasins. After replacement of shrubland with grassland in areas with land slope less than 20 percent and excluding riparian areas, the modeled 20-year (1994 through 2013) water yields to Lake Alan Henry increased by 114,000 acre-feet or about 5,700 acre-feet per year. In terms of the increase in water yield per acre of shrubland replaced with grassland, the average annual increase in water yield was 17,300 gallons per acre. Within the modeled subbasins, the increase in average annual water yield ranged from 5,850 to 34,400 gallons per acre of shrubland replaced with grassland. Subbasins downstream from the Justiceburg gage had a higher average annual increase in water yield (21,700 gallons per acre) than subbasins upstream from the streamflow-gaging station (16,800 gallons per acre).

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 (2016) used in Texas (U.S. Department of Agriculture, Natural Resources Conservation Service, 2009; Texas State Soil and Water Conservation Board, 2014). Brush-management conservation practices (hereinafter referred to as “brush management”) generally include the removal of woody plants for many purposes including (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 (U.S. Department of Agriculture, 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 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).

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, 2014). As defined in the State Water Supply Enhancement Plan, “the statutory-defined purpose of the WSEP is to increase surface and groundwater through the selective control, removal, or reduction of noxious brush species, such as juniper, mesquite, saltcedar, or other phreatophytes that consume water to a degree that is detrimental to water conservation, and through the revegetation of land on which noxious brush has been controlled, removed, or reduced" (Texas State Soil and Water Conservation Board, 2014, p. 21).

Lake Alan Henry located in the Double Mountain Fork Brazos River watershed in western Texas is the water resource identified by the WSEP that could potentially receive increased inflow as a result of brush management. In an effort to effectively manage brush in the Double Mountain Fork Brazos River watershed upstream from Lake Alan Henry and evaluate potential increases in water yields to the lake, the U.S. Geological Survey (USGS), in cooperation with the City of Lubbock and the TSSWCB, developed a Soil and Water Assessment Tool (SWAT) (Arnold and others, 1998; Arnold and others, 2012) watershed model of the Double Mountain Fork Brazos River watershed to simulate the effects of the replacement of shrubland (brush) with grasslands and to estimate the effects of brush management on water yields to the lake. Simulation results will be used as part of a WSEP feasibility study to quantify possible water-yield changes in subbasins in the Double Mountain Fork Brazos River watershed as a result of brush management.

Watershed models that simulate surface and near-surface processes can provide insights into the possible effects of brush management on water yields. The SWAT was used previously in the TSSWCB brush-management feasibility studies for eight watersheds in Texas (Bednarz and others, 2000). The studies simulated average annual water-yield increases ranging from about 6,650 to about 172,000 gallons per acre (gal/acre) of simulated brush management.

Wu and others (2001) used the "Simulation of Production and Utilization of Rangelands" model (Wight and Skiles, 1987) to evaluate brush management in the Cusenbary Draw Basin in south-central Texas, and their simulations showed increased water yields for a variety of brush-management scenarios. The 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 in southern Texas using the "Hydrological Simulation Program—FORTRAN (HSPF)" simulated increased water yields immediately following brush management for several subbasins in the watershed (Brown and Raines, 2002).

Lemberg and others (2002) interfaced SWAT with the hydrologic-based phytomass growth simulation model (Stuth and others, 2003) to assess the effects of brush management on water yields in the Frio River Basin in south-central Texas. The simulations indicated brush management would result in increased water yields, but brush management was not cost effective at that time. Afinowicz and others (2005) showed water-yield increases for multiple brush-management scenarios 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 in south-central Texas. More recently, Bumgarner and Thompson (2012) simulated increases in average annual water yields using a SWAT model that ranged from 6,640 to 72,700 gal/acre for different scenarios where ashe juniper was replaced with grasslands in subbasins that drain to Canyon Lake in south-central Texas.

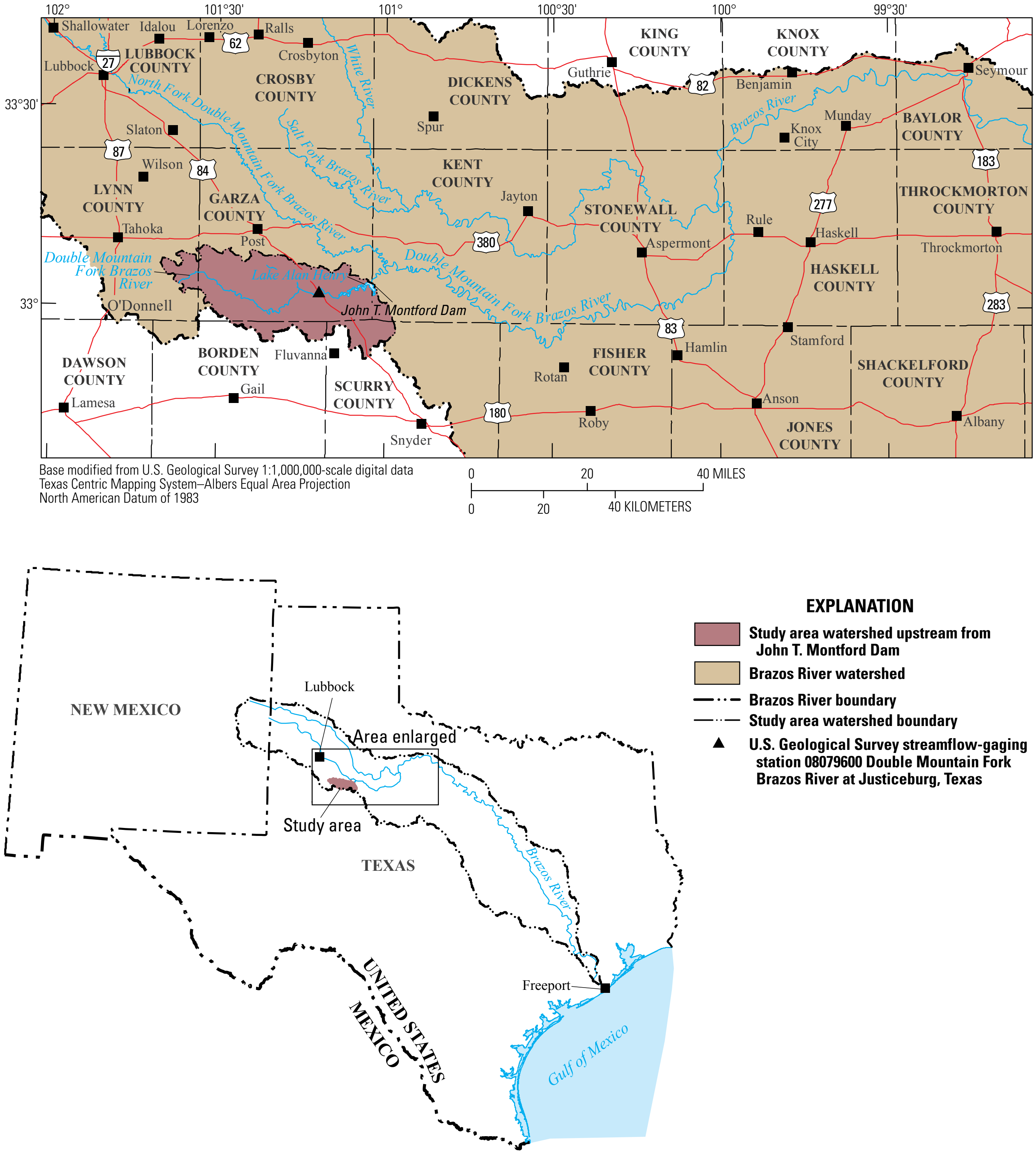
Purpose and Scope

This report documents the development, calibration, and validation of a SWAT watershed model of the Double Mountain Fork Brazos River watershed to simulate monthly mean streamflow and to evaluate the effects of brush management on water yields in the watershed, particularly to Lake Alan Henry, for calendar years 1994–2013. Model simulations were done to quantify the possible change in water yield of individual subbasins in the Double Mountain Fork Brazos River watershed as a result of the replacement of shrubland with grassland. Limitations of the model and model uncertainty are discussed. For this report, the term "brush" refers to land classified as shrubland, and the term "brush management" refers to the replacement of shrubland with grassland.

Description of the Double Mountain Fork Brazos River Watershed

The Brazos River extends about 1,050 miles (mi) from its source in eastern New Mexico to its mouth at the Gulf of Mexico near Freeport, Texas (fig. 1) (Brazos River Authority, 2015). The upper Brazos River Basin includes the Salt Fork Brazos River and the Double Mountain Fork Brazos River. The Salt Fork and the Double Mountain Fork Brazos Rivers join together to form the Brazos River northeast of Aspermont, Tex., in Stonewall County. The North Fork Double Mountain Fork Brazos River joins the Double Mountain Fork Brazos River in Kent County downstream from Lake Alan Henry, the main reservoir within the Double Mountain Fork Brazos River watershed.

Lake Alan Henry is owned and operated by the City of Lubbock and is considered a primary drinking water supply. Lake Alan Henry is impounded by the John T. Montford Dam that was constructed between 1991 and 1993. At conservation pool elevation (2,220 feet [ft] above the National Geodetic Vertical Datum of 1929), the lake has a capacity of about 115,937 acre-feet (acre-ft), a surface area of 4.5 mi^2, and about 95 mi of shoreline (City of Lubbock, 2015; Texas Water Development Board, 2016). Lake Alan Henry first reached conservation pool elevation around October 3, 2004 (Asquith and Vrabel, 2011). The contributing area to the lake is about 395 mi^2. The USGS streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Tex. (hereinafter referred to as the "Justiceburg gage"), provides real-time inflow data to Lake Alan Henry. The Justiceburg gage has been in continuous operation since December 1, 1961, and the contributing area to the Justiceburg gage is about 244 mi^2; therefore, approximately 62 percent of the contributing area to Lake Alan Henry is gaged for streamflow (figs. 1 and 2).



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

Figure 1. Location of the Double Mountain Fork Brazos River watershed study area, western Texas.

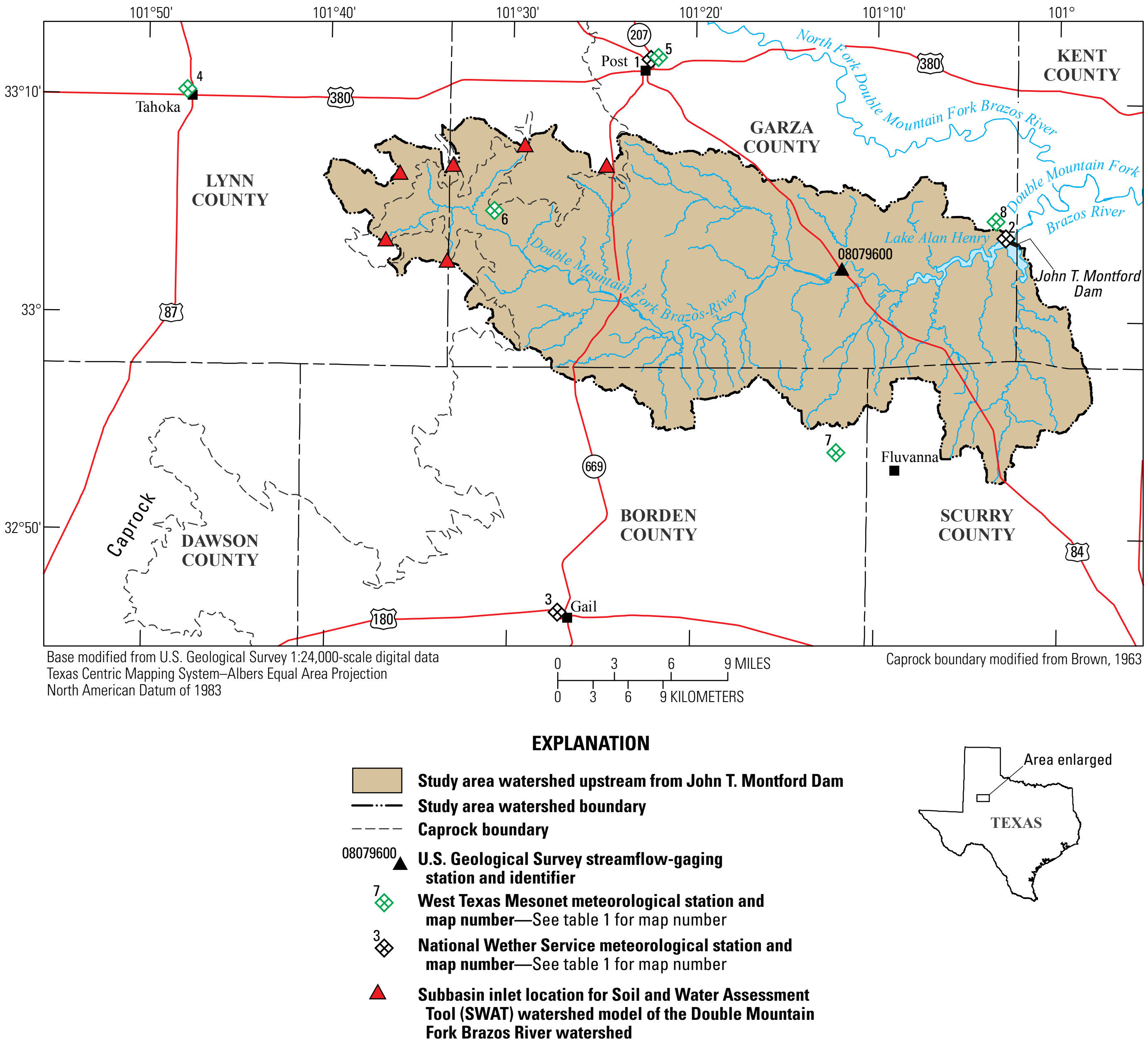


Figure 2. Location of U.S. Geological Survey streamflow-gaging station and National Weather Service and West Texas Mesonet meteorological stations providing data for the Double Mountain Fork Brazos River watershed model, western Texas.

The contributing area to the Lake Alan Henry study area is within the Low Rolling Plains climate division (National Oceanic and Atmospheric Administration, 2016; Texas Water Development Board, 2016). As calculated by data retrieved from the National Oceanic and Atmospheric Administration (2015a), average annual precipitation for calendar years 1901–2013 for the Low Rolling Plains was 22.84 inches (in.). The months of May and June accounted for 27.6 percent of the total amount of precipitation during this period. Precipitation events were also common during September and October with these 2 months accounting for 22.0 percent of the total amount of precipitation (National Oceanic and Atmospheric Administration, 2015a). Average daily temperature for calendar years 1901–2013 was 62.6 degrees Fahrenheit (ºF). Average daily minimum temperature was 49.5 ºF for the same period and ranged from 28.4 ºF in January to 70.5 ºF in July. Average daily maximum temperature was 75.7 ºF and ranged from 54.1 ºF in January to 95.8 ºF in July (National Oceanic and Atmospheric Administration, 2015a).

Soils in the watershed consist primarily of those belonging to hydrologic soil groups C and D, which are characterized by low and very low infiltration rates and cover 41.5 and 32.9 percent of the contributing area to Lake Alan Henry, respectively (U.S. Department of Agriculture, Natural Resources Conservation Service, 2007; Soil and Water Assessment Tool, 2015a). Type D soils in the watershed are characterized as having average clay, silt, and sand content (as percentage of soil weight) of 35.9, 31.2, and 29.9 percent, respectively, and type C soils with 22.8, 47.8, and 23.6 percent, respectively. Type B soils cover 20.8 percent of the watershed, and average clay, silt, and sand content is 22.8, 32.0, and 45.2 percent, respectively. Lastly, type A soils cover the least amount of area (4.8 percent), and average clay, silt, and sand content is 11.8, 10.3, and 78.0 percent, respectively. Type A soils have the highest infiltration rates and the lowest runoff potential, primarily because of their high sand content. Conversely, types C and D soils have lower sand content and higher clay and silt content and, therefore, higher runoff potential and lower infiltration rates.

