In cooperation with the San Antonio Water System

Simulation of Streamflow and Estimation of Recharge to the Edwards Aquifer in the Hondo Creek, Verde Creek, and San Geronimo Creek Watersheds, South-Central Texas, 1951–2003

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Simulation of Streamflow and Estimation of Recharge to the Edwards Aquifer in the Hondo Creek, Verde Creek, and San Geronimo Creek Watersheds, South-Central Texas, 1951–2003

By Darwin J. Ockerman

Abstract

The U.S. Geological Survey, in cooperation with the San Antonio Water System, constructed three watershed models using the Hydrological Simulation Program—FORTRAN (HSPF) to simulate streamflow and estimate recharge to the Edwards aquifer in the Hondo Creek, Verde Creek, and San Geronimo Creek watersheds in south-central Texas. The three models were calibrated and tested with available data collected during 1992–2003. Simulations of streamflow and recharge were done for 1951–2003. The approach to construct the models was to first calibrate the Hondo Creek model (with an hourly time step) using 1992–99 data and test the model using 2000–2003 data. The Hondo Creek model parameters then were applied to the Verde Creek and San Geronimo Creek watersheds to construct the Verde Creek and San Geronimo Creek models. The simulated streamflows for Hondo Creek are considered acceptable. Annual, monthly, and daily simulated streamflows adequately match measured values, but simulated hourly streamflows do not. The accuracy of streamflow simulations for Verde Creek is uncertain. For San Geronimo Creek, the match of measured and simulated annual and monthly streamflows is acceptable (or nearly so); but for daily and hourly streamflows, the calibration is relatively poor. Simulated average annual total streamflow for 1951–2003 to Hondo Creek, Verde Creek, and San Geronimo Creek is 45,400; 32,400; and 11,100 acre-feet, respectively. Simulated average annual streamflow at the respective watershed outlets is 13,000; 16,200; and 6,920 acre-feet. The difference between total streamflow and streamflow at the watershed outlet is streamflow lost to channel infiltration. Estimated average annual Edwards aquifer recharge for Hondo Creek, Verde Creek, and San Geronimo Creek watersheds for 1951–2003 is 37,900 acre-feet (5.04 inches), 26,000 acre-feet (3.36 inches), and 5,940 acre-feet (1.97 inches), respectively. Most of the recharge (about 77 percent for the three watersheds together) occurs as streamflow channel infiltration. Diffuse recharge (direct infiltration of rainfall to the aquifer) accounts for the remaining 23 percent of recharge. For the Hondo Creek watershed, the HSPF recharge estimates for 1992–2003 averaged about 22 percent less than those estimated by the Puente method, a method the U.S. Geological Survey has used to compute annual recharge to the Edwards aquifer since 1978. HSPF recharge estimates for the Verde Creek watershed average about 40 percent less than those estimated by the Puente method.

Introduction

The Edwards aquifer is one of the most productive aquifers in the United States and is the major source of public water supply for San Antonio and numerous smaller municipalities in south-central Texas. In addition, the Edwards aquifer supplies large quantities of water for agriculture, industry, military installations, and recreational activities. The aquifer also is a source of water to major springs in the region. These springs provide habitat for several threatened and endangered species and supply water to downstream users.

Parts of each of the study-area watersheds are within the recharge zone of the Edwards aquifer. Recharge to the Edwards aquifer is an important issue for water-resource managers in the San Antonio area. As part of a continuing program in cooperation with the Edwards Aquifer Authority (EAA), the U.S. Geological Survey (USGS) computes annual estimates of Edwards aquifer recharge. These estimates are based on a method for computing recharge developed by Puente (1978) using data collected from a network of USGS streamflow-gaging stations and a network of rain gages, some operated by the National Weather Service (NWS) and some by the EAA. The USGS has compiled annual estimates of Edwards aquifer recharge from 1934 to present (2004).

The method to estimate Edwards aquifer recharge (hereinafter referred to as the Puente method) uses monthly time periods. A watershed model, which uses smaller time steps (hourly) that more realistically simulate the relatively rapid rainfall-runoff-recharge processes in the study-area watersheds, might provide a more accurate estimation of aquifer recharge for these watersheds. Also, a calibrated watershed model enables predictive scenarios to estimate changes in recharge resulting from land-use changes including implementation of best-management practices (BMPs). Removal of juniper (*Juniperus ashei*) trees (Owens and others, 2001), construction of flood-control or recharge-enhancement structures (HDR Engineering, 1998), and rainfall enhancement (Edwards Aquifer Authority, 2004) are examples of BMPs that have been proposed or implemented in the three or similar watersheds in the region.

To address the need for accurate recharge estimates for the Edwards aquifer, the USGS, in cooperation with the San Antonio Water System conducted a study to apply a watershed model to simulate streamflow and recharge to the Edwards aquifer in the Hondo Creek, Verde Creek, and San Geronimo Creek watersheds in south-central Texas (fig. 1).

Purpose and Scope

The purpose of this report is to document application of the Hydrological Simulation Program—FORTRAN (HSPF) watershed model (Bicknell and others, 2001) to simulate streamflow and estimate recharge to the Edwards aquifer in the Hondo Creek, Verde Creek, and San Geronimo Creek watersheds. Calibration and testing of a model for each watershed are based on data collected during 1992–2003. Model simulations of streamflow and estimates of recharge are provided for 1951–2003. Model estimates of Edwards aquifer recharge also are compared to previous recharge estimates computed by the USGS using the Puente method.

Description of Study-Area Watersheds

The study-area watersheds are in south-central Texas west of San Antonio, along the southern part of the Edwards Plateau (often referred to as the Texas Hill Country) and near the transition to the Gulf Coastal Plain. The study-area watersheds encompass parts of the Edwards aquifer outcrop, which is essentially coincident with the recharge zone (fig. 1).

Hondo and Verde Creeks are part of the Frio-Nueces River system. Hondo Creek originates in south-central Bandera County and flows southeast for about 65 miles (mi) through Bandera, Medina, and Frio Counties to its confluence with the Frio River about 5 mi northwest of Pearsall. For this study, only the upper part of Hondo Creek, above the confluence with Verde Creek and including 161 square miles (mi^2) of drainage area, is included in the model simulations. Verde Creek begins in three branches in south-central Bandera County and runs south for about 20 mi to its confluence with Hondo Creek, about 4 mi east of the town of Hondo. The drainage area of the watershed is 219 mi^2. San Geronimo Creek enters the Medina River, which is part of the San Antonio-Guadalupe River system. San Geronimo Creek, beginning in northwestern Bexar County, runs southwest for about 20 mi through Bexar, Bandera, and Medina Counties to its mouth on the Medina River. The drainage area of the watershed is 68.5 mi^2.

The study area is described as having a subtropical, subhumid climate, characterized by hot summers and mild, dry winters (Larkin and Bomar, 1983). Heaviest rainfall tends to occur in spring, early summer, and fall, but heavy rainfall can occur throughout the year. Average annual rainfall (1961–90) in the study area is about 30 inches per year (in/yr). The San Antonio average monthly low temperatures range from 37.9 degrees Fahrenheit (°F) in January to 75.0 °F in July. Average monthly high temperatures range from 60.8 °F in January to 95.3 °F in August (Bomar, 1995).

The surface of the area upstream from the Edwards aquifer recharge zone (outcrop), the upper part of each watershed, is composed of Glen Rose Limestone (the uppermost unit of the Trinity aquifer, which is juxtaposed against the northern boundary of the Edwards aquifer). Glen Rose Limestone generally has low permeability compared to rocks of the Edwards Group, which compose almost all of the Edwards aquifer (Clark, 2003). Uneroded remnants of Edwards Group rocks (hilltops) that overlie Glen Rose Limestone in places are moderately permeable but are not connected to the Edwards aquifer. The central part of each watershed is in the Edwards aquifer recharge zone. In the Edwards aquifer recharge zone, outcropping Edwards Group rocks are characterized by high permeability because of faults, sinkholes, and other karst features. Relatively impermeable confining units overlie the Edwards aquifer south of the recharge zone, which is coincident with the lower part of each watershed. Relatively thin alluvial deposits of sand and silt also are at the surface, mainly along stream channels (Small and Clark, 2000).

Streams in the study-area watersheds originate in the topographically rugged Texas Hill Country north of the recharge zone and generally flow south, crossing the recharge zone and continuing onto units that overlie and confine the Edwards aquifer south of the recharge zone. Most, if not all of the streamflow is lost to faults, fractures, caves, and sinkholes as the streams cross the recharge zone. Although major streams on the Glen Rose Limestone outcrop (upstream from the recharge zone) are not classified as perennial, flow is much more frequent than on the Edwards Group outcrop (recharge zone). Hondo Creek at USGS streamflow-gaging station 08200000 Hondo Creek near Tarpley (upstream from the recharge zone) flows more than 90 percent of the time (1952–2004) and in some years is continuous. In contrast, Hondo Creek at USGS streamflow-gaging station 08200700 Hondo Creek at King Waterhole near Hondo

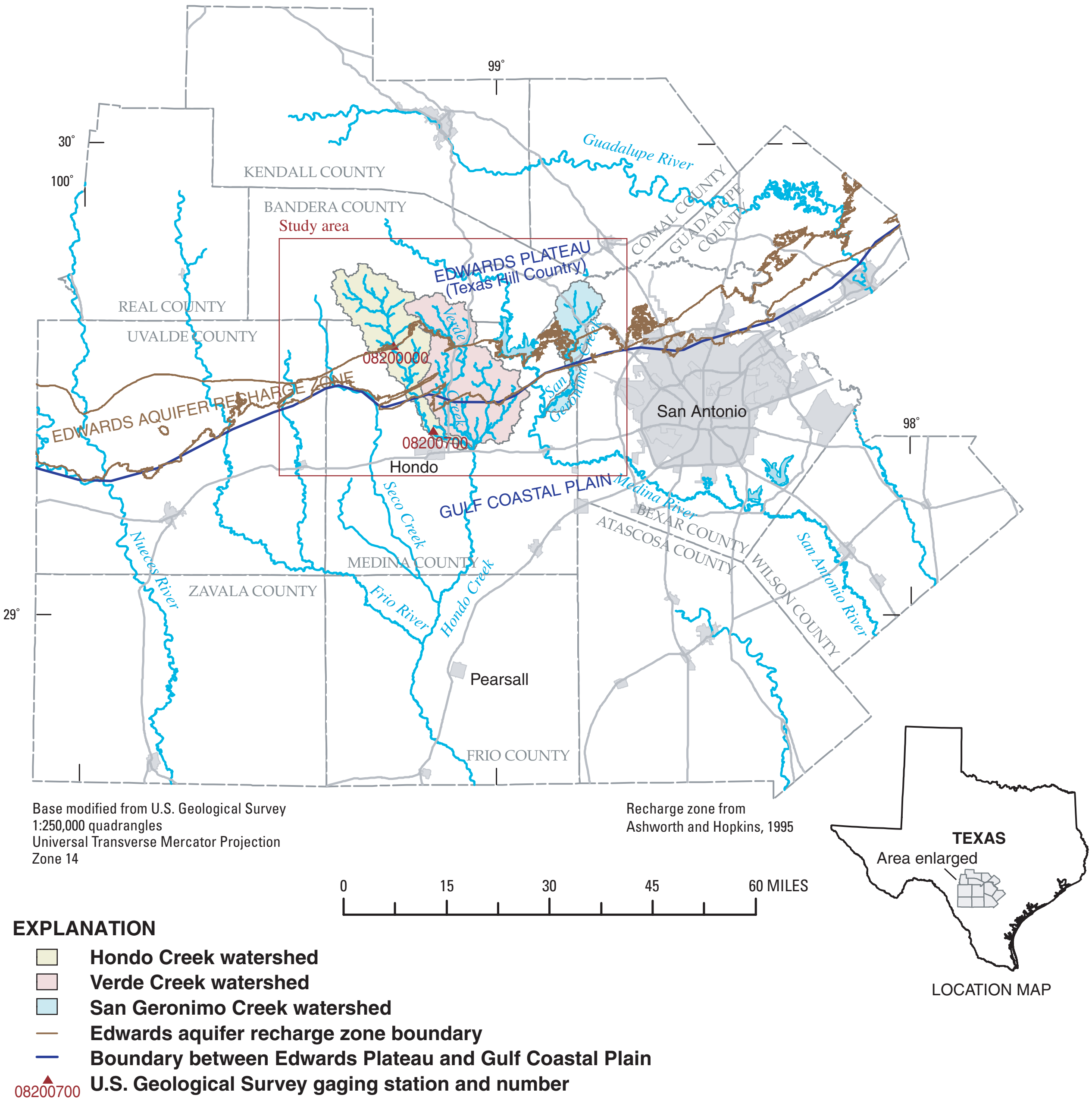

Figure 1. Location of Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas.

(downstream from the recharge zone) flows less than 10 percent of the time (1961–2004) and in some years does not flow (Aragon Long and others, 2005).

Streamflow losses in the Edwards aquifer recharge zone are believed to contribute directly to Edwards aquifer recharge (Puente, 1978; Land and others, 1983). Most recharge to the Edwards aquifer occurs as streamflow losses directly out of channels and other water courses. Infiltration of rainfall, or diffuse recharge, is relatively small compared to recharge occurring through streamflow losses (Maclay, 1995).

Land cover in the study-area watersheds (fig. 2), especially in the upper and middle parts of each watershed, is oak-juniper forest and rangeland (shrubland and grassland). Much of the lower part of each watershed (south of the recharge zone) is pasture and cultivated land. Development in the study-area watersheds is sparse, limited to farms, ranches, and a few small towns.

Land-surface elevation in the study-area watersheds ranges from about 730 to 2,000 feet above sea level. Land slopes generally are steeper in the upper parts of the watershed