Land cover in the watershed is dominated by shrubland and grassland, covering 45.8 and 42.1 percent of the study area watershed, respectively (Homer and others, 2015). Elevation in the watershed ranges from about 2,140 to 3,000 ft (Gesch, 2007), and land slopes vary from zero to greater than 40 percent.

Model Development

The SWAT watershed model is a process-based, semidistributed 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), a delineated watershed in SWAT is divided into subbasins, each identified by a single stream 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 parameter values uniquely defined for each HRU. The SWAT watershed model version used for this study was the SWAT2012.exe revision 622 (Soil and Water Assessment Tool, 2016).

At the beginning of model development, default values are assigned to the model parameters by the modeling software based on the unique HRU characteristics. The simulated streamflow and constituent loads simulated by SWAT are aggregated within their corresponding subbasins, are allocated to the subbasin stream reach, and exit a subbasin through outlet points on the stream network. The model accounts for in-stream processes, and streamflow and constituent fluxes are kinematically routed (Chow and others, 1988; Neitsch and others, 2011) downstream from upstream subbasins to the watershed outlet. Model output includes streamflow for any subbasin outlet, including the delineated watershed outlet. Model input data (such as land use, soil, slope, precipitation, and air temperature), user-specified model settings (such as slope classification settings and HRU definition thresholds), and parameter values determine the model that is developed. A complete description of the SWAT model and its simulated processes can be found in Neitsch and others (2011).

The hydrologic component of SWAT uses the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) (formerly the Soil Conservation Service) runoff curve-number (CN) equation (U.S. Department of Agriculture, 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, shrubland and forested land cover have lower CNs than grasslands and produce less runoff. Daily CN values were calculated in the model as a function of soil moisture as described by Arnold and others (2012).

The SWAT model can be executed from within a geographic information system (GIS), which incorporates spatially distributed data. For this study, ArcGIS 10.1, build 3143 (Esri, 2016) and the ArcGIS extension ArcSWAT version 2012.10_1.14 (Winchell and others, 2013) were used to execute SWAT. The model and simulations presented in this report can be replicated by following the steps described in the ArcSWAT user's manual (Winchell and others, 2013) and the user input model settings, data, and calibration specifications described in this report.

Model Input Data

Input data for the Double Mountain Fork Brazos River watershed model included spatial and temporal datasets. The spatial data consisted of land-surface elevation, soils, land cover, location of a streamflow-gaging station, and locations of 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 using the DEM and a streamflow accumulation process in the ArcSWAT application. The 408-mi^2 domain of the SWAT watershed model is defined by the dam that impounds Lake Alan Henry (fig. 1) and six user-defined inlet locations (figs. 2–3). The inlet locations are at or very near the top of a large escarpment capped with caliche referred to as the “caprock” (Cronin, 1969). Inflow at all six inlets was set to zero for the entire 20-year period of model calibration and validation (1994–2013) because the nearly-flat caprock was considered as effectively noncontributing.

Thirty-five subbasins were delineated using the elevation data and the user-selected subbasin (fig. 3) outlets on the stream network and were used to generate HRUs for model calibration and simulations. A single subbasin outlet was selected for calibration because of its proximity to the Justiceburg gage. Another subbasin outlet was selected at the John T. Montford Dam to represent the whole basin outlet. A slope raster, which was used in HRU generation, also was created from the elevation models and classified into three categories: (1) less than or equal to 5 percent, (2) greater than 5 percent to 10 percent, and (3) greater than 10 percent (fig. 4).

The Soil Survey Geographic Database from the U.S. Department of Agriculture NRCS was downloaded and used as the soils input data (Soil and Water Assessment Tool, 2015a). One of the more important database attributes assigned to a soil by the NRCS is the hydrologic soils group, which is used to represent the relative infiltration rate of a soil (high, moderate, low, and very low) and is used to determine the CN for estimating surface runoff from an HRU (fig. 5).

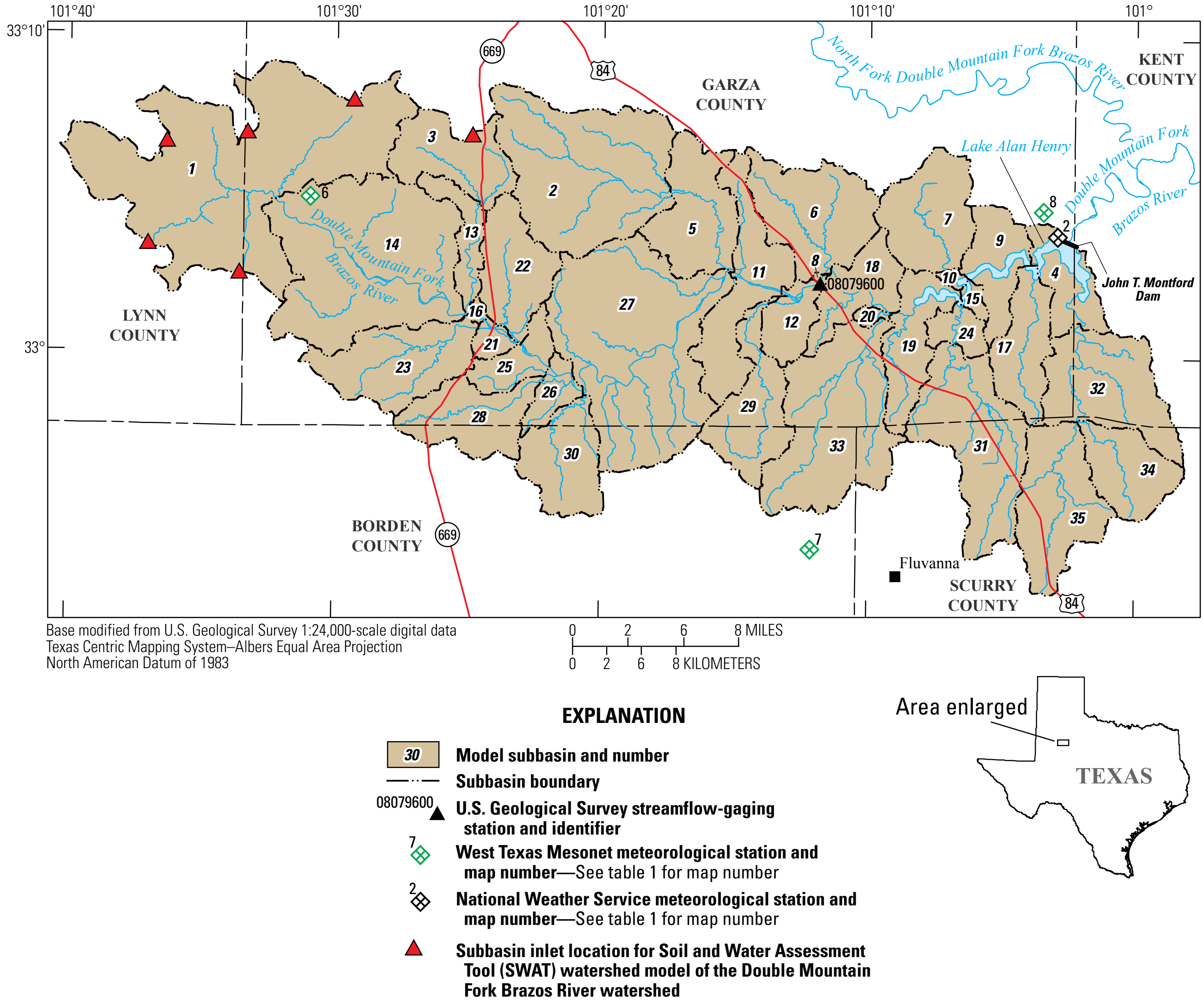
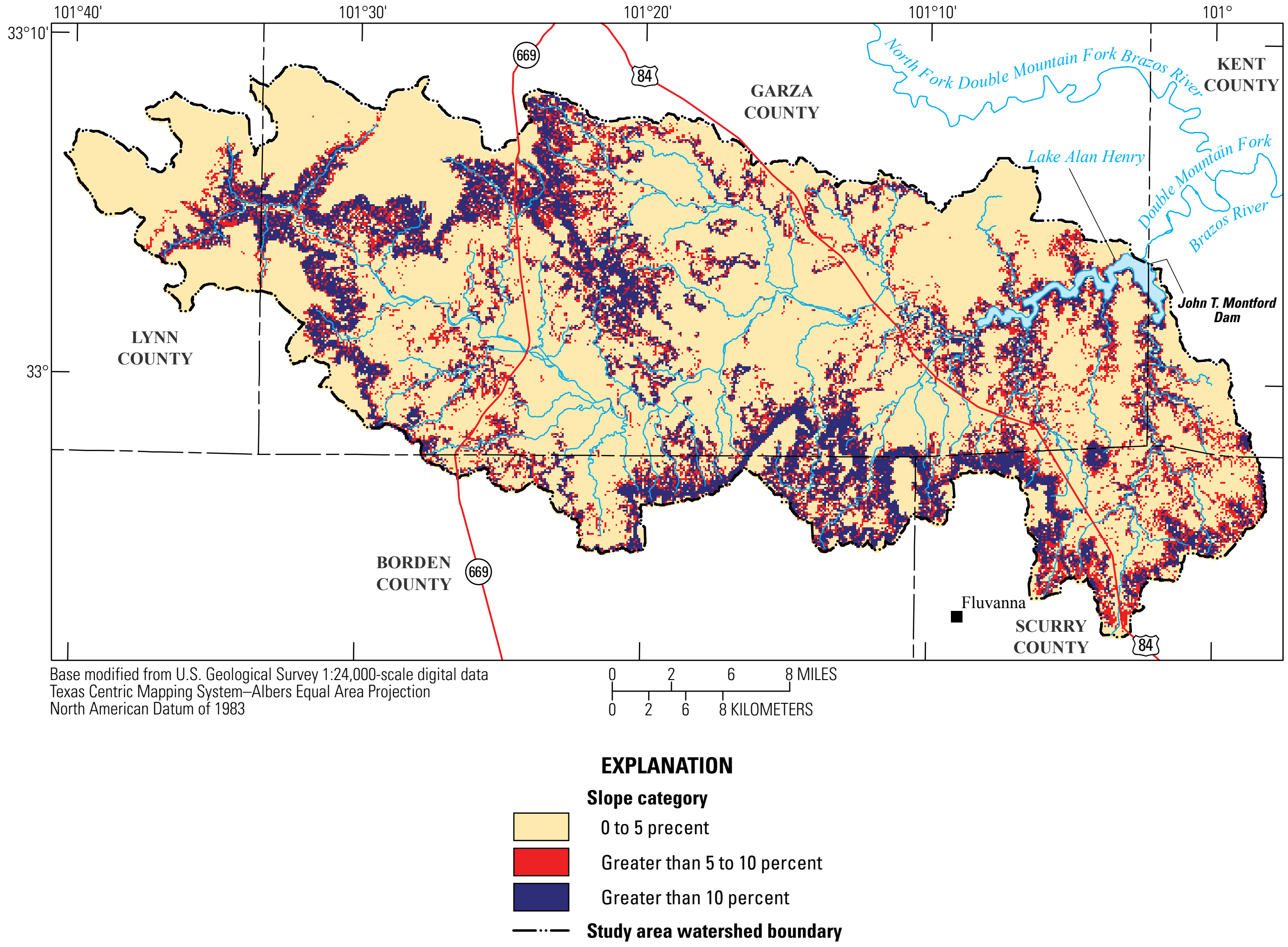


Figure 3. Subbasin delineation for the Double Mountain Fork Brazos River watershed model, western Texas.



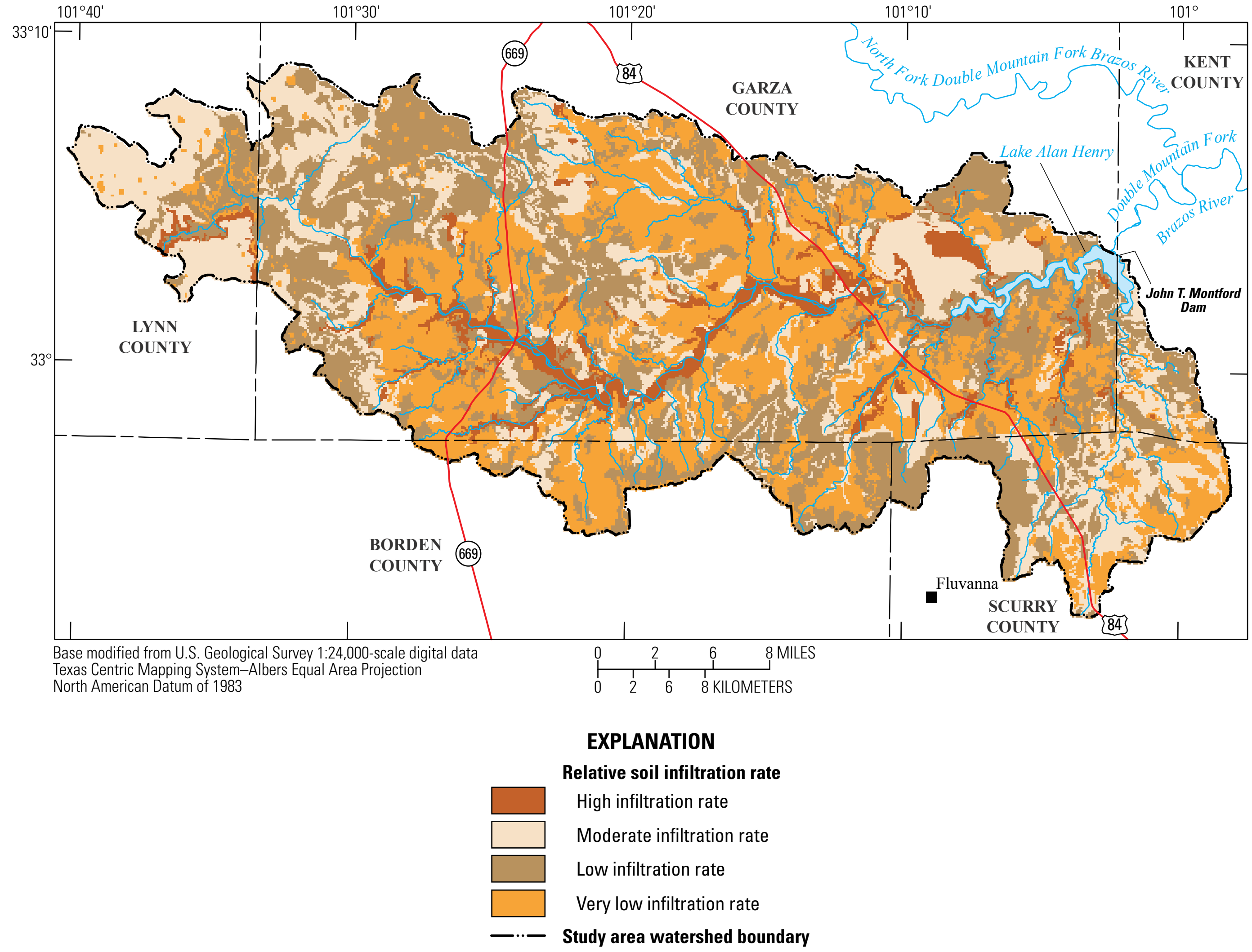
Base modified from U.S. Geological Survey 1:24,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

Figure 4. Slope categories used for the Double Mountain Fork Brazos River watershed model, western Texas.