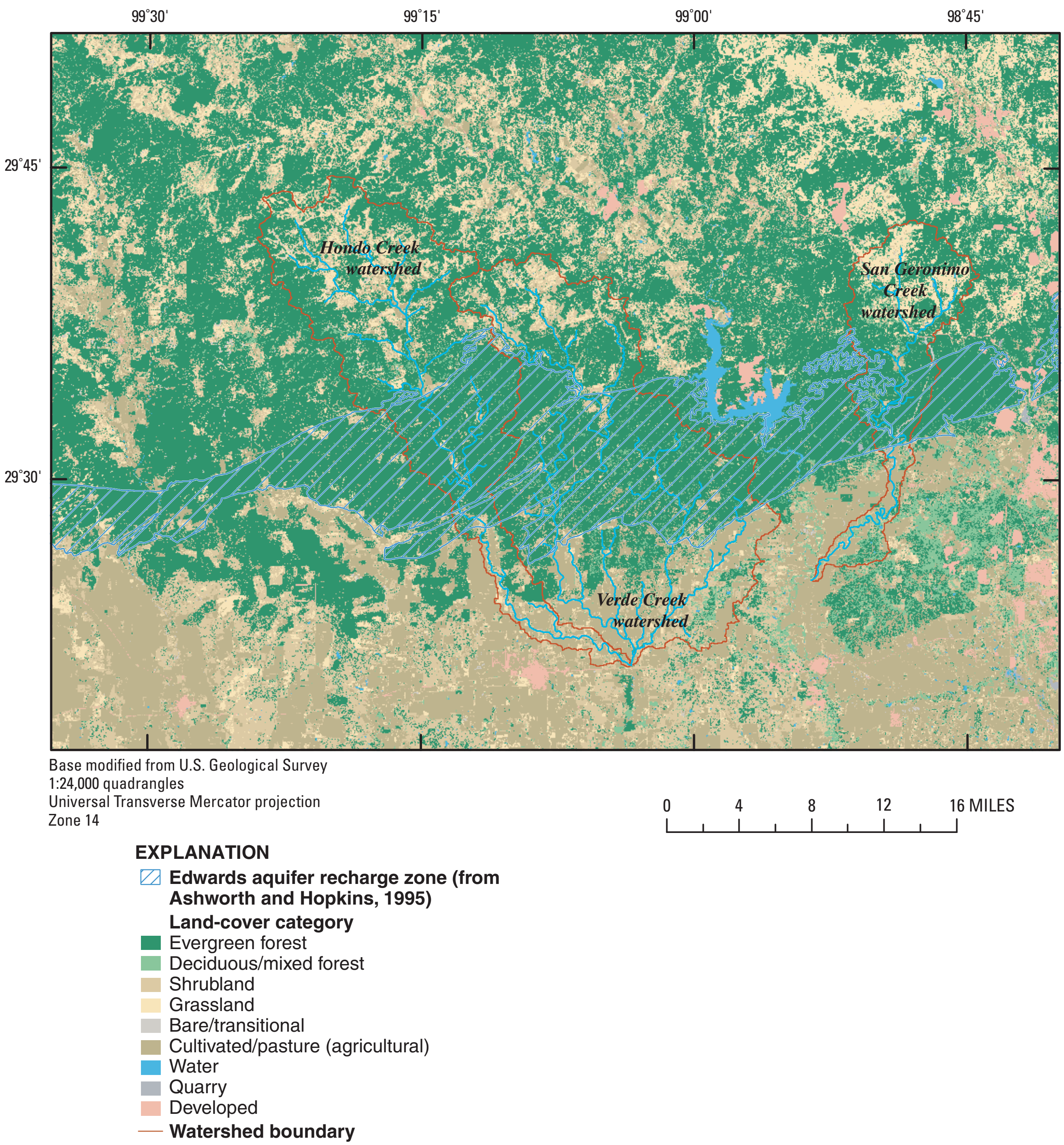

Figure 2. Land cover in Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas, early to mid-1990s (U.S. Geological Survey, 2003).

than in the lower parts. Soils in most of the watersheds, especially upstream from and on the Edwards aquifer recharge zone are thin, rocky, and clayey. In the lower parts of the watersheds, in the transition to Gulf Coastal Plains, the soils are deeper clay and sand loams.

Several small (less than about 1,000 acre-feet [acre-ft]) reservoirs and numerous smaller stock ponds are in the three watersheds. Most of these reservoirs (many constructed in the 1960s and 1970s) are in the upper parts of the watersheds, above the Edwards aquifer recharge zone, and probably have little influence on recharge to the Edwards aquifer. However, two structures in the recharge zone in the Verde Creek and San Geronimo Creek watersheds were constructed to enhance recharge to the Edwards aquifer by retaining and allowing for infiltration of streamflow that might otherwise exit the recharge zone (Edwards Aquifer Authority, 2004). The EAA has estimated that these two structures have increased recharge by an average of 1,699 acre-feet per year (acre-ft/yr) since their construction in the late 1970s (Edwards Aquifer Authority, 2004).

Domestic and agricultural water supply in the watersheds is obtained from Edwards aquifer wells in the lower parts and Trinity aquifer wells in the upper parts. No wastewater treatment discharge occurs in the study-area watersheds.

Simulation Approach

Because numerous watershed characteristics and hydrologic processes affect streamflow and recharge in the study-area watersheds, a comprehensive watershed model was needed to account for the complex interactions between watershed characteristics and hydrologic processes and to simulate streamflow and recharge. Also, a watershed model is necessary to evaluate changes in streamflow and recharge that might occur because of future changes in watershed characteristics (for example, land-use changes and possible implementation of BMPs).

The HSPF model was selected to model the study watersheds because it is one of the most comprehensive watershed models available, can simulate a wide variety of stream and watershed conditions with reasonable accuracy, and enables flexibility in adjusting model inputs to simulate alternative conditions, or scenarios (Donigian and others, 1995). HSPF is a watershed model used to simulate hydrologic processes in complex agricultural, rural, and urban watersheds. HSPF uses such information as the time history of rainfall, temperature, evaporation, and parameters related to land cover, land-use practices, and soil characteristics to simulate the hydrologic processes that occur in a watershed. The result of an HSPF simulation is a time history of the quantity of water transported over the land surface and through the various soil zones down to an aquifer (Donigian and others, 1995).

HSPF is an empirical model; conceptually, the process-related parameters of the model have physical meaning but are not physically measurable (or are difficult to measure) and must be specified by calibration. The HSPF model is divided into three components to simulate the hydrology of a watershed: pervious areas (segments), impervious areas (segments), and stream (and reservoir) segments. Pervious land conceptually is represented within HSPF by a series of interconnected water-storage zones: an upper zone, a lower zone, and a ground-water zone. Impervious land is represented by much simpler surface storage, evaporation, and runoff (overland flow) processes. Each user-defined, pervious or impervious land segment represents its own unique hydrologic response on the basis of soil type, land cover, watershed slope, or other important basin characteristics. These land segments do not need to be contiguous. Stream or reservoir segments (open or closed channels, or completely mixed lakes) are simulated using hydraulic routing methods (Donigian and others, 1995).

A schematic diagram depicting how HSPF simulates water movement through and across pervious and impervious land to the atmosphere, ground water, or surface runoff is shown in figure 3. The flow of water between the storage zones, stream, and atmosphere is affected by the process-related parameters listed in table 1.

The process-related model parameters for each land segment are adjusted to calibrate the model. Some process-related parameters can be adjusted monthly to account for seasonal variations: interception storage capacity (CEPSC), interflow index (INTFW), interflow recession coefficient (IRC), lower-zone evapotranspiration (LZETP), Manning's roughness coefficient (n) for assumed overland flow plane (NSUR), and upper-zone nominal storage (UZSN). For this study, monthly variation was implemented only for the parameter LZETP.

The six basin-related model parameters listed in table 2 define the areal extent of each land segment and other characteristics of each stream or reservoir segment, including length and tables of surface area, volume, and discharge, as a function of depth. Collectively, these parameters represent the physical characteristics of each land or stream segment in a watershed and generally remain unchanged during calibration of the model.

The HSPEXP computerized expert system (Lumb and others, 1994) was used to assist with process-related parameter adjustment for model calibration. The HSPEXP procedures consist of a set of hierarchical rules designed to guide the calibration of the model through a systematic evaluation of the model parameters. Simulation errors are evaluated on the basis of seven criteria: total streamflow volume, low-flow recession, highest 10 percent of daily flow volumes, lowest 50 percent of daily flow volumes, storm volumes, seasonal volumes, and summer storm volumes. Statistics computed by HSPEXP provide the analyst with an evaluation of the agreement between simulated and observed runoff values. Specifically for this study, simulation errors were evaluated by comparing total streamflow volume, 50-percent lowest flows, 10-percent highest flows, and selected storm peaks.

The Hondo Creek watershed includes two long-term gaging stations. Few streamflow data are available from the Verde Creek and San Geronimo Creek watersheds. The approach used in calibrating the study-area watershed models was to first calibrate and test the Hondo Creek model using available data for 1992–2003. Then the resulting calibrated parameters were transferred to the Verde Creek and San Geronimo Creek watersheds to create the Verde and San Geronimo models. The few streamflow data available from the San Geronimo Creek watershed were used for testing transferability of Hondo Creek model parameters to the other two watersheds.