Land-cover data were obtained from the National Land Cover Database (NLCD) 2006 (Fry and others, 2011) (fig. 6). The NLCD 2006 was selected because 2006 is close to the middle of the 20-year calibration and validation period and because land use did not change appreciably between 2006 and 2011. The NLCD 2011 (Homer and others, 2015) is the most recent land-cover data available. Land use among all land-use categories did not change by more than 1 percent between NLCD 2006 and NLCD 2011.

There were 1,111 HRUs generated as a result of intersecting the 35 model subbasins (fig. 3), land-cover data, soils data, three slope classes, and HRU definition threshold values of 5 percent for land use, soils, and slope. The HRU definition threshold values of 5 percent determine the HRU distribution within each subbasin based on the percentage of subbasin coverage of the land use, soils, and slope. The SWAT land-use refinement tool was used when setting thresholds for HRU generation. Specifically, the land-use threshold exemption tool under the land-use refinement tool was used for land cover classified as shrubland and grassland, which exempted these two land covers from the HRU definition threshold level of 5 percent. This approach made it possible to keep the amount of land classified as shrubland and grassland the same during model runs, and any land-cover categories representing less than 5 percent of a particular subbasin were repartitioned among the predominate land-use categories other than shrubland or grassland.

Daily mean streamflow data from the Justiceburg gage (fig. 2; table 1) for the study period from 1994 through 2013 were obtained from the USGS National Water Information System Web interface (U.S. Geological Survey, 2015). Minimum monthly streamflow during 1994–2013 was no flow or zero cubic feet per second (ft^3/s) during 47 of the 240 months, and maximum single month streamflow was 876 ft^3/s in July 2010. Mean monthly streamflow was 31.6 ft^3/s, and median monthly streamflow was 2.99 ft^3/s (U.S. Geological Survey, 2015). Monthly mean streamflow is computed from the daily mean streamflow values for a given



Base modified from U.S. Geological Survey 1:24,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

EXPLANATION

Relative soil infiltration rate

- 🟫 High infiltration rate
- ▨ Moderate infiltration rate
- 🟫 Low infiltration rate
- 🟧 Very low infiltration rate
- —··— **Study area watershed boundary**

Figure 5. Relative soil infiltration rates in the Double Mountain Fork Brazos River watershed, western Texas.

month. Mean monthly streamflow is the mean computed from several monthly mean streamflow values. For example, the mean monthly streamflow of 31.6 ft^3/s was computed from 240 months of monthly mean streamflow values over the 20-year study period.

Daily precipitation and daily maximum and minimum air temperature model input data were obtained from four National Weather Service (NWS) cooperative (COOP) stations (National Oceanic and Atmospheric Administration, 2015b) and four meteorological stations operated as part of the West Texas Mesonet network at Texas Tech University (fig. 2; table 1) (Schroeder and others, 2005; West Texas Mesonet, 2015). The NWS station data were downloaded directly from the referenced Web site, and West Texas Mesonet data were obtained from Mesonet program staff at Texas Tech University. The NWS stations began collecting data as early as 1897 (COOP ID 413411) and as recently as 1994 (COOP ID 414967). West Texas Mesonet stations POST and ALAN began collecting data in 2001 and 2005, respectively (table 1). The model was run using the 1989–93 meteorological data and the ending conditions within the model (vegetation, soil moisture conditions, shallow groundwater levels, and so on) from that 5-year simulation or warmup period were used as the initial conditions in the model for the 1994–2013 calibration and validation period simulations, and for the brush-management scenario simulations (Arnold and others, 2012).

Precipitation and air temperature data from the NWS stations were used to simulate missing data for the West Texas Mesonet stations. A complete explanation of the methods used to simulate missing data is included in appendix 1. Precipitation and air temperature data from NWS stations and West Texas Mesonet stations are available in a zip file when the report is downloaded.

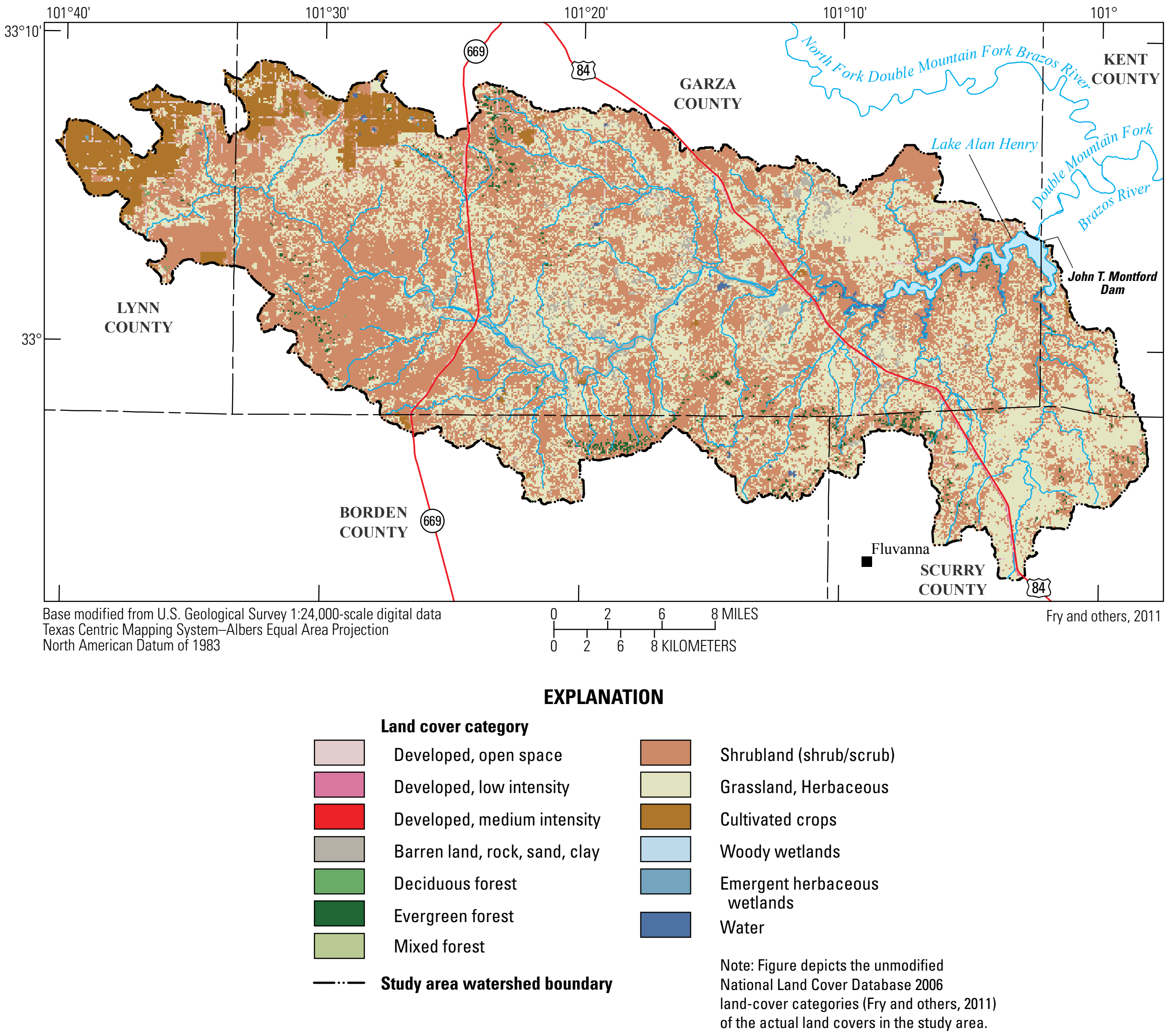


Figure 6. National Land Cover Database 2006 land-cover categories in the Double Mountain Fork Brazos River watershed, western Texas.

Descriptions of additional pertinent SWAT model settings and methods used to develop the model are included to facilitate reproduction of results. The WGEN_US_COOP_1960_2010 database (Winchell and others, 2013) included in the ArcSWAT install package was selected to provide simulated meteorological data when measured data were not available. The WGEN_US_COOP_1960_2010 database contains weather information for 18,254 first order and second order COOP climate stations around the United States for the period from 1960 to 2010. The Hargreaves method, requiring only air temperature data (Hargeaves and others, 1985; Neitsch and others, 2011), was selected to estimate evapotranspiration because air temperature data were available from the NWS and West Texas Mesonet meteorological stations. The variable storage method (Neitsch and others, 2011) was used to route streamflow within the stream channel. For HRUs with slopes greater than 5 percent, the option to automatically adjust CNs for slopes was selected, as discussed in the SWAT theoretical documentation (Neitsch and others, 2011) and based on the equation published by Williams (1995). The skewed distribution option in SWAT was used to generate daily precipitation amounts (Neitsch and others, 2011).

Table 1. Precipitation, air temperature, and streamflow data collection sites for the Double Mountain Fork Brazos River watershed model, western Texas.

[NWS, National Weather Service; COOP ID, cooperative station identification; max, maximum; min, minimum; temp, temperature; USGS, U.S. Geological Survey]

Map number (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 417206, Post, Garza County, Texas	33.199	101.374	Daily precipitation; daily max and min air temp (1910–present).
2	NWS station COOP ID 414967, Lake Alan Henry, Garza County, Texas	33.064	101.049	Daily precipitation; daily max and min air temp (1994–present).
3	NWS station COOP ID 413411, Gail, Borden County, Texas	32.774	101.454	Daily precipitation; daily max and min air temp (1897–present).
4	NWS station COOP ID 418818, Tahoka, Lynn County, Texas	33.171	101.798	Daily precipitation; daily max and min air temp (1913–present).
5	POST, NWS station ID KPT1/XPTS, West Texas Mesonet, Post, Garza County, Texas	33.200	101.368	Daily precipitation; daily max and min air temp (2001–present).
6	MACY, NWS station ID KGHS/XGHS, West Texas Mesonet, Graham, Garza County, Texas	33.082	101.516	Daily precipitation; daily max and min air temp (2002–present).
7	FLUV, NWS station ID KFVS/XFVS, West Texas Mesonet, Fluvanna, Borden County, Texas	32.899	101.202	Daily precipitation; daily max and min air temp (2002–present).
8	ALAN, NWS station ID KAHS/XAHS, West Texas Mesonet, Lake Alan Henry, Garza County, Texas	33.077	101.058	Daily precipitation; daily max and min air temp (2005–present).
08079600	USGS streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas	33.038	101.197	Daily mean streamflow (1961–present).

Model Calibration and Validation

Hydrograph separation was performed on the daily mean streamflow data for the Justiceburg gage using a base-flow filter program described by Arnold and others (1995) and Arnold and Allen (1999). The base-flow filter program is available from the SWAT Web site (Soil and Water Assessment Tool, 2015b). Results of hydrograph separation indicate that the hydrology of the Double Mountain Fork Brazos River watershed is dominated by direct surface runoff during and immediately after storm events. These periods account for about 90 percent of the total streamflow during 1962–2013 and about 90 percent during the study period from 1994 through 2013 (streamflow data were aggregated on a calendar year basis); therefore, base flow accounts for about 10 percent or less of the total streamflow. Frequently there is no flow at the Justiceburg gage, and the channel is often dry. No-flow conditions occurred more frequently during the study period compared to a longer period of record at the Justiceburg gage from 1962 through 2013. During 1962–2013, daily mean streamflow at the Justiceburg gage was no flow (zero) about 47 percent of the time. During the study period from 1994 through 2013, daily mean streamflow at the Justiceburg gage was zero about 59 percent of the time.

The estimated mean annual actual evapotranspiration ranges from about 16 to 20 inches per year (in/yr). The mean annual ratio of actual evapotranspiration to precipitation ranges from about 0.80 to 0.89 (Sanford and Selnick, 2012).

The Double Mountain Fork Brazos River watershed model was calibrated on a monthly time step over the 15-year period from 1994 through 2008 and validated over the 5-year period from 2009 through 2013. Calibration of the model required adjusting parameter values to minimize the differences between simulated and measured streamflows at the Justiceburg gage while also simulating the relative amounts of surface runoff, base flow, and evapotranspiration. The SWAT parameter values can vary within parameter specific uncertainty ranges defined in the SWAT tool input and output file documentation (Arnold and others, 2012). The SWAT parameters included in the calibration process were those that were determined (either alone or in combination with other parameters) to decrease the groundwater contribution to streamflow, increase the surface-runoff contribution to streamflow, and influence the amount of simulated evapotranspiration.

Table 2 lists the parameter values adjusted to calibrate the simulated watershed hydrology. The default parameter values, which are described in detail in Neitsch and others (2011), were used for the remaining parameter values. Shrubland and grassland land-cover categories also were varied in an equitable manner that maintained the relative parameter differences between the different categories. The combination of calibrated parameters listed in table 2 related to groundwater (SWAT input file location.gw) decrease the contributions from base flow to realistically small amounts. The parameter average slope length (SLSUBBSN) also decreases the relative amount of base flow by decreasing the percentage of water coming from lateral subsurface flow to the reaches. Increasing the CN for moisture condition II (CN2) an additional 8 percent functions to increase the relative amount of surface runoff. Lastly, adjustment of the parameters related to evaporation (ESCO), plant uptake (EPCO), and canopy storage (CANMX) have several influences on the simulated values with respect to surface runoff, base flow, and evapotranspiration.

Model performance was evaluated using three calibration metrics (1) the percentage bias (PBIAS) of simulated streamflow to measured streamflow, (2) the coefficient of determination (R^2) of the linear regression, and (3) the Nash–Sutcliffe coefficient of model efficiency (NSE) (Nash and Sutcliffe, 1970; Singh and others, 2004; Moriasi and others, 2007).

Table 2. Summary of the calibrated parameter values and changes applied to default parameter values for the Soil and Water Assessment Tool watershed model of the Double Mountain Fork Brazos River watershed, western Texas, 1994–2013.

[SWAT, Soil and Water Assessment Tool; --, dimensionless; **, values varied and were therefore increased by percentage, constant value, or replaced; mm, millimeters;; HRU, Hydrologic Response Unit; m, meters; 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 (file name extension)	Default parameter value	Calibrated parameter values and changes applied to default parameter values
CN2	Curve number for moisture condition II (--)	management (.mgt)	**	Increase default value for all land-use categories by 8 percent.[1]
GW_DELAY	Groundwater delay time (days)	groundwater (.gw)	31	Replace default value with 87.
GWQMN	Threshold depth of water in shallow aquifer required for return flow to occur (mm)	groundwater (.gw)	1,000	Replace default value with 2,400.
GW_REVAP	Groundwater revap coefficient that represents water movement from the shallow aquifer to the root zone (--)	groundwater (.gw)	0.02	Replace default value with 0.15.
RCHRG_DP	Deep aquifer percolation factor (--)	groundwater (.gw)	0.05	Replace default value with 0.30.
REVAPMN	Threshold depth of water in shallow aquifer for percolation to the deep aquifer to occur (mm)	groundwater (.gw)	750	Replace default value with 50.
CANMX	Maximum canopy storage (mm)	HRU (.hru)	**	Increase default value for all land-use categories by 25.
EPCO	Plant uptake compensation factor (--)	HRU (.hru)	1.00	Replace default value with 0.14.
ESCO	Soil evaporation compensation factor (--)	HRU (.hru)	0.95	Replace default value with 0.29.
SLSUBBSN	Average slope length (m)	HRU (.hru)	**	Replace default value with 90.

[1] Multiply the default parameter value by 1.08 for all land-use categories.

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

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

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 zero the PBIAS value, the more equally balanced the overpredictions and the underpredictions of streamflow for the period being evaluated. A negative PBIAS value indicates that a model has a tendency to overpredict streamflow, whereas a positive value indicates a tendency to underpredict. The PBIAS values between zero 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).

The fraction of the variance explained by linear regression is described by the R^2 value, which ranges from zero to one. When the R^2 value equals one, the variance of the simulated values equals the variance of the corresponding measured values (Helsel and Hirsch, 2002). Gassman and others (2007) used 0.50 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 measured streamflow deviates greatly from the measured mean monthly streamflow. The NSE is calculated by

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

where

Y^{mean} is the measured mean monthly streamflow (other variables were previously defined in equation 1).

The NSE can range from negative infinity to one. An NSE of one indicates a perfect fit between simulated and measured data. An NSE of zero indicates that the model predictions are only as accurate as the mean of the measured data, and an NSE of less than zero indicates that the mean of the measured data 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 0.50 and less than 0.65, and unsatisfactory if the monthly NSE is less than 0.50. Gassman and others (2007) used NSE values of greater than or equal to 0.50 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, validation, and overall performance for the 20-year calibration and validation period.

The PBIAS for the monthly 15-year calibration period was +5 (underprediction), the monthly R^2 was 0.59, and the monthly NSE was 0.49 (table 3). These PBIAS and R^2 values are very good and satisfactory, respectively, according to the references given. Although the NSE value of 0.49 would be classified as unsatisfactory according to the references (less than 0.50), in reality, the model differences implied between an NSE of 0.49 and 0.50 are not substantial. There was also a tradeoff between optimizing NSE and minimizing the PBIAS when calibrating the model. Other combinations of parameter values could maximize NSE to values greater than 0.50 but PBIAS increased as well; therefore, the combination of parameter values that maximized NSE while minimizing PBIAS was selected.

The monthly NSE of 0.49 was substantially influenced by the simulated monthly mean streamflow during November 2004 when the model overpredicted streamflow. If data from November 2004 were excluded from the computation of all the monthly calibration metrics, the PBIAS increased from +5 to +11, the R^2 increased from 0.59 to 0.61, and the NSE increased from 0.49 to 0.60 for the 15-year calibration period (table 3). Precipitation data during this period were checked to try to explain the difference between simulated and measured streamflow; however, the data were reasonable and similar amounts of monthly precipitation were recorded at all four of the Mesonet stations. November 2004 precipitation values ranged from 7.43 in. for MACY to 8.73 in. for POST. The previous record for the most amount of precipitation in Lubbock, Tex., during the month of November was exceeded by more than 3 in. in November 2004, which was the wettest November ever for Texas as a whole (National Weather Service, 2015a). The form of precipitation might have hindered the ability of the model to accurately predict streamflow during November 2004. Precipitation during November 2004 was characterized by the NWS as a mixture of rain and snow for some parts of the study area (National Weather Service, 2015b). The SWAT is more efficient simulating precipitation consisting of only rain rather than a mixture of rain and snow (Fontaine and others, 2002).

Table 3. Calibration results for the Soil and Water Assessment Tool watershed model of the Double Mountain Fork Brazos River watershed at U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, 1994–2013.

[Bold font indicates the time step for which the model was calibrated and validated; min, minimum; max, maximum; ft^3/s, cubic feet per second]

Period[1] (time step)	Percentage of bias (PBIAS)	Coefficient of determination (R^2)	Nash-Sutcliffe coefficient of model efficiency (NSE)	Volume percentage error
15-year calibration period (monthly)	5 (11)[2]	0.59 (0.61)[2]	0.49 (0.60)[2]	5
5-year validation period (monthly)	11	0.96	0.95	11
20-year model period (daily)	7	0.60	0.51	7
20-year model period (monthly)	6 (11)[2]	0.73 (0.77)[2]	0.71 (0.77)[2]	7
20-year model period (annual)	7	0.84	0.82	7

Measured

Period[1] (time step)	Min streamflow (ft^3/s)	25th percentile (ft^3/s)	Median streamflow (ft^3/s)	75th percentile (ft^3/s)	Mean streamflow (ft^3/s)	Max streamflow (ft^3/s)	Volume (acre-feet)[3]
15-year calibration period (monthly)	0	0.03	4.47	29.7	32.4	418	353,000
5-year validation period (monthly)	0	0.04	1.12	18.0	29.0	876	106,000
20-year model period (daily)	0	0	0	0.55	31.7	16,600	459,000
20-year model period (monthly)	0	0.03	2.99	24.5	31.6	876	459,000
20-year model period (annual)	0.47	11.9	26.5	42.2	31.7	114	459,000

Simulated

Period[1] (time step)	Min streamflow (ft^3/s)	25th percentile (ft^3/s)	Median streamflow (ft^3/s)	75th percentile (ft^3/s)	Mean streamflow (ft^3/s)	Max streamflow (ft^3/s)	Volume (acre-feet)[3]
15-year calibration period (monthly)	0	0.04	3.04	26.9	30.9	647	335,000
5-year validation period (monthly)	0	0	0.36	11.7	25.9	709	94,200
20-year model period (daily)	0	0	0	0.17	29.6	18,100	429,000
20-year model period (monthly)	0	0.02	2.17	22.3	29.6	709	429,000
20-year model period (annual)	1.29	8.1	19.7	33.6	29.6	104	429,000

[1] Calibration period is from January 1, 1994, through December 31, 2008, and validation period is from January 1, 2009, through December 31, 2013.

[2] PBIAS, R^2, and NSE values with November 2004 excluded from calculation of model performance metrics on monthly calibration time step.

[3] Total volume of water flowing past the streamflow-gaging station during the period.

The respective PBIAS, R^2, and NSE values for the monthly 5-year validation period were +11, 0.96, and 0.95 (table 3). These values indicate the model performed well during a period characterized by extreme conditions; the highest and lowest annual water volumes recorded at the Justiceburg gage between 1962 and 2013 were measured in 2010 (82,700 acre-ft) and 2011 (341 acre-ft). An NSE of 0.95 for the 5-year validation period is very good given that the NSE assesses the ability of a model to correctly simulate streamflow during periods when measured streamflow deviates greatly from the measured mean streamflow.

The respective PBIAS, R^2, and NSE values for the monthly 20-year study period were +6, 0.73, and 0.71 (table 3). These calibration metrics indicate an overall good fit between simulated and measured streamflow over the 20-year study period (figs. 7 and 8; table 3). Minimum simulated monthly streamflow was zero ft^3/s during 48 of the 240 months, maximum single month simulated streamflow was 709 ft^3/s in July 2010, simulated mean monthly streamflow was 29.6 ft^3/s, and simulated median monthly streamflow was 2.17 ft^3/s (table 3). When the measured monthly mean streamflow was zero, the model simulated 1,500 acre-ft of streamflow, or 0.35 percent of the total simulated streamflow volume and simulated daily mean streamflow was zero about 66 percent of the time, indicating no flow conditions were simulated well by the model. Differences between the 25th percentiles of measured and simulated streamflow were small, as were the differences between the 75th percentiles of measured and simulated streamflow (table 3).

Although 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 for the 20-year study period was 0.51, and the annual NSE was 0.82, which indicate a satisfactory fit and very good fit between the simulated and measured daily and annual streamflow values, respectively (table 3).

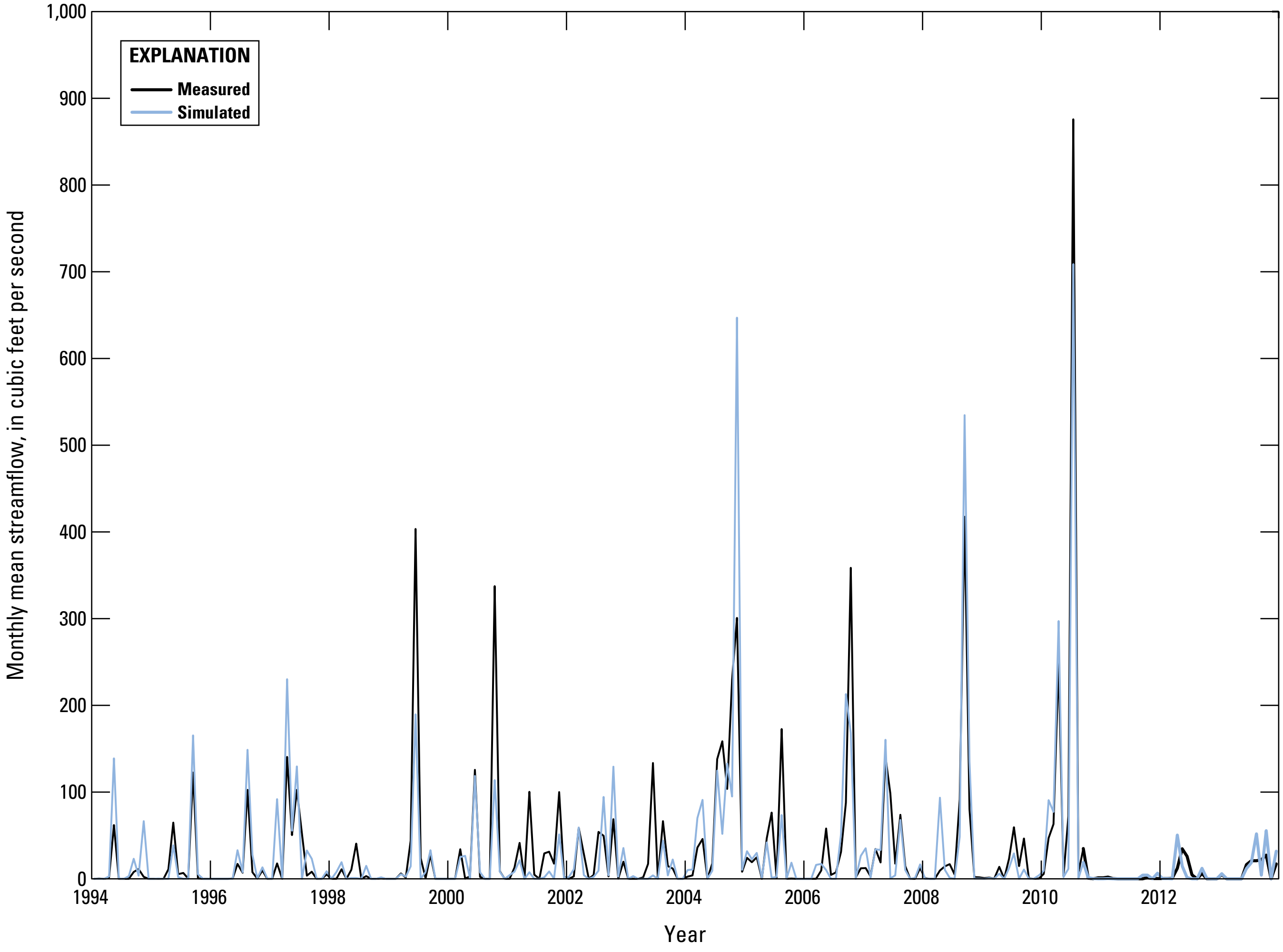


Figure 7. Simulated monthly mean streamflow and measured monthly mean streamflow at U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, 1994–2013.

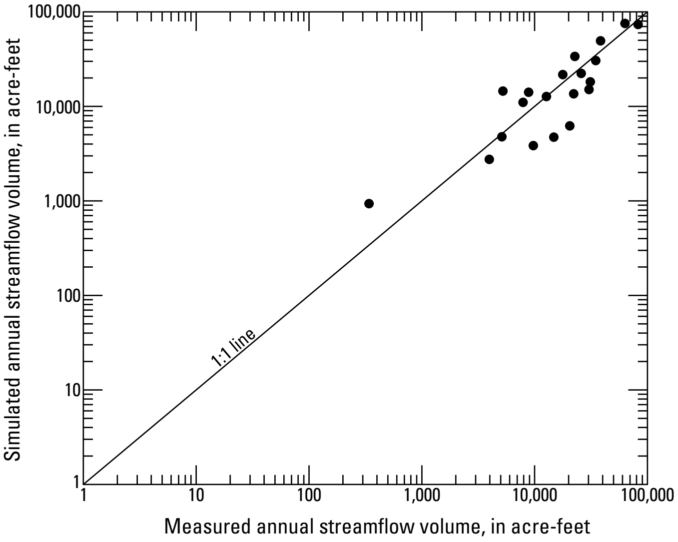


Figure 8. Relation of simulated annual streamflow volume and measured annual streamflow volume at U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, 1994–2013.

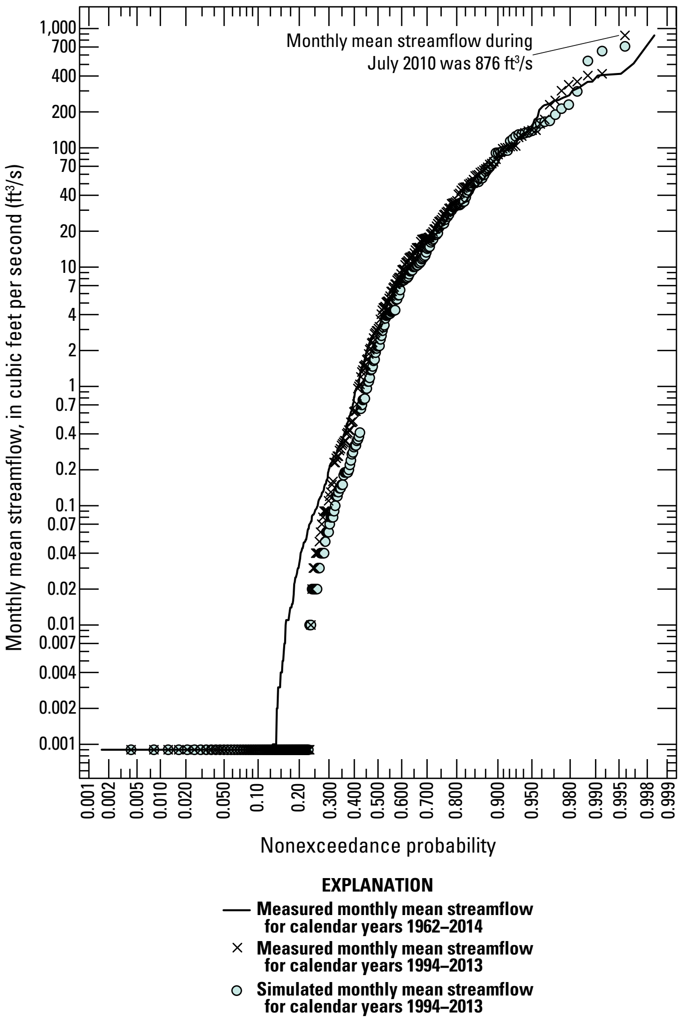


Figure 9. Empirical distributions of monthly mean streamflow when considered as a single random variable for U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, in conjunction with empirical distribution of simulated monthly mean streamflow from the Double Mountain Fork Brazos River watershed model.