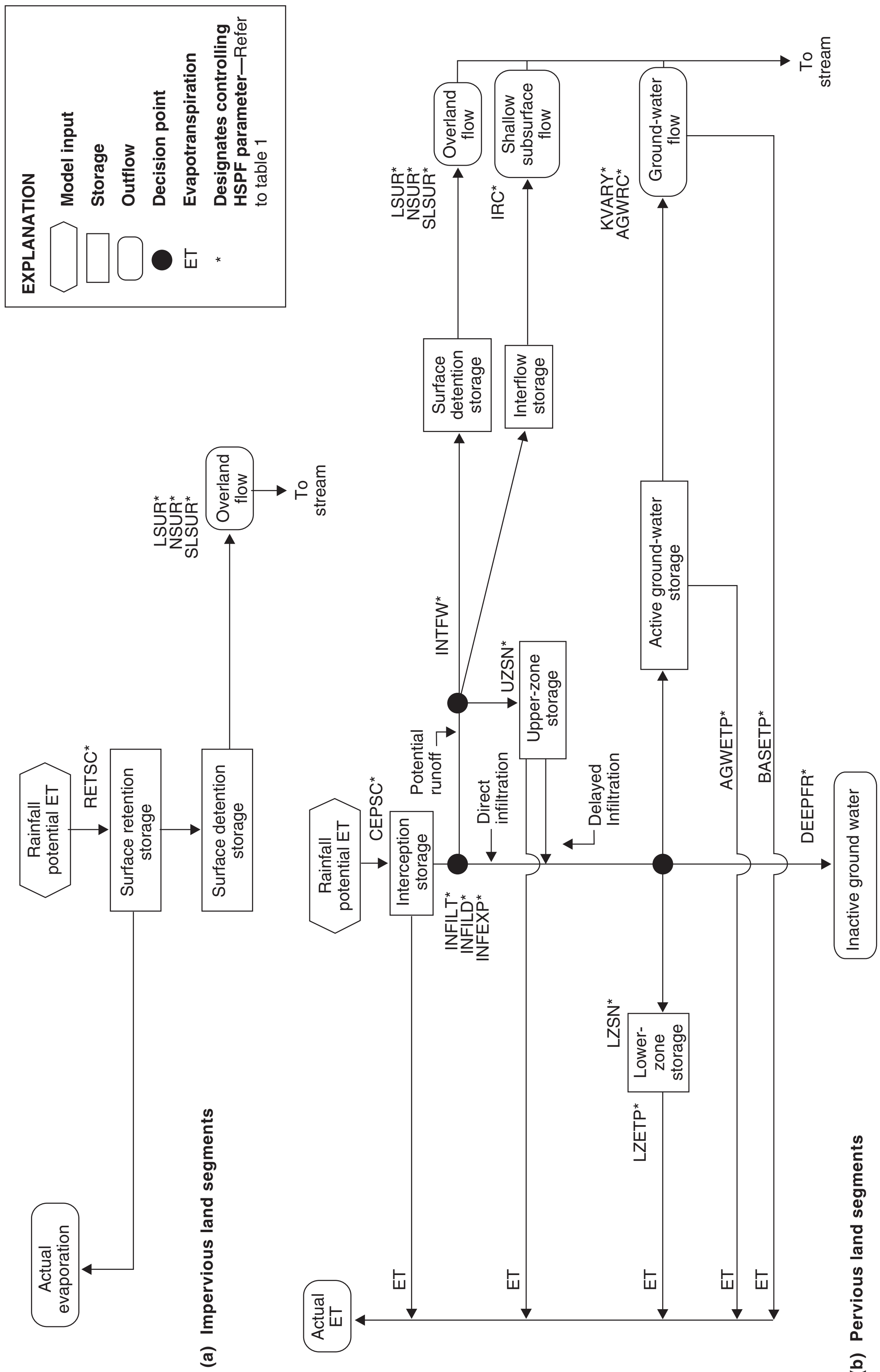

Figure 3. Hydrological Simulation Program—FORTRAN (HSPF) flowchart for (a) impervious and (b) pervious land segments (modified from Wicklein and Schiffer, 2002, fig. 3).

Table 1. Process-related model parameters for the Hydrological Simulation Program—FORTRAN (modified from Wicklein and Schiffer, 2002, table 1).

[PERLND, pervious segment; IMPLND, impervious segment]

Parameter	Description[1]	Land area
AGWETP	Fraction of available potential evapotranspiration demand that can be met from stored ground water	PERLND
AGWRC	Ground-water recession parameter. Index of the rate at which ground water drains from land	PERLND
BASETP	Fraction of available potential evapotranspiration demand that can be met from ground-water outflow; simulates evapotranspiration from riparian vegetation	PERLND
CEPSC	Interception storage capacity	PERLND
DEEPFR	Fraction of ground water that does not discharge to surface within boundaries of modeled area	PERLND
INFEXP	Infiltration equation exponent; controls rate of infiltration decrease as a function of increasing soil moisture	PERLND
INFILD	Ratio of maximum and mean infiltration capacities	PERLND
INFILT	Index to infiltration capacity of soil; also affects percolation to ground-water zone	PERLND
INTFW	Interflow index; controls amount of infiltrated water that flows as shallow subsurface flow	PERLND
IRC	Interflow recession coefficient; index for rate of shallow subsurface flow	PERLND
KVARY	Ground-water outflow modifier; index of how much effect recent recharge has on ground-water outflow	PERLND
LSUR	Length of assumed overland flow plane	PERLND or IMPLND
LZETP	Lower-zone evapotranspiration; index value (ranging from 0 to 0.99) representing density of deep-rooted vegetation	PERLND
LZSN	Lower-zone nominal storage; index to soil moisture holding capacity of unsaturated zone	PERLND
NSUR	Manning's n for assumed overland flow plane	PERLND or IMPLND
RETSC	Impervious retention storage capacity	IMPLND
SLSUR	Slope of assumed overland flow plane	PERLND or IMPLND
UZSN	Upper-zone nominal storage; index to amount of surface storage in depressions and upper few inches of soil	PERLND

[1] Users manual for Hydrological Simulation Program—FORTRAN (Bicknell and others, 2001) provides a more complete description of each parameter.

Simulation of Streamflow and Estimation of Recharge

The major steps for simulating streamflow and estimating Edwards aquifer recharge for the study area included data collection and compilation, model development, model calibration and testing, and simulation of streamflow and recharge during 1951–2003.

Data Collection and Compilation

Input data for the HSPF models include spatial data (land cover, geology-soils, topography, and stream characteristics such as stream-segment length and cross-section dimensions) and meteorologic time-series data (rainfall and pan evaporation). Spatial data were used to develop model hydrologic response units (HRUs) (PERLND [PERvious LaND] and IMPLND [IMPervious LaND], in HSPF terminology). Time series of rainfall, streamflow, and evapotranspiration were used as input for model calibration, testing, and simulations.

Land-cover spatial data were derived from early to mid-1990s satellite data (U.S. Geological Survey, 2003). The resulting land-cover map (fig. 2) comprises nine land-cover categories.

Geology is based on that of Maclay (1995) and Small and Clark (2000). Watershed topography was obtained from USGS 7.5-minute digital elevation model (DEM) files (U.S. Geological Survey, 2001). The DEMs also were used to delineate subbasins as part of the model construction. Channel characteristics

Table 2. Basin-related model parameters for the Hydrological Simulation Program—FORTRAN.