The summary statistics (table 3) and the relation between simulated and measured annual streamflow (fig. 8) were augmented by a representation of the empirical distribution of monthly mean streamflow when considered as a single random variable (fig. 9). The Weibull plotting-position formula (Helsel and Hirsch, 2002) was used to develop the nonexceedance probability plot of measured monthly mean streamflow from 1962 to 2014 and the simulated and measured monthly mean streamflow during the study period from 1994 to 2013. For graphing purposes, zero-flow months were assigned a value of 0.0009 because the base-10 logarithm ($\log_{10}$) of zero is undefined. The horizontal axis shows the probability scale for a normal distribution. Three major interpretations can be made from figure 9: (1) the general distribution of measured monthly mean streamflow for the study period is reasonably consistent with that of the longer period of record, so the observed conditions during the study period are similar to decades not simulated; (2) the distributions of the simulated and measured monthly mean streamflow (data points in fig. 9) are scattered amongst each other throughout the streamflow spectrum; (3) the data points plot appreciably below the black line within the nonexceedance probability range of about 0.15–0.35, consistent with the observation that there were more exceptionally dry months within the study period (1994–2013) compared to the longer period of record (1962–2014). In the upper right part of the graph (fig. 9), one data point for the measured monthly mean streamflow (July 2010) plots well above the black line because July 2010 is the month with the historically highest streamflow, consistent with the observation that the study period included historically high streamflow.

The standard deviations of the annual mean streamflow computed from the simulated and measured monthly mean values for the Justiceburg gage are 29.8 and 28.3, respectively, for the 1994–2013 study period. Similarly, the standard deviations of the transformed ($\log_{10}$) annual mean simulated and measured streamflow are 0.48 and 0.52, respectively; therefore, the simulated and measured streamflow values have similar variation for the study period.

Kendall's *tau* (Hollander and Wolfe, 1973; Helsel and Hirsch, 2002) is a useful statistical test for quantifying the presence of monotonic changes in the central tendency of streamflow data in time (Asquith and Heitmuller, 2008; Asquith and Barbie, 2014). Specifically, the nonparametric Kendall's *tau* statistical test is used to assess for a monotonic trend in annual mean streamflow. The test uses the relation between time and ranked streamflow, rather than streamflow magnitude, for computations. A statistically significant positive Kendall's *tau* indicates an upward streamflow trend, whereas a statistically significant negative Kendall's *tau* indicates a downward trend. The Kendall's *tau* p-value is a measure of the statistical significance of the trend. Small p-values (less than 0.05 for this analysis) indicate a statistically significant trend, and p-values greater than 0.05 indicate the absence of a statistically significant trend (Hollander and Wolfe, 1973; Helsel and Hirsch, 2002).

To establish that annual mean streamflow has been reasonably independent of time, Kendall's *tau* was computed for the Justiceburg gage annual mean streamflow data for the period from 1962 through 2014. Kendall's *tau* was less than -0.02 in absolute magnitude with a corresponding p-value of about 0.82; therefore, annual streamflow volumes at the Justiceburg gage have not changed over time, and the study period does not represent a moving target of streamflow.

The model was evaluated throughout the entire process of calibration with respect to contributions from surface runoff, base flow, and evapotranspiration. Mean annual basin values from SWAT output indicate that surface runoff accounts for about 93.2 percent of total simulated streamflow, and base flow accounts for about 6.8 percent of total simulated streamflow. Mean annual simulated evapotranspiration is about 17.9 in/yr, and the mean annual ratio of simulated evapotranspiration to precipitation is 0.91. These simulated values compare well with actual computed and published values of percentage of surface runoff (90 percent), percentage of base flow (10 percent), and mean annual actual evapotranspiration (16–20 in/yr) (Sanford and Selnick, 2012).

Permitted surface-water withdrawals (water rights) were evaluated but not included in the model because they were negligible. According to publicly available data reported to the Texas Commission on Environmental Quality, total volume of water withdrawn under water rights upstream from the Justiceburg gage during the model calibration period was 835 acre-ft, or about 0.24 percent of the total volume of water recorded at the streamflow-gaging station during the same period (Texas Commission on Environmental Quality, 2015). Streamflow discharges to the Double Mountain Fork Brazos River and its tributaries for municipal, industrial, and agricultural operations also were evaluated for inclusion in the model, but none were found within the contributing watershed area (U.S. Environmental Protection Agency, 2015).

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 inability of the model 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 Double Mountain Fork Brazos River watershed model were: (1) 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); (2) the model was calibrated using data from the only available streamflow-gaging station; and (3) point measurements of precipitation data were distributed spatially across the model domain. In an effort to mitigate the potential shortcomings pertaining to constant land cover, simulations were limited to a 20-year time period encompassing the data compilation date of the NLCD 2006. The inherent assumption is that watershed land cover did not appreciably change during the 20-year time period and, as already mentioned, the percentage of watershed coverage among all land-use categories did not increase or decrease by more than 1 percent between the NLCD 2006 and NLCD 2011.

The model was calibrated to streamflow data collected from a single streamflow-gaging station because other stations do not currently (2016) or historically exist upstream from Lake Alan Henry. 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.

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 and have different statistical properties throughout the basin (Strauch and Linard, 2009). If precipitation in the study area is isolated to a small area surrounding a precipitation gage, the model might overpredict the amount of rainfall-produced runoff from an HRU. Furthermore, a substantially higher amount of precipitation might occur between precipitation gages than was recorded at the precipitation gages, and thus, the model might underpredict rainfall-produced runoff from an HRU. The trajectory and speed of a storm affect watershed response; some storm paths might not be represented by the recorded data, which might affect model calibration. Lastly, precipitation data input into the model are daily totals, and surface runoff after large storm events can vary appreciably during time steps smaller than daily.

The development of the Double Mountain Fork Brazos River watershed model was intended to simulate monthly mean streamflow and to evaluate the effects of brush management on water yields in the watershed as a result of the replacement of shrubland with grassland. The evaluation of possible reductions in water-yield increases as regrowth of shrubland occurs was beyond the scope of the study.

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

The 35 subbasins of the calibrated watershed model (fig. 3) were investigated for the effects of brush management on water yields to Lake Alan Henry. Modified land cover input datasets were created to simulate brush management in each of the 35 subbasins. The HRUs were generated in the model using the modified land cover input datasets while keeping all other settings from the calibrated model the same. Water-yield changes were calculated as the difference between water yields from the brush-management simulation and water yields from the unmodified model simulation with the original land-cover dataset.

Simulation Methods

The NLCD 2006 was modified to simulate Shrubland replacement with Herbaceous/Grassland in each of the 35 model subbasins. Shrubland and Herbaceous/Grassland are the NLCD 2006 land-cover category names. The terms “brush” and “brush management” are used to be consistent with other publications and feasibility studies. As explained in the “Purpose and Scope” section of this report, the term “brush” refers to land classified as shrubland, and the term “brush management” refers to the replacement of shrubland with grassland.

The Ecological Mapping Systems of Texas (EMST) land-cover dataset (Elliott and others, 2014), available from Texas Parks and Wildlife, was also considered as model input data for brush-management simulations. Compared to the NLCD 2006, the EMST land-cover dataset is more refined because specific vegetation types are identified. Specifically, the EMST land-cover dataset was investigated for the possibility of performing brush-management simulations while focusing on the replacement of saltcedar with grassland. Saltcedar was identified in EMST land-cover dataset as present in the modeled watershed, but the land coverage of saltcedar was not quantified; therefore, the EMST land-cover dataset was not used as input data for brush-management simulations.

The GIS methods used to simulate 100 percent replacement of shrubland with grassland in the NLCD 2006 are included in detail in appendix 2. In general, areas classified as shrubland in the NLCD 2006 were reclassified as grassland if the land slope was between 4 and 20 percent, depending on the simulation scenario, and if these areas were not within a riparian area defined as within 10 m (32.8 ft) of a lake or stream. Riparian areas were excluded from brush-management simulations because potential increases in sediment loading resulting from removing brush in riparian areas would exclude them from removal strategies. Criteria used in this study for exclusion of riparian area (less than 10 m [32.8 ft]) approximate the 35-ft guidelines given by the TSSWCB to prevent negative impacts from brush removal too near streambanks as well as accommodate the raster input data cell size of 10 m (Texas State Soil and Water Conservation Board, 2014).

The model was run for four different brush-management simulation scenarios including replacement of shrubland with grassland in areas with land slope less than 4, 8, 16, and 20 percent. For comparability and consistency with other brush management feasibility studies, water yield increases resulting from 100 percent replacement of shrubland with grassland in areas with slopes less than 20 percent and not within riparian areas are presented for the 35 subbasins. As referenced in the State Water Supply Enhancement Plan, accepted forestry practice excludes hillsides with slopes greater than 20 percent from clearing (Food and Agriculture Organization of the United Nations, 1977; Texas State Soil and Water Conservation Board, 2014). However, replacement of shrubland with grassland within other land slope categories (4, 8, and 16 percent) was investigated to identify the most critical areas for brush management. Brush removal from areas with gentle slopes is presumably much easier compared to areas with steeper slopes, particularly for mechanical removal methods.

Modification of land-cover data to simulate brush removal was done similarly to the removal methods used in the previous TSSWCB feasibility studies (Bednarz and others, 2000; Bednarz and others, 2003; Bumgarner and Thompson, 2012) and the maximum removal scenarios used by Afinowicz and others (2005). Table 4 lists the areal coverage of unmodified NLCD 2006 land-cover categories for each subbasin in the watershed (fig. 6). The predominant land-cover categories in the area upstream and downstream from the Justiceburg gage are shrubland and grassland, accounting for a combined 85.4 and 92.4 percent of the area, respectively. Shrubland accounts for about 51 and 40 percent of the area upstream and downstream from the Justiceburg gage (table 4). Table 5 lists the areal coverage of the NLCD land-cover categories after modification of the NLCD 2006 for each subbasin (fig. 10). After replacement of shrubland with grassland in areas with land slope less than 20 percent and excluding riparian areas, the amount of shrubland remaining in the area upstream and downstream from the Justiceburg gage is 4.3 and 4.6 percent and grassland accounts for about 81.1 and 87.7 percent, respectively (table 5).

Table 4. Percentage of areal coverage of unmodified National Land Cover Database 2006 land-cover categories for the subbasins used for the Double Mountain Fork Brazos River watershed model, western Texas.

[Shaded cells include subbasins upstream from and directly contributing to U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, whereas cells that are not shaded include subbasins downstream from the station that contribute directly to Lake Alan Henry]

Subbasin number	Subbasin area (acres)	Open water (percent)	Developed, open space (percent)	Developed, low intensity (percent)	Developed, medium intensity (percent)	Barren land (percent)	Deciduous forest (percent)	Evergreen forest (percent)	Mixed forest (percent)	Shrubland (percent)	Grassland/ Herbaceous (percent)	Cultivated crops (percent)	Woody wetlands (percent)	Emergent herbaceous wetlands (percent)
1	33,533	0.235	3.44	0.018	0	0.172	0.245	0.105	0	39.6	21.1	34.8	0.051	0.100
2	18,108	0.153	1.53	0.038	0	2.99	0.381	1.94	0	52.7	38.9	1.24	0.089	0
3	6,232.5	0.078	4.84	0.184	0	0.219	0.238	1.77	0	42.3	33.6	16.4	0.005	0.316
4	4,321.7	20.8	0.649	0	0	0.483	0	0.285	0.685	47.0	28.9	1.14	0	0
5	7,613.3	0.087	1.55	0.151	0	7.22	0.020	0.015	0	47.9	43.1	0	0	0
6	9,151.4	0.031	1.27	0.567	0	9.25	0.022	0	0	40.0	48.7	0.113	0	0
7	7,453.5	0.055	1.91	0.029	0.007	0.689	0	0	0.042	45.6	51.5	0.228	0	0
8	114.36	0	7.41	4.12	0.451	5.93	0	0	0	38.5	36.1	7.49	0	0
9	4,725.4	9.15	2.04	0	0	0.498	0	1.31	0.227	49.2	37.6	0	0	0
10	351.39	23.1	1.60	0.398	0.224	0	0	0	0.314	46.4	28.0	0	0	0
11	8,058.6	0.713	1.31	0.366	0	5.03	0.202	0.421	0	51.3	40.1	0.463	0.047	0
12	2,971.6	0.037	0.163	0.274	0.047	14.1	0.216	0	0	39.3	45.8	0	0.037	0
13	2,864.4	0	0.559	0	0	4.53	0	0	0	47.8	47.1	0	0.075	0
14	22,426	0.069	0.317	0.021	0	1.59	0.028	0.809	0	68.3	28.8	0	0.043	0
15	573.03	12.0	0	0	0	0.039	0	2.36	0.193	60.4	25.0	0	0	0
16	291.73	0	0	0	0	19.5	0	0	0	26.5	54.0	0	0	0
17	5,387.2	2.93	0	0	0	1.23	0	0.788	0.092	44.6	50.2	0.168	0	0
18	4,621.8	3.90	1.69	1.15	0	2.21	0.234	0.357	0.258	43.4	46.0	0.728	0.057	0
19	5,483.7	7.97	2.18	0.783	0	4.23	0	0.273	0.020	38.8	45.7	0	0	0
20	412.94	15.1	0	0	0	0	0	0.285	0	56.5	28.2	0	0	0
21	1,034.9	0	3.34	0.213	0	13.9	0	0	0	46.4	36.0	0	0.171	0
22	6,263.8	0.159	1.36	0	0	5.69	0.224	0.345	0	45.1	46.9	0	0.222	0
23	8,429.1	0.149	0.153	0	0	1.13	0.039	0.749	0	77.4	20.3	0	0.052	0
24	1,848.1	8.09	0	0	0	0.99	0	0.032	0.167	58.5	32.2	0	0	0
25	2,988.0	0.133	0.144	0	0	11.0	0.044	0	0	52.3	36.4	0	0	0
26	1,955.2	0.057	0	0	0	14.1	1.01	0.158	0	43.0	41.6	0	0.079	0
27	23,878	0.148	0.042	0	0	10.0	0.396	1.73	0	41.7	45.8	0.144	0.072	0
28	6,367.3	0.238	1.14	0.031	0	3.37	0.038	0	0	57.0	35.4	2.69	0.052	0

Table 4. Percentage of areal coverage of unmodified National Land Cover Database 2006 land-cover categories for the subbasins used for the Double Mountain Fork Brazos River watershed model, western Texas.—Continued

[Shaded cells include subbasins upstream from and directly contributing to U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, whereas cells that are not shaded include subbasins downstream from the station that contribute directly to Lake Alan Henry]

Subbasin number	Subbasin area (acres)	Open water (percent)	Developed, open space (percent)	Developed, low intensity (percent)	Developed, medium intensity (percent)	Barren land (percent)	Deciduous forest (percent)	Evergreen forest (percent)	Mixed forest (percent)	Shrubland (percent)	Grassland/ Herbaceous (percent)	Cultivated crops (percent)	Woody wetlands (percent)	Emergent herbaceous wetlands (percent)
29	6,795.2	0.504	0	0	0	0.583	0.461	1.35	0.039	56.9	40.2	0	0	0
30	6,124.1	0.065	0.522	0.083	0	2.26	0.257	0.341	0	50.3	45.5	0.386	0.245	0
31	12,093	0.067	2.24	1.19	0	1.21	0	2.61	0	39.5	53.1	0.051	0.040	0
32	9,488.5	0.132	0.831	0.054	0	0.240	0	0.514	0	39.9	58.1	0.213	0	0
33	14,979	0.309	0.399	0.308	0.019	2.44	0.119	2.22	0	44.3	49.8	0.091	0.040	0
34	5,364.3	0	0.308	0.136	0	0	0	1.11	0	33.2	65.1	0.053	0.091	0
35	8,961.6	0.017	1.64	0.945	0	0.255	0	0.439	0	17.8	78.9	0	0.032	0
Study area watershed upstream from streamflow gage 08079600	165,935	0.186	1.39	0.053	0.001	3.92	0.228	0.800	0.002	50.6	34.8	7.95	0.065	0.032
Study area watershed downstream from streamflow gage 08079600	95,331	2.67	1.23	0.465	0.005	2.02	0.032	1.01	0.070	40.3	52.1	0.179	0.022	0

Table 5. Percentage of areal coverage of modified National Land Cover Database 2006 land-cover categories after all land classified as shrubland was changed to grassland in areas with land slope less than twenty percent and excluding riparian areas for the subbasins used for the Double Mountain Fork Brazos River watershed model, western Texas.

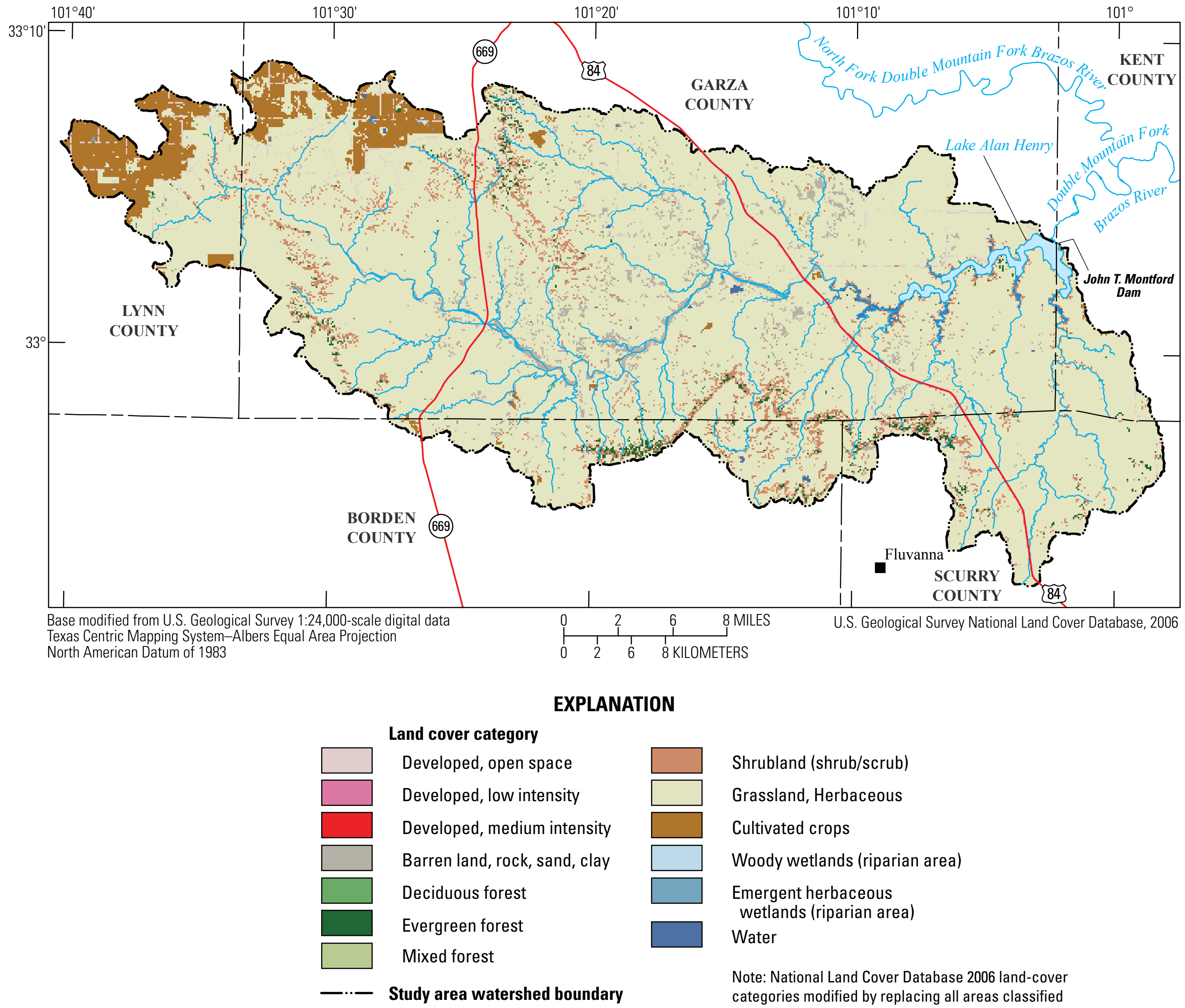
[Shaded cells include subbasins upstream from and directly contributing to U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, whereas cells that are not shaded include subbasins downstream from the station that contribute directly to Lake Alan Henry]

Subbasin number	Subbasin area (acres)	Open water (percent)	Developed, open space (percent)	Developed, low intensity (percent)	Developed, medium intensity (percent)	Barren land (percent)	Deciduous forest (percent)	Evergreen forest (percent)	Mixed forest (percent)	Shrubland (percent)	Grassland/Herbaceous (percent)	Cultivated crops (percent)	Woody wetlands (percent)	Emergent herbaceous wetlands (percent)
1	33,533	0.235	3.44	0.018	0	0.172	0.245	0.105	0	1.79	59.0	34.8	0.051	0.100
2	18,108	0.153	1.53	0.038	0	2.99	0.381	1.94	0	5.99	85.6	1.24	0.089	0
3	6,232.5	0.078	4.84	0.184	0	0.219	0.238	1.77	0	8.12	67.8	16.4	0.005	0.316
4	4,321.7	20.8	0.649	0	0	0.483	0	0.285	0.685	7.65	68.3	1.14	0	0
5	7,613.3	0.087	1.55	0.151	0	7.22	0.020	0.015	0	1.23	89.7	0	0	0
6	9,151.4	0.031	1.27	0.567	0	9.25	0.022	0	0	1.02	87.7	0.113	0	0
7	7,453.5	0.055	1.91	0.029	0.007	0.689	0	0	0.042	0.60	96.4	0.228	0	0
8	114.36	0	7.41	4.12	0.451	5.93	0	0	0	2.28	72.3	7.49	0	0
9	4,725.4	9.15	2.04	0	0	0.498	0	1.31	0.227	5.37	81.4	0	0	0
10	351.39	23.1	1.60	0.398	0.224	0	0	0	0.314	12.7	61.7	0	0	0
11	8,058.6	0.713	1.31	0.366	0	5.03	0.202	0.421	0	2.82	88.6	0.463	0.047	0
12	2,971.6	0.037	0.163	0.274	0.047	14.1	0.216	0	0	1.30	83.8	0	0.037	0
13	2,864.4	0	0.559	0	0	4.53	0	0	0	4.30	90.5	0	0.075	0
14	22,426	0.069	0.317	0.021	0	1.59	0.028	0.809	0	6.89	90.2	0	0.043	0
15	573.03	12.0	0	0	0	0.039	0	2.36	0.193	8.06	77.4	0	0	0
16	291.73	0	0	0	0	19.5	0	0	0	0.093	80.4	0	0	0
17	5,387.2	2.93	0	0	0	1.23	0	0.788	0.092	2.59	92.2	0.168	0	0
18	4,621.8	3.90	1.69	1.15	0	2.21	0.234	0.357	0.258	2.29	87.1	0.728	0.057	0
19	5,483.7	7.97	2.18	0.783	0	4.23	0	0.273	0.020	5.88	78.7	0	0	0
20	412.94	15.1	0	0	0	0	0	0.285	0	6.33	78.3	0	0	0
21	1,034.9	0	3.34	0.213	0	13.9	0	0	0	0.372	82.0	0	0.171	0
22	6,263.8	0.159	1.36	0	0	5.69	0.224	0.345	0	3.52	88.5	0	0.222	0
23	8,429.1	0.149	0.153	0	0	1.13	0.039	0.749	0	3.71	94.0	0	0.052	0
24	1,848.1	8.09	0	0	0	0.987	0	0.032	0.167	7.55	83.2	0	0	0
25	2,988.0	0.133	0.144	0	0	11.0	0.044	0	0	0.115	88.6	0	0	0
26	1,955.2	0.057	0	0	0	14.1	1.01	0.158	0	0.797	83.8	0	0.079	0
27	23,878	0.148	0.042	0	0	9.97	0.396	1.73	0	5.27	82.2	0.144	0.072	0

Table 5. Percentage of areal coverage of modified National Land Cover Database 2006 land-cover categories after all land classified as shrubland was changed to grassland in areas with land slope less than twenty percent and excluding riparian areas for the subbasins used for the Double Mountain Fork Brazos River watershed model, western Texas.—Continued

[Shaded cells include subbasins upstream from and directly contributing to U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, whereas cells that are not shaded include subbasins downstream from the station that contribute directly to Lake Alan Henry]

Subbasin number	Subbasin area (acres)	Open water (percent)	Developed, open space (percent)	Developed, low intensity (percent)	Developed, medium intensity (percent)	Barren land (percent)	Deciduous forest (percent)	Evergreen forest (percent)	Mixed forest (percent)	Shrubland (percent)	Grassland/ Herbaceous (percent)	Cultivated crops (percent)	Woody wetlands (percent)	Emergent herbaceous wetlands (percent)
28	6,367.3	0.238	1.144	0.031	0	3.37	0.038	0	0	1.12	91.3	2.69	0.052	0
29	6,795.2	0.504	0	0	0	0.583	0.461	1.35	0.039	11.5	85.6	0	0	0
30	6,124.1	0.065	0.522	0.083	0	2.26	0.257	0.341	0	3.82	92.0	0.386	0.245	0
31	12,093	0.067	2.24	1.19	0	1.21	0	2.61	0	6.83	85.8	0.051	0.040	0
32	9,488.5	0.132	0.831	0.054	0	0.240	0	0.514	0	2.42	95.6	0.213	0	0
33	14,979	0.309	0.399	0.308	0.019	2.44	0.119	2.22	0	10.4	83.7	0.091	0.040	0
34	5,364.3	0	0.308	0.136	0	0	0	1.11	0	1.39	96.9	0.053	0.091	0
35	8,961.6	0.017	1.64	0.945	0	0.255	0	0.439	0	1.84	94.8	0	0.032	0
Study area watershed upstream from streamflow gage 08079600	165,935	0.186	1.39	0.053	0.001	3.92	0.228	0.800	0.002	4.3	81.1	7.95	0.065	0.032
Study area watershed downstream from streamflow gage 08079600	95,331	2.67	1.23	0.465	0.005	2.02	0.032	1.01	0.070	4.6	87.7	0.179	0.022	0



Base modified from U.S. Geological Survey 1:24,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

U.S. Geological Survey National Land Cover Database, 2006

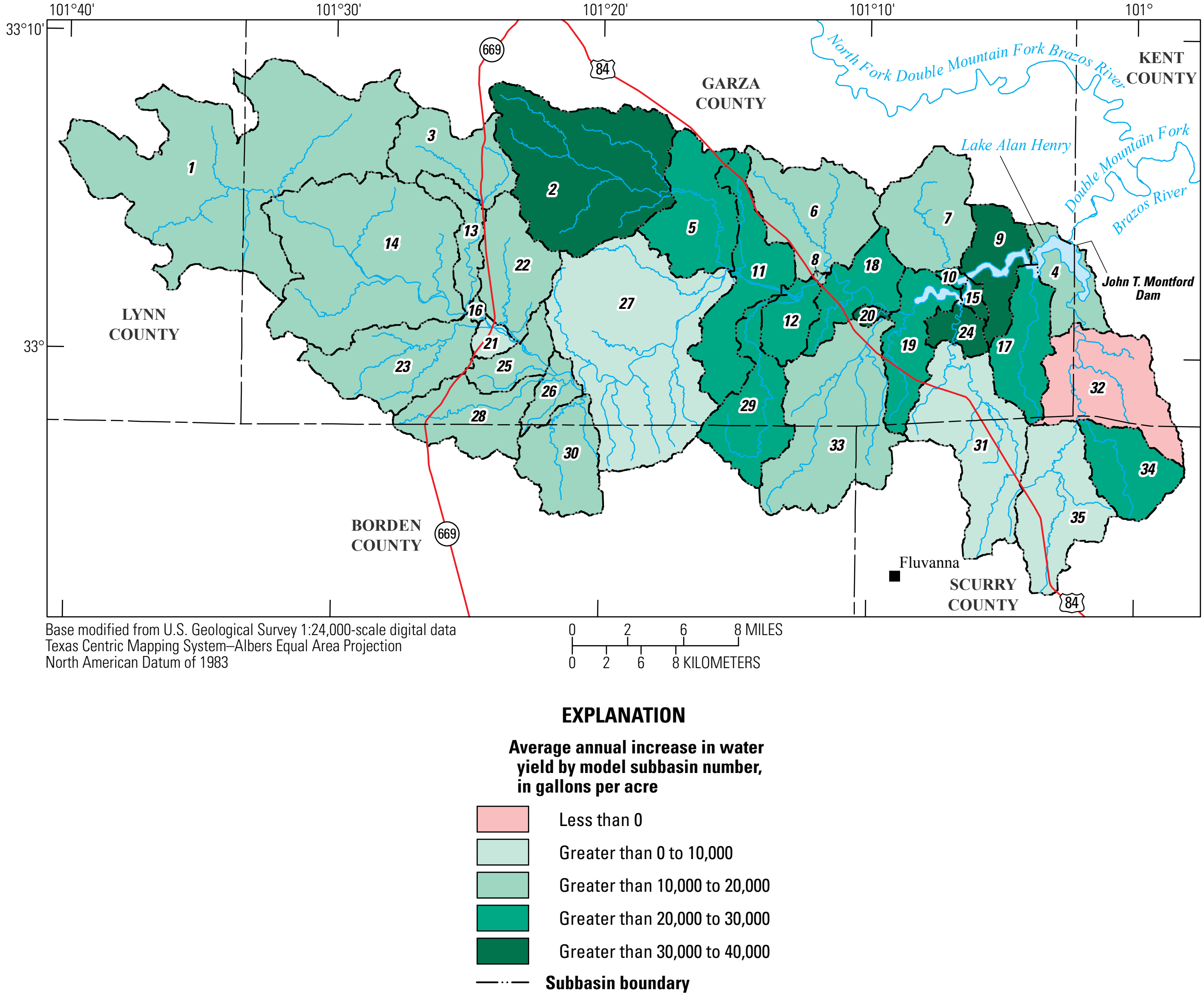
Note: National Land Cover Database 2006 land-cover categories modified by replacing all areas classified as shrubland with grassland in areas with land slope less than 20 percent (excluding riparian areas).

Figure 10. National Land Cover Database 2006 used for brush-management simulations modified by replacing all areas classified as shrubland with grassland in areas with land slope less than 20 percent and excluding riparian areas.

For each brush-management simulation, the HRUs were generated in the model using the modified land-cover data, keeping all parameter values and settings used for calibration constant, and allowing the model parameters associated with land cover to be automatically modified accordingly by the modeling software (Neitsch and others, 2011). 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 shrubland replaced with grassland. Change in water yield was calculated as the difference in annual water yield to the reach in a given subbasin using the model output parameter WYLD in the output.sub file (produced from a SWAT run); WYLD is the net amount of water that leaves a given subbasin and contributes to streamflow in the stream reach through surface runoff, lateral subsurface flow, and groundwater discharge over a given time step. Effective hydraulic conductivity in the main channel and tributary channel alluvium (CH_K) was not modified from its default SWAT value of zero, which effectively assumes there are no transmission losses; therefore, any increase in volume from a given subbasin computed from the WYLD output parameter in the output.sub file, following a brush-management simulation, represents an actual simulated increase in water yield to Lake Alan Henry.