[PERLND, pervious segment; IMPLND, impervious segment, FTABLE, table of depth, surface area, volume, and discharge for each stream reach]

Parameter	Description	Units
AREA	Drainage area of each PERLND or IMPLND	Acres
LEN	Stream reach length	Miles
DEPTH	FTABLE depth	Feet
SAREA	FTABLE surface area	Acres
VOL	FTABLE volume	Acre-feet
DISCH	FTABLE discharge	Cubic feet per second

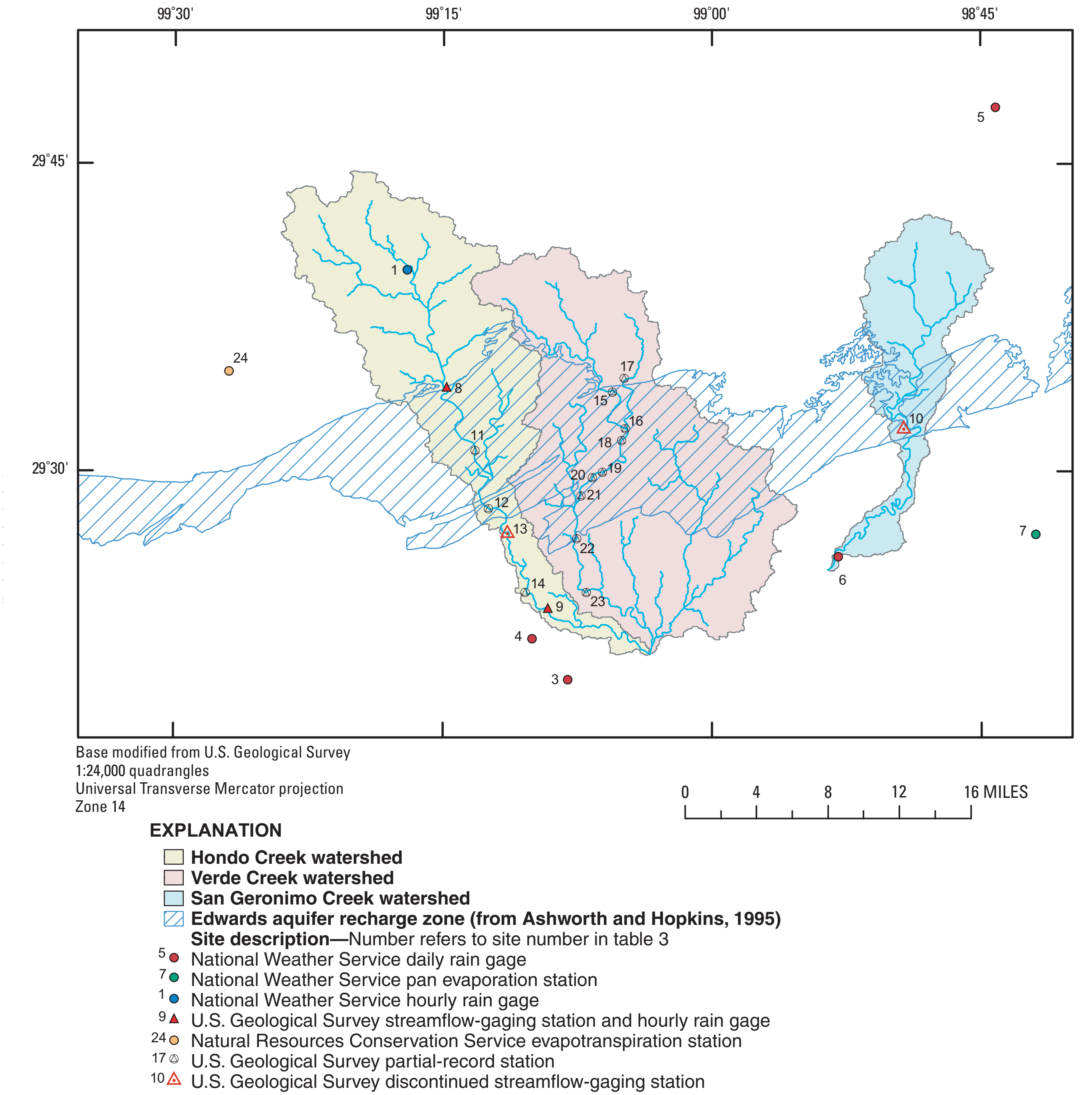

Figure 4. Location of data-collection sites used for Hydrological Simulation Program—FORTRAN (HSPF) model calibration, testing, and simulations, Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas.

for each segment (surface area, volume, and discharge as a function of depth) also were determined from DEM files using geographic information system tools available through the Watershed Modeling System software (U.S. Army Corps of Engineers, Coastal and Hydraulic Laboratory, 2004).

Meteorologic data compiled and used as input to the watershed models included rainfall and pan evaporation data. Data-collection sites are shown in figure 4. Station information for each data-collection site identified in figure 4 is listed in table 3. Five rain gages were used as the primary source of rainfall data to the models (sites 1, 4, 5, 6, and 8 in fig. 4 and table 3). Because some of the gages were not in operation during the entire study period (1992–2003), data from three additional sites (2, 3, and 6a in table 3) also were used. Because hourly

Table 3. Data-collection stations used for Hydrological Simulation Program—FORTRAN model input, calibration, and simulations for Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas.

[dd, degrees; mm, minutes; ss, seconds; NWS, National Weather Service; --, unknown; USGS, U.S. Geological Survey; CR, County Road; FM, Farm Road; SH, State Highway, NRCS, Natural Resources Conservation Service]

Site number (fig. 4)	Station name, number (short name)	Latitude (ddmmss)	Longitude (ddmmss)	Type of data	Period of record used
1	NWS near Tarpley, Tex., 418845 (Tarpley NWS)	29°40'--"	99°17'--"	Hourly rainfall	1951–2003
[1]2	NWS near Leaky, Tex., 414254 (Leaky NWS)	29°44'--"	99°46'--"	Hourly rainfall	1951–2003
3	NWS near Hondo, Tex., 414254 (Hondo NWS)	29°20'--"	99°08'--"	Daily rainfall	1952–75
4	NWS at Hondo Airport, Tex., 414256 (Hondo Airport NWS)	29°22'--"	99°10'--"	Daily rainfall	1975–2003
5	NWS at Boerne, Tex., 410902 (Boerne NWS)	29°48'--"	98°44'--"	Daily rainfall	1951–2003
6	NWS at Rio Medina, Tex., 417628 (Rio Medina NWS)	29°26'--"	98°53'--"	Daily rainfall	1951–2003
[1]6a	NWS at San Antonio International Airport, San Antonio, Tex., 417945 (San Antonio Airport NWS)	29°32'--"	98°28'--"	Hourly rainfall	1951–2003
7	NWS at Sea World, San Antonio, Tex., 418169 (Sea World NWS)	29°27'--"	98°42'--"	Pan evaporation	1988–2003
[1]7a	NWS at Canyon Dam, Comal County, Tex., 411429 (Canyon Dam NWS)	29°52'--"	98°12'--"	Pan evaporation	1961–88
8	USGS Hondo Creek near Tarpley, Tex., 08200000 (Tarpley USGS)	29°34'10"	99°14'47"	Streamflow and hourly rainfall	1992–2003
9	USGS Hondo Creek at King Waterhole near Hondo, Tex., 08200700 (King Waterhole)	29°23' 26"	99°09' 04"	Streamflow and hourly rainfall	1992–2003
10	USGS San Geronimo Creek Reservoir inflow near Rio Medina, Tex., 08180590 (discontinued) (San Geronimo Creek Reservoir inflow)	29°32'23"	98°49'06"	Streamflow	1992–93
11	USGS Hondo Creek at CR 232 near Hondo, Tex., 08200020	29°31'37"	99°13'22"	Partial-record streamflow measurement	1981
12	USGS Hondo Creek at FM 462 near Hondo, Tex., 08200100	29°28'23"	99°12'16"	Partial-record streamflow measurement	1981
13	USGS Hondo Creek near Hondo, Tex., 08200500 (discontinued)[2]	29°27'05"	99°11'07"	Partial-record streamflow measurement	1981
14	USGS Hondo Creek near FM 462 near Hondo, Tex., 08200650	29°24'17"	99°10'22"	Partial-record streamflow measurement	1981
15	USGS Middle Verde Creek upstream SH 173 near Bandera, Tex., 08200976	29°34'08"	99°05'55"	Partial-record streamflow measurement	1980–81
16	USGS Middle Verde Creek above East Verde Creek near Bandera, Tex., 08200978	29°32'17"	99°04'47"	Partial-record streamflow measurement	1980–81
17	USGS East Verde Creek near Bandera, Tex., 08200979	29°34'41"	99°04'48"	Partial-record streamflow measurement	1980–81
18	USGS Middle Verde Creek below East Verde Creek near Bandera, Tex., 0820097960	29°31'17"	99°05'04"	Partial-record streamflow measurement	1980–81
19	USGS Middle Verde Creek below reservoir near Bandera, Tex., 08200992	29°30'11"	99°06'02"	Partial-record streamflow measurement	1980–81
20	USGS Middle Verde Creek Reservoir outflow near Hondo, Tex., 08201000	29°30'05"	99°06'31"	Partial-record streamflow measurement	1980–81
21	USGS Middle Verde Creek above Martin Creek near Hondo, Tex., 08201005	29°29'01"	99°07'18"	Partial-record streamflow measurement	1980–81
22	USGS Verde Creek at Seifert Ranch near Hondo, Tex., 08201030	29°27'00"	99°07'30"	Partial-record streamflow measurement	1980–81
23	USGS Verde Creek near Hondo, Tex., 08201050	29°24'16"	99°06'59"	Partial-record streamflow measurement	1980–81
24	NRCS Seco Creek study area, Uvalde County, Tex.	29°35'--"	99°27'--"	Evapotranspiration	1992–95