Simulation Results

After replacement of shrubland with grassland in areas with land slope less than 20 percent and excluding riparian areas, the 20-year water yields to Lake Alan Henry increased in 34 of the 35 subbasins (fig. 11; table 6). The total increase in volume from these 34 subbasins was about 114,000 acre-ft, or about 5,700 acre-ft/yr. Because decreased water yields were simulated from subbasin 32 as a result of brush management, this subbasin was excluded from the sums listed at the bottom of table 6. Brush management would not be done in a subbasin where the result would be a decrease in water yield. In terms of the simulated increase in water yield per acre of shrubland replaced with grassland, the average annual increase in water yield was about 17,300 gal/acre (5,700 acre-ft converted to gallons divided by 107,260 acres, the total amount of area in the study watershed modified for brush-management simulation by replacing shrubland with grassland [table 6]) for the 34 subbasins in which an increase in water volume was simulated. The increase in average annual water yield in the same 34 subbasins ranged from 5,850 to 34,400 gal/acre of shrubland replaced with grassland. A higher average annual increase in water yield (21,700 gal/acre) was simulated in the subbasins downstream from the Justiceburg gage (excluding subbasin 32) than in the subbasins upstream from the Justiceburg gage (16,800 gal/acre).



Base modified from U.S. Geological Survey 1:24,000-scale digital data
Texas Centric Mapping System–Albers Equal Area Projection
North American Datum of 1983

Figure 11. Simulated average annual increase in water yield to Lake Alan Henry for the 35 subbasins of the Double Mountain Fork Brazos River watershed model after replacement of shrubland with grassland in areas with land slope less than 20 percent and excluding riparian areas, 1994–2013.

Table 6. Effects of brush management in areas with land slope less than 20 percent and excluding riparian areas on water yields to Lake Alan Henry simulated by the Soil and Water Assessment Tool watershed model of the Double Mountain Fork Brazos River watershed, western Texas, 1994–2013.

[Shaded cells include subbasins upstream from and directly contributing to U.S. Geological Survey streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Texas, while cells that are not shaded include subbasins downstream from the station that contribute directly to Lake Alan Henry; <, less than]

Subbasin number	Subbasin area (acres)	Amount of area in subbasin modified for brush-management simulation by replacing shrubland with grassland (acres)	Percentage of subbasin modified	Simulated increase or decrease in volume of water to Lake Alan Henry over entire 20-year period as a result of brush-management (acre-feet)	Increased average annual water yield to Lake Alan Henry per acre of shrubland replaced with grassland from each subbasin (gallons per acre)[1]
1	33,533	12,691	38	12,000	15,400
2	18,108	8,464	47	15,900	30,600
3	6,232.5	2,132	34	1,940	14,800
4	4,321.7	1,701	39	2,030	19,400
5	7,613.3	3,552	47	4,610	21,100
6	9,151.4	3,567	39	4,270	19,500
7	7,453.5	3,351	45	2,790	13,600
8	114.36	41.44	36	28.7	11,300
9	4,725.4	2,069	44	4,370	34,400
10	351.39	118.5	34	218	30,000
11	8,058.6	3,907	48	7,000	29,200
12	2,971.6	1,129	38	1,540	22,200
13	2,864.4	1,245	43	1,070	14,000
14	22,426	13,770	61	11,100	13,100
15	573.03	300.0	52	578	31,400
16	291.73	77.01	26	70.6	14,900
17	5,387.2	2,263	42	3,580	25,800
18	4,621.8	1,900	41	3,420	29,300
19	5,483.7	1,808	33	2,280	20,500
20	412.94	207.1	50	385	30,300
21	1,034.9	476.7	46	185	6,330
22	6,263.8	2,606	42	2,180	13,600
23	8,429.1	6,210	74	5,540	14,500
24	1,848.1	942.0	51	1,750	30,200
25	2,988.0	1,559	52	1,270	13,300
26	1,955.2	825.2	42	719	14,200
27	23,878	8,691	36	3,120	5,850
28	6,367.3	3,561	56	4,050	18,500
29	6,795.2	3,087	45	4,160	22,000
30	6,124.1	2,847	46	3,370	19,300
31	12,093	3,945	33	2,430	10,000
32	9,488.5	3,555	37	-3,400	<0
33	14,979	5,079	34	3,460	11,100
34	5,364.3	1,705	32	2,240	21,400
35	8,961.6	1,428	16	808	9,220
Sum[2]		**107,260**		**114,000**	

[1] The difference in annual water yield to the reach in a given 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 stream reach through surface runoff, lateral subsurface flow, and groundwater discharge over a given time step. Because there are no transmission losses through the main channel or tributary channel beds, the differences in the WYLD volumes between after brush-management and before brush-management model runs represent actual simulated increases in water yields to Lake Alan Henry.

[2] Sums do not include subbasin 32 because brush management would not be done in a subbasin where the result would be a decrease in water yield.

The simulated decrease in water yield from subbasin 32 is likely related to the relatively small amount of the subbasin area covered by very low infiltration rate soils (hydrologic soil group D). The relation between percentage of subbasin coverage of type D soils and subbasin water yield is statistically significant. Water yield increases as the percentage of coverage of type D soils increases (Kendall’s *tau* equals 0.34 with a corresponding p-value less than 0.01). Subbasin 32 has about 13 percent coverage of type D soils. The median and mean percentage of coverage of type D soils in all other subbasins is 31 and 34 percent, respectively. The simulated decrease in water yield from subbasin 32 could also be related to other subbasin attributes such as hydrologic soil group distribution by land slope.

The simulated average annual water yield increase into Lake Alan Henry from results of the Double Mountain Fork Brazos River watershed model (table 6) are compared with 22 other Texas watersheds where brush-management feasibility studies have been documented (fig. 12). Simulated increases in average annual water yields from 22 previous brush-management assessments in Texas (fig. 12) are from the State Water Supply Enhancement Plan (Texas State Soil and Water Conservation Board, 2014, chap. 9). The average annual water yield increase simulated by these 22 previous brush-management studies is 78,200 gal/acre, and the median is 64,900 gal/acre. The simulated average annual water yield increase for the Lake Alan Henry watershed from this analysis was less than the 25th percentile (23,700 gal/acre) reported by the 22 brush-management studies. For 4 of the 22 previous studies, the areal extent of the watershed ranged from 306 to 510 mi^2, which is within 25 percent of the size of the Lake Alan Henry watershed area (408 mi^2). The simulated average annual water yield increase per acre of brush replaced with grass for the Lake Alan Henry watershed was much

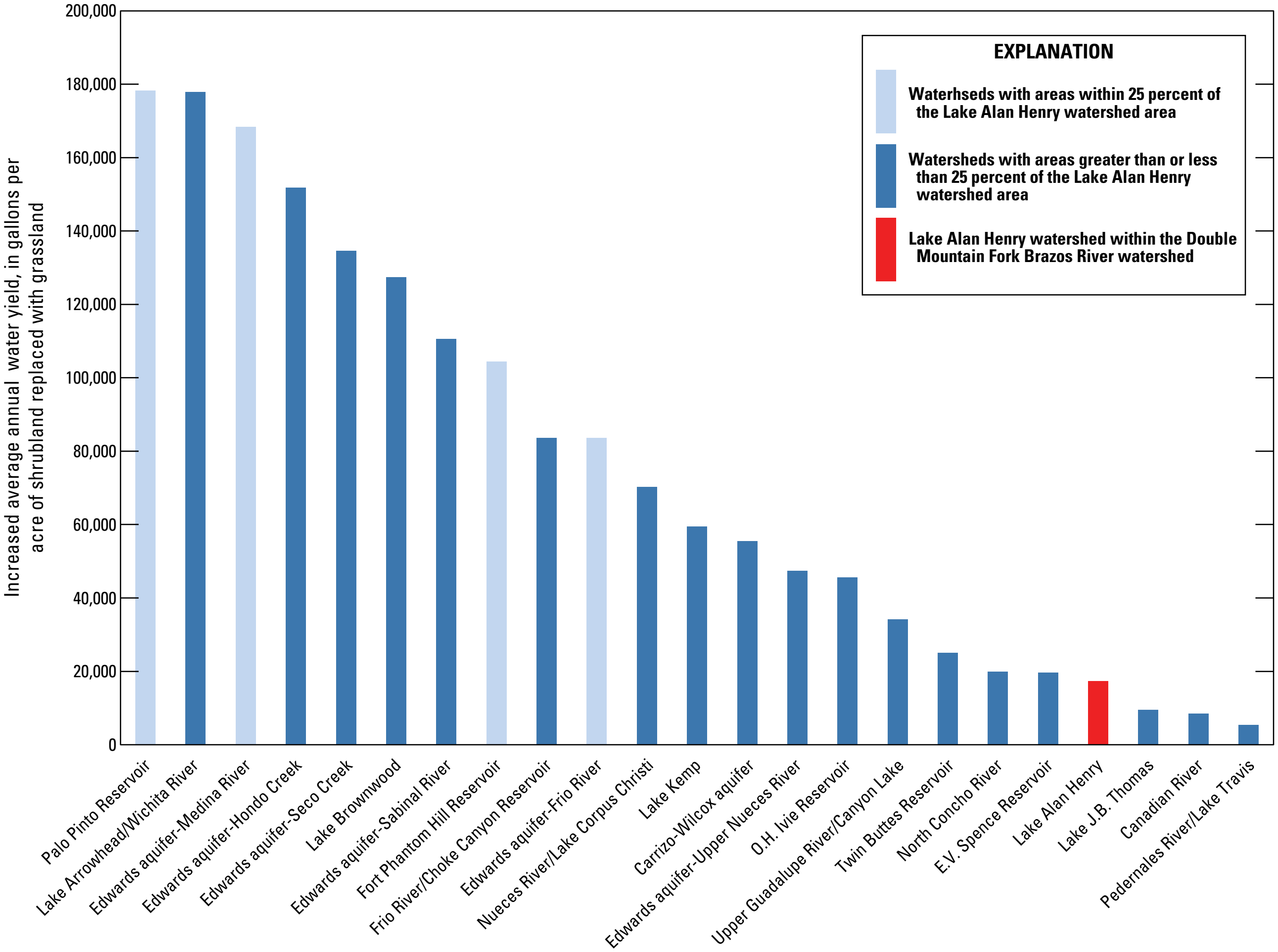


Figure 12. Modeled increases in average annual water yield resulting from brush management in 22 Texas watersheds (Texas State Soil and Water Conservation Board, 2014) for which feasibility studies have been documented and Lake Alan Henry simulated increases from results of the Double Mountain Fork Brazos River watershed model, 1994–2013.

lower compared to the simulated average annual water yield increase from these four studies of similar size watersheds in Texas (fig. 12). The relatively low yield resulting from brush-replacement in the Lake Alan Henry watershed is not surprising given average annual precipitation for the watershed is about 20 in. (Texas Water Development Board, 2012). The average annual precipitation falling on the Lake Alan Henry watershed is only slightly larger than the minimum precipitation threshold identified by Fish and Rainwater (2007) for yielding an increase in water yield from brush management. Citing the work of Hibbert (1979, 1983), Fish and Rainwater (2007) concluded that water yields would likely only be enhanced from brush management in watersheds receiving more than 18.0 in. of annual precipitation because vegetation would be expected to consume all available precipitation in areas receiving annual precipitation of less than this amount.

The results of additional analyses of the relation between water yield increases and land slope are presented in figures 13 and 14. The interpretations of the results presented in these figures of the relation between water yield increases and land slope assume that the relations between the data points in the figures are linear (figs. 13–14). For areas with land slope between 4 and 8 percent, every acre of shrubland replaced with grassland results in a corresponding increase in water volume to Lake Alan Henry. However, for areas with land slope between 8 and 16 percent, the rate of change of the water volume line is greater than the line representing the amount of shrubland replaced with grassland, indicating greater water yields to the lake when shrubland is replaced with grassland in this land slope category. The same relation of a greater increase in water yield per acre is evident when shrubland is replaced with grassland in areas with land slope between 16 and 20 percent.

Figure 14 presents the same fundamental information as figure 13 but depicted a different way. The increase in average annual water yield is put in terms of gallons per acre of shrubland replaced with grassland so the land-slope categories with the best yields are inferred from the slope of the blue line. The slope of the water yield line is the smallest with land slope between 4 and 8 percent, the greatest with land slope between 8 and 16 percent, and decreases slightly with land slope between 16 and 20 percent.

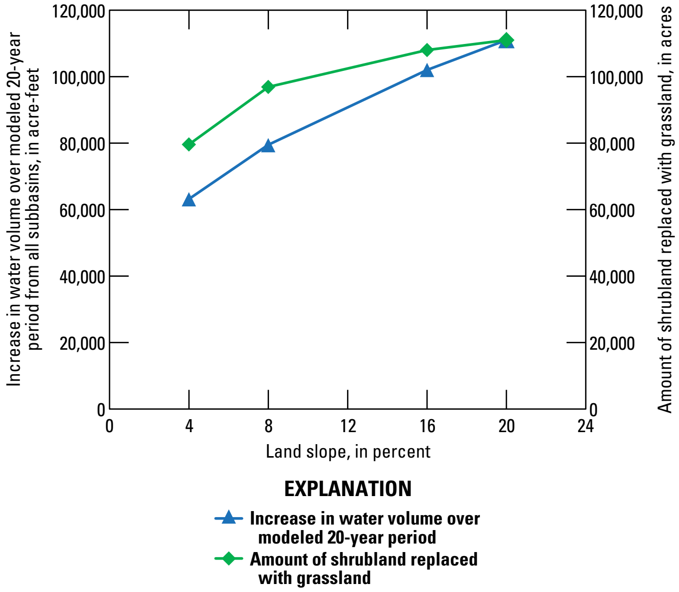


Figure 13. Relations between increase in water volume over modeled 20-year study period to Lake Alan Henry from all modeled subbasins and amount of shrubland replaced with grassland in areas with land slope of 4, 8, 16, and 20 percent and excluding riparian areas, 1994–2013.

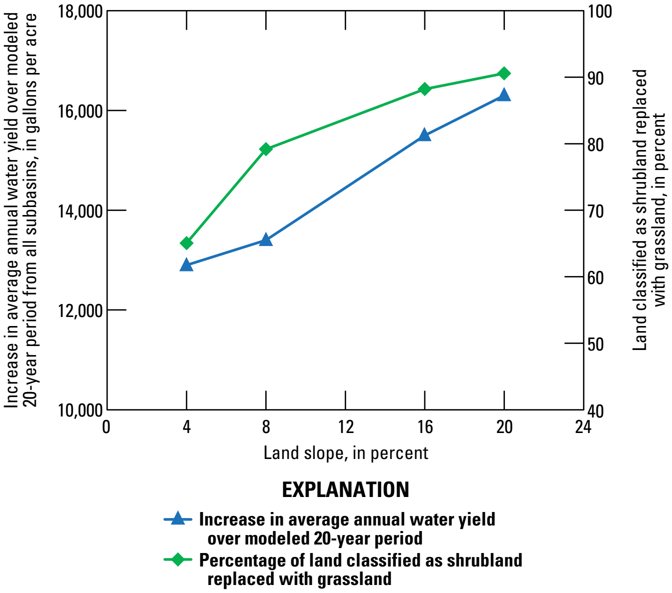


Figure 14. Relations between increase in average annual water yield over modeled 20-year study period to Lake Alan Henry from all modeled subbasins and percentage of land classified as shrubland replaced with grassland in areas with land slope of 4, 8, 16, and 20 percent and excluding riparian areas, 1994–2013.

Summary

The U.S. Geological Survey (USGS), in cooperation with the City of Lubbock and the Texas State Soil and Water Conservation Board (TSSWCB), developed a Soil and Water Assessment Tool (SWAT) watershed model of the Double Mountain Fork Brazos River watershed in western Texas to simulate monthly mean streamflow and to evaluate the effects of brush management on water yields in the watershed, particularly to Lake Alan Henry, from calendar years 1994–2013. 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. Woody plants have encroached into semiarid grasslands and savannas in Texas and their potential to decrease groundwater recharge and streamflow is well documented.

The 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. The purpose of the WSEP is to increase surface and groundwater through the selective control, removal, or reduction of noxious brush species, such as juniper, mesquite, or saltcedar that consume water to a degree that is detrimental to water conservation, and through the revegetation of land on which noxious brush has been controlled, removed, or reduced.

The SWAT watershed model simulations were done to quantify the possible changes in water yield of individual subbasins in the Double Mountain Fork Brazos River watershed as a result of the replacement of shrubland with grassland. The evaluation of possible reductions in water-yield increases as regrowth of shrubland occurs was beyond the scope of the study. Resource managers with the City of Lubbock and TSSWCB plan to use the model results as a tool to guide brush management in the Double Mountain Fork Brazos River watershed.

The model was calibrated on a monthly time step over the 15-year period from 1994 through 2008 and validated over the 5-year period from 2009 through 2013 with streamflow data collected at the USGS streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Tex. Calibration of the model required adjusting parameter values to minimize the differences between simulated and measured streamflows while also simulating the relative amounts of surface runoff, base flow, and evapotranspiration. Simulated monthly mean streamflow was a “good” fit to measured monthly data for the entire 20-year model and calibration period (percentage bias of +6, coefficient of determination of 0.73, and a Nash–Sutcliffe coefficient of model efficiency of 0.71). The model was evaluated throughout the entire process of calibration with respect to contributions from surface runoff, base flow, and evapotranspiration. Mean annual basin values from SWAT output indicate that surface runoff accounts for about 93.2 percent of total simulated streamflow, and base flow accounts for about 6.8 percent of total simulated streamflow. Mean annual simulated evapotranspiration is about 17.9 inches per year, and the mean annual ratio of simulated evapotranspiration to precipitation is 0.91. These simulated values compare well with actual computed and published values of percentage of surface runoff (90 percent), percentage of base flow (10 percent), and mean annual evapotranspiration (20–24 inches per year).

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 (1) the spatial distribution of the land-cover data did not change over time, (2) the model was calibrated using data from the only available streamflow-gaging station, and (3) 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 Database 2006, which was the land-cover data used to develop the watershed model, was modified to simulate shrubland replacement with grassland in each of the 35 model subbasins, and the model parameters associated with land cover were automatically modified accordingly by the modeling software. Change in water yield was calculated as the difference in annual water yield to the reach in a given subbasin using the model output parameter WYLD in the output.sub file; WYLD is the net amount of water that leaves a given subbasin and contributes to streamflow in the stream reach through surface runoff, lateral subsurface flow, and groundwater discharge over a given time step.

After replacement of shrubland with grassland in areas with land slope less than 20 percent and excluding riparian areas, the modeled 20-year water yields to Lake Alan Henry increased by 114,000 acre-feet, or about 5,700 acre-feet per year. In terms of the increase in water yield per acre of shrubland replaced with grassland, the average annual increase in water yield was 17,300 gallons per acre. Within the modeled subbasins, the increase in average annual water yield ranged from 5,850 to 34,400 gallons per acre of shrubland replaced with grassland. Subbasins downstream from USGS streamflow-gaging station 08079600 Double Mountain Fork Brazos River at Justiceburg, Tex., had a higher average annual increase in water yield (21,700 gallons per acre) than subbasins upstream from the streamflow-gaging station (16,800 gallons per acre).

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Appendixes

Appendix 1. Adjustment of Precipitation and Air Temperature Data from National Weather Service Meteorological Stations for Input into Soil and Water Assessment Tool (SWAT) Watershed Model of the Double Mountain Fork Brazos River Watershed, Western Texas

Precipitation and air temperature data from the National Weather Service (NWS) stations were used to simulate missing data for the West Texas Mesonet stations. To do this, raw precipitation and air temperature data from four NWS COOP (cooperative) stations were adjusted. The NWS COOP station precipitation data were bias adjusted using monthly bias correction factors, and maximum and minimum air temperature data were computed from regression equations.

The Soil and Water Assessment Tool (SWAT) automatically selects the nearest meteorological station for a given subbasin and uses data from the selected station for the entire simulated period. The SWAT does not make adjustments for the station that is assigned to a given subbasin when data from two different sources and different time periods are involved. For example, the MACY Mesonet station was assigned by SWAT to provide precipitation and air temperature data to 10 of the 35 subbasins, including subbasin number 1 at the far western edge of the watershed (fig. 3). The MACY Mesonet station began collecting data on January 1, 2002. Even though measured daily precipitation and air temperature data are available prior to January 1, 2002, from the NWS station COOP ID 418818 in Tahoka, Tex., SWAT will not automatically adjust and use these data. Measured data from COOP ID 418818 are not used, and simulated precipitation and air temperature data from the user-selected Weather Generator Database (WGEN), built into SWAT, are used instead. For this assessment, the WGEN_US_COOP_1960_2010 database was selected to provide simulated meteorological data when measured data were not available (Winchell and others, 2013). To take advantage of all the available measured data, precipitation and air temperature data from COOP ID 418818 and three other NWS stations were used to simulate missing data for the West Texas Mesonet stations: (1) NWS station COOP ID 414967 was used to simulate missing data for West Texas Mesonet station ALAN, located less than 1.0 mile (mi) away; and (2) NWS station COOP ID 413411 was used to simulate missing data for West Texas Mesonet station FLUV, located about 16.8 mi away; (3) NWS station COOP ID 418818 was used to simulate missing data for West Texas Mesonet station MACY, located about 17.5 mi away; (4) NWS station COOP ID 417206 was used to simulate missing data for West Texas Mesonet station POST, located less than 0.5 mi away.

The NWS station precipitation data were adjusted to the respective West Texas Mesonet station by totaling monthly precipitation when both stations had data and computing the ratio of Mesonet station precipitation to NWS station precipitation. To simulate missing data prior to activation of the respective Mesonet station, daily NWS station precipitation data were multiplied by the appropriate monthly correction factor to obtain a bias-adjusted Mesonet daily precipitation total for model input. Monthly totals and correction factors for the stations are included in appendix tables 1.1–1.4. The unadjusted and adjusted precipitation data used in the model are available in a zip file when report is downloaded.

To adjust maximum and minimum air temperature data, linear regression equations were developed to estimate daily maximum and minimum air temperature at West Texas Mesonet stations from NWS station data. The regression equations and regression model performance information are included in appendix table 1.5. The computed maximum and minimum air temperature data were used to simulate missing data prior to activation of the Mesonet stations. The unadjusted and adjusted air temperature data used in the model are available in a zip file when the report is downloaded.

Appendix 1.1. Total monthly precipitation when ALAN, NWS station ID KAHS/XAHS, West Texas Mesonet, Lake Alan Henry and NWS station COOP ID 414967, Lake Alan Henry both have data from September 1, 2005, through December 31, 2013.

[NWS, National Weather Service; COOP ID, cooperative station identification; mm, millimeters]

Month	(A) ALAN, NWS station ID KAHS/XAHS, West Texas Mesonet, Lake Alan Henry, monthly precipitation (mm)[1]	(B) NWS station COOP ID 414967, Lake Alan Henry, monthly precipitation (mm)[2]	Correction factor (ratio of A to B)[3]
January	132.59	119.63	1.11
February	186.43	145.03	1.29
March	280.14	262.89	1.07
April	485.37	390.40	1.24
May	357.07	351.03	1.02
June	670.28	609.85	1.10
July	624.79	550.42	1.14
August	540.75	526.03	1.03
September	463.28	433.83	1.07
October	412.46	394.21	1.05
November	46.72	46.99	0.99
December	237.19	203.20	1.17

[1] West Texas Mesonet, 2015.

[2] National Oceanic and Atmospheric Administration, 2015b.

[3] Correction was used to convert NWS station COOP ID 414967, Lake Alan Henry daily precipitation data to ALAN, NWS station ID KAHS/XAHS, West Texas Mesonet, Lake Alan Henry daily precipitation data from May 1, 1994, through August 31, 2005, and to fill in record after August 31, 2005.

Appendix 1.2. Total monthly precipitation when FLUV, NWS station ID KFVS/XFVS, West Texas Mesonet, Fluvanna and NWS station COOP ID 413411, Gail both have data from June 9, 2002, through December 31, 2013.

[NWS, National Weather Service; COOP ID, cooperative station identification; mm, millimeters]

Month	(A) FLUV, NWS station ID KFVS/XFVS, West Texas Mesonet, Fluvanna, monthly precipitation (mm)[1]	(B) NWS station COOP ID 413411, Gail, monthly precipitation (mm)[2]	Correction factor (ratio of A to B)[3]
January	170.38	166.12	1.03
February	230.02	185.93	1.24
March	293.05	299.21	0.98
April	562.58	434.09	1.30
May	536.88	696.96	0.77
June	799.33	596.15	1.34
July	643.31	701.01	0.92
August	707.58	685.53	1.03
September	575.03	746.75	0.77
October	514.28	481.59	1.07
November	221.46	215.89	1.03
December	198.33	188.45	1.05

[1] West Texas Mesonet, 2015.

[2] National Oceanic and Atmospheric Administration, 2015b.

[3] Correction was used to convert NWS station COOP ID 413411, Gail daily precipitation data to FLUV, NWS station ID KFVS/XFVS, West Texas Mesonet, Fluvanna daily precipitation data from January 1, 1989, through June 7, 2002, and to fill in record after June 7, 2002.

Appendix 1.3. Total monthly precipitation when MACY, NWS station ID KGHS/XGHS, West Texas Mesonet, Graham and NWS station COOP ID 418818, Tahoka both have data from January 1, 2002, through December 31, 2013.

[NWS, National Weather Service; COOP ID, cooperative station identification; mm, millimeters]

Month	(A) MACY, NWS station ID KGHS/XGHS, West Texas Mesonet, Graham, monthly precipitation (mm)[1]	(B) NWS station COOP ID 418818, Tahoka, monthly precipitation (mm)[2]	Correction factor (ratio of A to B)[3]
January	188.40	218.80	0.86
February	268.66	279.10	0.96
March	313.63	420.30	0.75
April	406.06	441.70	0.92
May	565.34	641.20	0.88
June	615.15	801.30	0.77
July	838.93	1,009.20	0.83
August	721.33	792.40	0.91
September	694.88	642.50	1.08
October	501.83	670.00	0.75
November	266.14	255.50	1.04
December	253.15	276.50	0.92

[1] West Texas Mesonet, 2015.

[2] National Oceanic and Atmospheric Administration, 2015b.

[3] Correction was used to convert NWS station COOP ID 418818, Tahoka daily precipitation data to MACY, NWS station ID KGHS/XGHS, West Texas Mesonet, Graham daily precipitation data from January 1, 1989, through December 31, 2001 and to fill in record after December 31, 2001.

Appendix 1.4. Total monthly precipitation when POST, NWS station ID KPT1/XPTS, West Texas Mesonet, Post and NWS station COOP ID 417206, Post both have data from November 1, 2001, through December 31, 2013.

[NWS, National Weather Service; COOP ID, cooperative station identification]

Month	(A) POST, NWS station ID KPT1/XPTS, West Texas Mesonet, Post, monthly precipitation (mm)[1]	(B) NWS station COOP ID 417206, Post, monthly precipitation (mm)[2]	Correction factor (ratio of A to B)[3]
January	224.77	216.00	1.04
February	306.52	295.90	1.04
March	389.57	360.00	1.08
April	476.42	456.40	1.04
May	624.27	617.30	1.01
June	723.35	934.40	0.77
July	969.40	981.00	0.99
August	858.73	924.10	0.93
September	813.99	820.70	0.99
October	610.03	697.60	0.87
November	423.17	455.20	0.93
December	290.03	330.00	0.88

[1] West Texas Mesonet, 2015.

[2] National Oceanic and Atmospheric Administration, 2015b.

[3] Correction was used to convert NWS station COOP ID 417206, Post daily precipitation data to POST, NWS station ID KPT1/XPTS, West Texas Mesonet, Post daily precipitation data from January 1, 1989, through October 31, 2001, and to fill in record after October 31, 2001.

Appendix 1.5. Regression equations used to convert daily maximum and minimum air temperature from NWS stations to daily maximum and daily minimum air temperature at West Texas Mesonet stations in degrees Celsius.

[NWS, National Weather Service; COOP ID, cooperative station identification; R^2, coefficient of determination; max, maximum; min, minimum; tmp, temperature; <, less than]

Predicted West Texas Mesonet station[1]	NWS station COOP ID used as independent variable[1]	Linear regression equation	Adjusted R^2	Residual standard error (degrees Celsius)	Intercept p-value	Slope p-value	Number of daily values used to generate regression
ALAN	414967	4.94 + 0.84 (max_air_ tmp 414967)	0.702	5.26	<0.00	<0.00	2,991
ALAN	414967	0.35 + 0.95 (min_air_ tmp 414967)	0.927	2.59	<0.00	<0.00	2,991
FLUV	413411	-1.63 + 1.01 (max_air_ tmp 413411)	0.914	2.80	<0.00	<0.00	3,740
FLUV	413411	-0.80 + 0.98 (min_air_ tmp 413411)	0.940	2.20	<0.00	<0.00	3,735
MACY	418818	3.52 + 0.85 (max_air_ tmp 418818)	0.712	5.08	<0.00	<0.00	4,365
MACY	418818	1.48 + 0.96 (min_air_ tmp 418818)	0.923	2.51	<0.00	<0.00	4,365
POST	417206	4.32 + 0.83 (max_air_ tmp 417206)	0.717	5.11	<0.00	<0.00	4,418
POST	417206	1.10 + 0.94 (min_air_ tmp 417206)	0.922	2.52	<0.00	<0.00	4,415

[1] For complete station information refer to table 1 of report.

Appendix 2. Methodology to Replace Shrubland with Grassland in National Land Cover Database 2006

Listed below are the steps used to replace 100 percent of land cover classified as “Shrubland” (National Land Cover Database [NLCD] code 52) with land cover classified as “Grassland” (NLCD code 71) in areas with slope within a specified range and not within a riparian zone. Riparian zones are defined as areas within 10 meters (32.8 feet) of a lake or stream. Slope categories included were areas with slope less than 4, 8, 16, and 20 percent.

1. As input data, use NLCD, and the slope raster and streams generated from the SWAT model;
2. Use the projected coordinate system, raster cell size, and study area that are consistent with the data used in the SWAT model;
3. Create a 10-meter buffer for riparian areas around lakes (NLCD water class) and the SWAT generated streams layer;
4. Combine the streams and lakes buffer zone rasters to create a single riparian buffer zone raster;
5. Reclassify the slope raster to differentiate areas with slope less than 20 percent and areas with slope greater than or equal to 20 percent;
6. Combine the reclassified slope raster and the riparian buffer raster so that both areas are represented in one raster;
7. Reclassify “Shrubland” (NLCD code 52) to “Grassland” (NLCD code 71) for areas with slope less than 20 percent and not within the riparian buffer zone; and
8. Repeat steps 5 through 7 for slope classes less than 4, 8, and 16 percent.

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