[1] Not shown in figure 4.
[2] Streamflow 1951–64.

Table 4. Sources of rainfall data used to provide missing record and time-step disaggregation for primary rainfall time series used in the Hydrological Simulation Program—FORTRAN (HSPF) model, Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas.

[NWS, National Weather Service; USGS, U.S. Geological Survey; --, not used]

Primary rain gage	Period of record	Data time step	Gages used to fill missing data	Gages used for disaggregation
Tarpley NWS	1951–2003	Hourly	Leakey NWS (1951–91); Tarpley USGS (1992–2003)	--
Tarpley USGS	1992–2003	Hourly	Tarpley NWS	--
Hondo Airport NWS	1975–2003	Daily	Tarpley NWS	Tarpley NWS, San Antonio Airport NWS
Boerne NWS	1951–2003	Daily	Rio Medina NWS	Tarpley NWS, San Antonio Airport NWS
Rio Medina NWS	1951–2003	Daily	Hondo Airport NWS, Hondo NWS	Tarpley NWS, San Antonio Airport NWS

rainfall data are preferred for the model simulations, data from NWS daily stations were disaggregated[1] to hourly data by using the nearest NWS or USGS stations with available hourly data. Information on which gages were used to fill missing record and gages used for dissaggregation is listed in table 4.

Two NWS stations were used as the source of potential evaporation data for the models. The Sea World NWS station at San Antonio (site 7a in table 3) provided data for 1961–88. Average 1988–2003 monthly values of pan evaporation from Sea World were used to estimate evaporation for 1951–60 (the Canyon Dam station began operation in 1961). The NWS daily (monthly, before 1961) pan evaporation data were disaggregated[1] to hourly rates for each day for model simulations.

Streamflow data for calibrating HSPF streamflow were available for 1992–2003 from two active USGS streamflow-gaging stations (fig. 4, table 3). Station 08200000 Hondo Creek near Tarpley monitors streamflow from the upper 95.6 mi^2 of the watershed; station 08200700 Hondo Creek at King Waterhole near Hondo monitors the upper 149 mi^2 of the watershed. Station 08200500 Hondo Creek near Hondo, operated during 1953–64, measured streamflow from the upper 132 mi^2 of the watershed. Verde Creek is ungaged. Supplementary streamflow measurements were made at selected sites on Hondo and Verde Creeks after several storms in 1980 and 1981 (Land and others, 1983) (sites 11–23, fig. 4 and table 3). These measurements were made to help quantify streamflow losses in the Edwards aquifer recharge zone. Data from a discontinued streamflow-gaging station on San Geronimo Creek (08180590 San Geronimo Creek Reservoir inflow near Rio Medina) were available for 1992–93.

Model Construction

HSPF models of the three watersheds were constructed by (1) defining subwatersheds for the watersheds; (2) classifying unique HRUs on the basis of combinations of land cover, geology, and slope; and (3) and determining initial (uncalibrated) values of associated model parameters. Initial parameter estimates were obtained primarily from previous studies (Brown and Raines, 2002; Ockerman, 2002) and secondarily from hydrologic judgment.

The HSPF models were configured by dividing each watershed into subwatersheds (fig. 5) to produce discrete HSPF stream and reservoir segments. Guidelines for developing the stream-segment configuration include defining segments with (1) similar flow travel times that approximate the model simulation time step, (2) homogeneous channel properties, such as slope and conveyance, and (3) outlets of subwatersheds at important points, such as streamflow-gaging stations, reservoirs, outcrop boundaries, and inflows or outflows. The area of each subwatershed is listed in table 5.

Five rain-gage sites provided the primary rainfall inputs to the models. Rainfall data were applied to the model subwatersheds (fig. 6) on the basis of a modified Thiessen distribution (Wanielista, 1990). A single pan evaporation time-series data set (Sea World NWS, fig. 4 and table 3) was applied to the model subwatersheds.

In each subwatershed, pervious and impervious HRUs were classified according to combinations of three factors: geology, land cover, and land slope. Five geology categories are (1) Glen Rose Limestone (Trinity aquifer outcrop), (2) Edwards Group outcrop (Edwards aquifer recharge zone), (3) Edwards Group remnants (hilltops) overlying Glen Rose Limestone, (4) Edwards upper confining units, and (5) alluvial deposits. Land cover was one or more of the eight categories (excluding water) shown in figure 2. Land slopes were classified into three categories: Low slope, 0–5 percent; medium slope, 5–10 percent; and steep slope, greater than 10 percent.

Combinations of geology, land cover, and land slope result in 120 possible unique HRUs, not including impervious land cover. The actual number of HRUs in the models is 111 because some combinations do not exist (for example, alluvial deposits

[1] The rainfall and potential evaporation disaggregation programs are part of the BASINS watershed modeling software package (U.S. Environmental Protection Agency, 2003). Daily rainfall is disaggregated according to the temporal rainfall distribution at one or more nearby hourly stations. Daily potential evaporation is distributed on the basis of latitude and time of year.

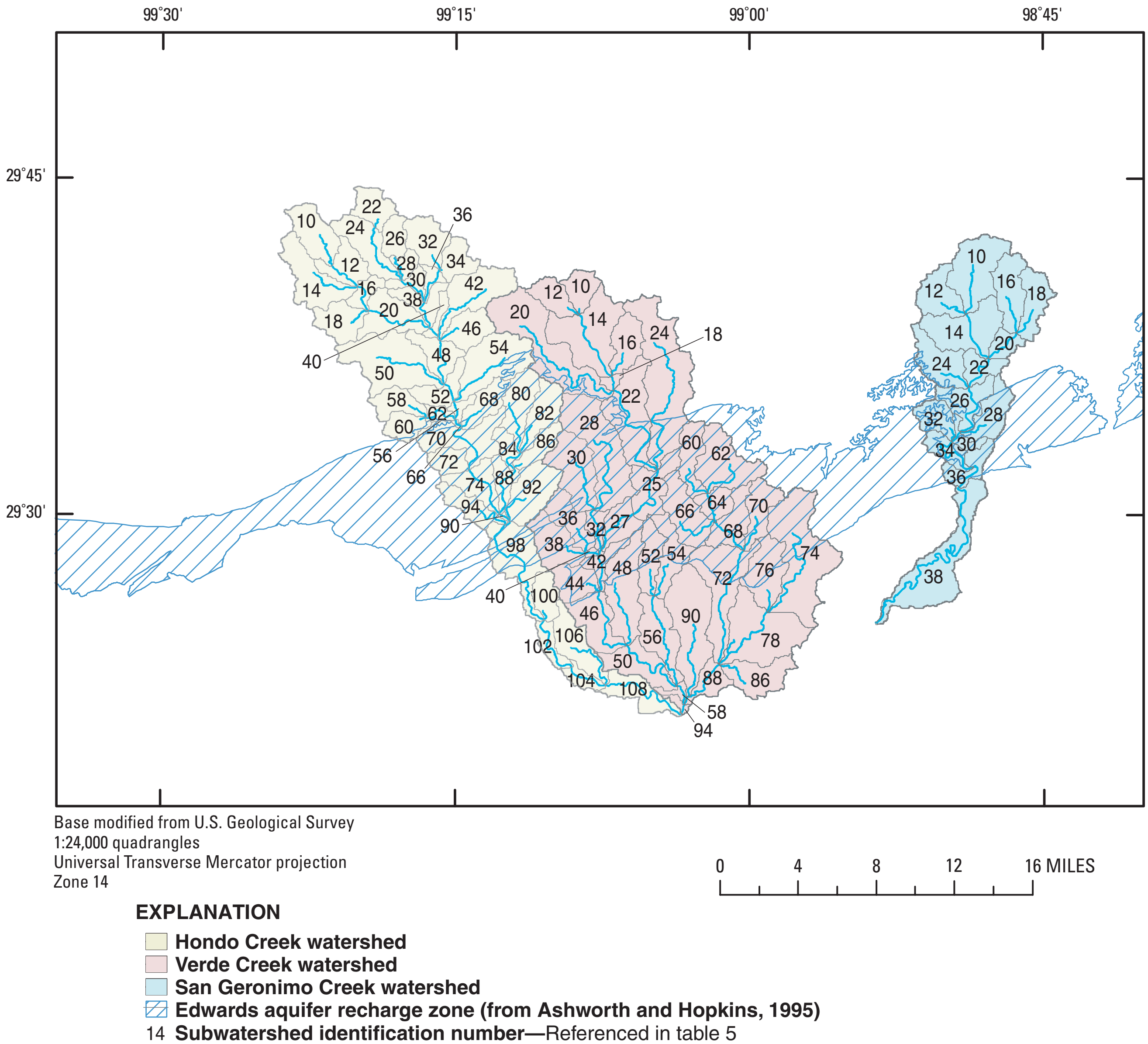

Figure 5. Subwatersheds in Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas, for Hydrological Simulation Program—FORTRAN (HSPF) model development.

on steep slopes). In HSPF teminology, HRUs correspond to PERLND and IMPLND segments.

In each watershed, substantial amounts of runoff are lost to streamflow channel infiltration (recharge) as the creeks flow across the Edwards aquifer recharge zone. HSPF does not include process parameters or specific features to account for natural streamflow losses. Instead, these losses are simulated as water withdrawals from each stream segment. The withdrawals are specified in the stream segment (FTABLE) configuration as a function of streamflow. The relation between streamflow losses and streamflow for a specific channel segment/watershed is based on gain-loss measurements made by Land and others (1983) at selected sites along Hondo and Verde Creeks. Additional streamflow measurements were made on Hondo Creek in June 2004 (Aragon Long and others, 2005).

Model construction was completed by assigning initial values to process-related HSPF parameters. These values represented a starting point for calibration of the models by trial-and-error parameter adjustment. Initial values of parameters related to streamflow and recharge were based on previous HSPF studies in the region (Brown and Raines, 2002; Ockerman, 2002).

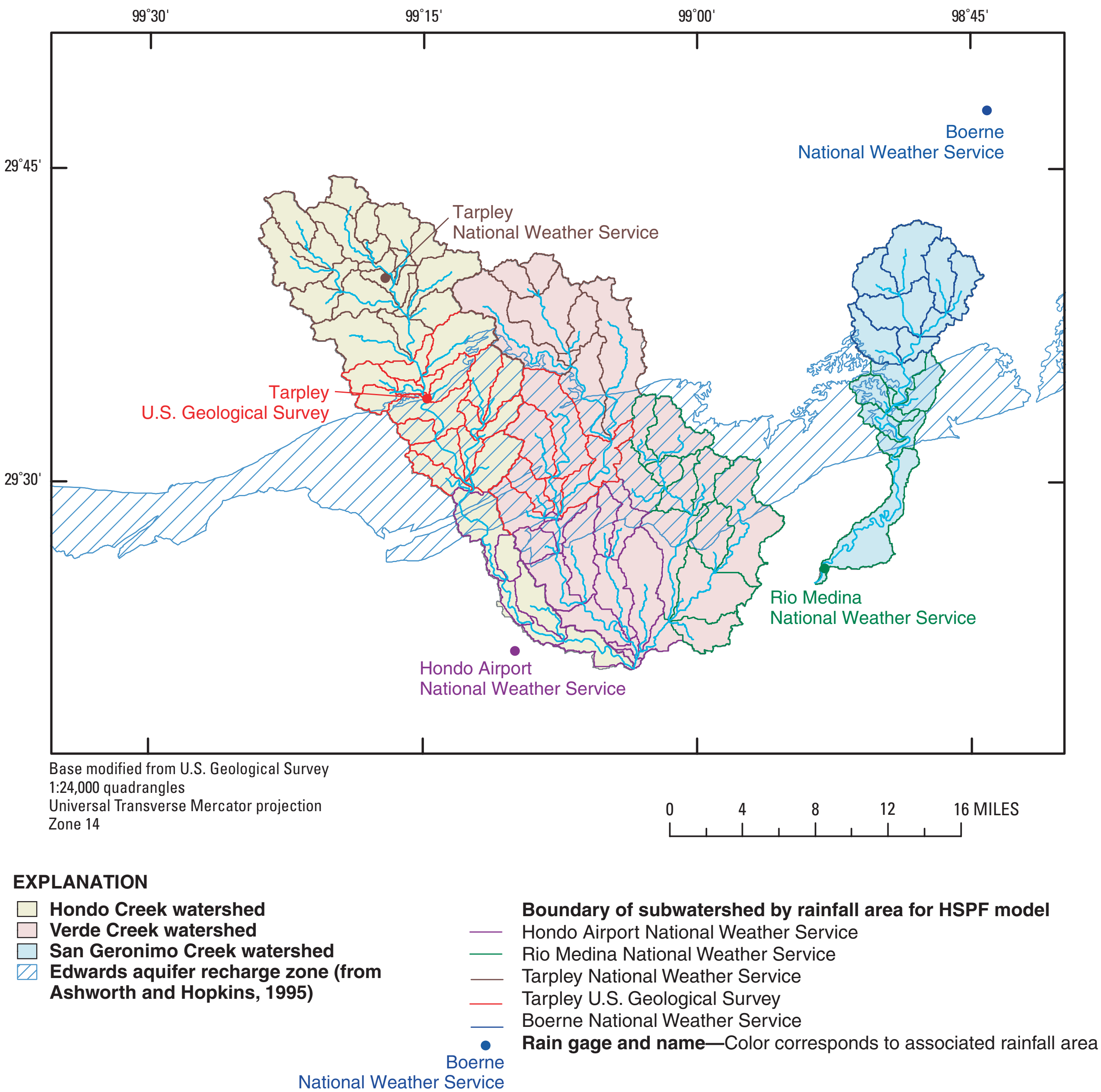

Figure 6. Primary rain gages and associated rainfall areas for Hydrological Simulation Program—FORTRAN (HSPF) model calibration, testing, and simulations, Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas.

Model Calibration and Testing

Streamflow

A primary goal of watershed-model calibration is to match simulated streamflow to actual streamflow measured at a gaging station. Two long-term USGS streamflow-gaging stations are in the Hondo Creek watershed; no long-term stations are in the Verde Creek and San Geronimo watersheds. The model was calibrated according to the guidelines of Donigian and others (1984) and Lumb and others (1994). Calibration generally involved adjusting the process-related parameter values to improve the model fit—that is, the match between simulated and measured streamflow. Criteria such as error in total streamflow volume for the calibration period, low-flow and high-flow

Table 5. Subwatershed drainage areas, Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas.

[ID, identification number; --, not applicable]

Hondo Creek watershed		Verde Creek watershed		San Geronimo Creek watershed	
Subwatershed ID (fig. 5)	Drainage area (acres)	Subwatershed ID (fig. 5)	Drainage area (acres)	Subwatershed ID (fig. 5)	Drainage area (acres)
10	3,160	10	1,761	10	5,016
12	2,335	12	1,940	12	2,871
14	4,262	14	6,328	14	4,905
16	1,143	16	2,476	16	3,241
18	2,600	18	410	18	2,555
20	3,490	20	8,135	20	1,200
22	2,071	22	5,652	22	1,637
24	3,365	24	10,089	24	3,339
26	1,523	25	3,154	26	2,659
28	869	27	2,030	28	2,596
30	1,001	28	7,190	30	753
32	2,809	30	4,451	32	1,921
34	1,829	32	1,028	34	1,621
36	681	36	2,476	36	1,808
38	1,788	38	3,194	38	7,769
40	700	40	170	--	--
42	4,277	42	1,262	--	--
46	2,413	44	2,244	--	--
48	2,275	46	3,400	--	--
50	6,687	48	5,057	--	--
52	1,981	50	3,258	--	--
54	5,231	52	2,340	--	--
56	531	54	2,751	--	--
58	2,003	56	3,777	--	--
60	1,640	58	469	--	--
62	653	60	2,465	--	--
66	91	62	4,617	--	--
68	2,156	64	1,553	--	--
70	4,230	66	3,605	--	--
72	1,498	68	2,668	--	--
74	2,548	70	2,536	--	--
80	3,028	72	5,965	--	--
82	2,647	74	9,216	--	--
84	1,065	76	3,662	--	--
86	1,579	78	6,983	--	--
88	1,434	86	3,158	--	--
90	197	88	1,632	--	--
92	3,811	90	6,647	--	--
94	2,088	94	314	--	--
98	4,910	--	--	--	--
100	1,738	--	--	--	--
102	1,327	--	--	--	--
104	1,008	--	--	--	--
106	3,259	--	--	--	--
108	2,774	--	--	--	--
Total	102,705		140,063		43,891

distribution, and error in peak flows were used to evaluate how well simulated streamflow matched measured streamflow. Because most process-related parameters cannot be measured directly, they are specified through iterative calibration.

Model basin-related parameter values were computed from available spatial data, to the extent possible. For example, average slopes of PERLNDS were computed from digital elevation data.

Hondo Creek Model

The Hondo Creek model was calibrated for the period January 1, 1992, to December 31, 1999, using an hourly time step. The response of the calibrated model was further tested using data for the period January 1, 2000, to December 31, 2003. Data from USGS streamflow-gaging station 08200000 Hondo Creek near Tarpley were used to calibrate model streamflow for the Hondo Creek watershed upstream from the gage (subwatersheds 10–66). Data from USGS streamflow-gaging station 08200500 Hondo Creek at King Waterhole near Hondo were used to calibrate subwatersheds 68–102. Calibrated parameters for PERLND and IMPLND HRUs in subwatersheds 68–102 were transferred to the lower, ungaged subwatersheds (104–108).

Streamflow calibration and testing results for Hondo Creek near Tarpley and Hondo Creek at King Waterhole near Hondo are listed in table 6. The measured and simulated streamflow and percentage differences are reported for total flow volume, highest 10 percent of daily flow volumes, lowest 50 percent of daily flow volumes, and selected storm peaks. Storm peaks included in the analyses are all measured peaks greater than 1,000 cubic feet per second (ft^3/s). There were 24 such streamflow peaks at the Tarpley station and 16 peaks at the King Waterhole station.

Two model-fit statistics were used to examine the quality of the model fit on an annual, monthly, daily, and hourly basis: (1) the coefficient of determination of the linear regression between measured and simulated streamflow, which provides a measure of the variance between measured and simulated streamflows explained by the regression—in other words, a rough measure of the goodness of fit of the regression; and (2) the coefficient of model-fit efficiency (Nash and Sutcliffe, 1970), which indicates how well the graph of simulated streamflow as a function of measured streamflow matches the line of equal value (Knapp and others, 2004). Thus model-fit efficiency is a measure of the match between measured and simulated streamflows.

Error in simulated total flow volume at the Tarpley gage for the calibration period (1992–99) was 0. Simulated annual flow volume for the testing period (2000–2003) exceeded measured annual flow volume by 2.7 percent. For the entire 1992–2003 period, simulated total flow volume exceeded the measured amount by 1.1 percent. Error in simulated total flow volume at the King Waterhole gage for the calibration period (1992–99) was 1.0 percent; for the testing period, 3.9 percent; and for the entire period, 1.1 percent.

Simulation errors for other criteria generally are within acceptable limits (compared to default criteria guidelines of HSPEXP [Lumb and others, 1994]). During the testing period (2000–2003), simulated lowest 50 percent of daily flow volumes at the Tarpley gage was 11.1 percent greater than measured flows. For the entire calibration and testing period the lowest 50 percent of simulated daily flow volumes was 2.6 percent greater than measured flows. Both Hondo Creek gages were rendered inoperative during a July 2002 flood, and daily mean streamflows at both sites were estimated (A.M. Miller, U.S. Geological Survey, oral commun., 2004). The July 2002 flood accounted for about 90 percent of the total streamflow volume at the King Waterhole gage during the 2000–2003 period. So, potential error in the estimates of gaged streamflow might affect the comparison statistics listed in table 6 (at end of report).

Simulated flows at both USGS gages were evaluated by graphical comparison of measured and simulated daily time series, exceedance-probability curves, and scatter plots (figs. 7, 8). General agreement between the measured and simulated exceedance-probability curves indicates adequate calibration over the range of flow conditions.

Donigian and others (1984) present general guidelines for characterizing HSPF calibrations. For annual and monthly runoff volumes, model calibration is considered very good when the error is less than 10 percent, good when the error is 10 to 15 percent, and fair when the error is 15 to 25 percent. By these guidelines, calibration results for annual flow volumes at both gages are very good. Coefficients of determination and model-fit efficiency near or above 0.9 indicate an acceptable match between measured and simulated streamflows. By this criterion, annual, monthly, and daily simulated streamflows adequately matched measured values, but simulated hourly streamflows did not.

Verde Creek Model

Process-related parameters from the calibrated Hondo Creek model were applied to the Verde Creek watershed to produce the Verde Creek model. Discrete discharge measurements made along Verde Creek in 1981 (Land and others, 1983) were used to help develop streamflow channel infiltration capacity for the FTABLEs of all models. No other streamflow data from Verde Creek were used to calibrate or test the Verde Creek model. Because the accuracy of the Verde Creek model is uncertain, results are not provided in this report.

San Geronimo Creek Model

Process-related parameters from the calibrated Hondo Creek model were applied to the San Geronimo Creek watershed to produce the San Geronimo Creek model. To assess the validity of using parameters from the Hondo Creek model in the San Geronimo Creek model, the simulated streamflow was compared to measured streamflow from a discontinued USGS streamflow-gaging station (San Geronimo Creek Reservoir

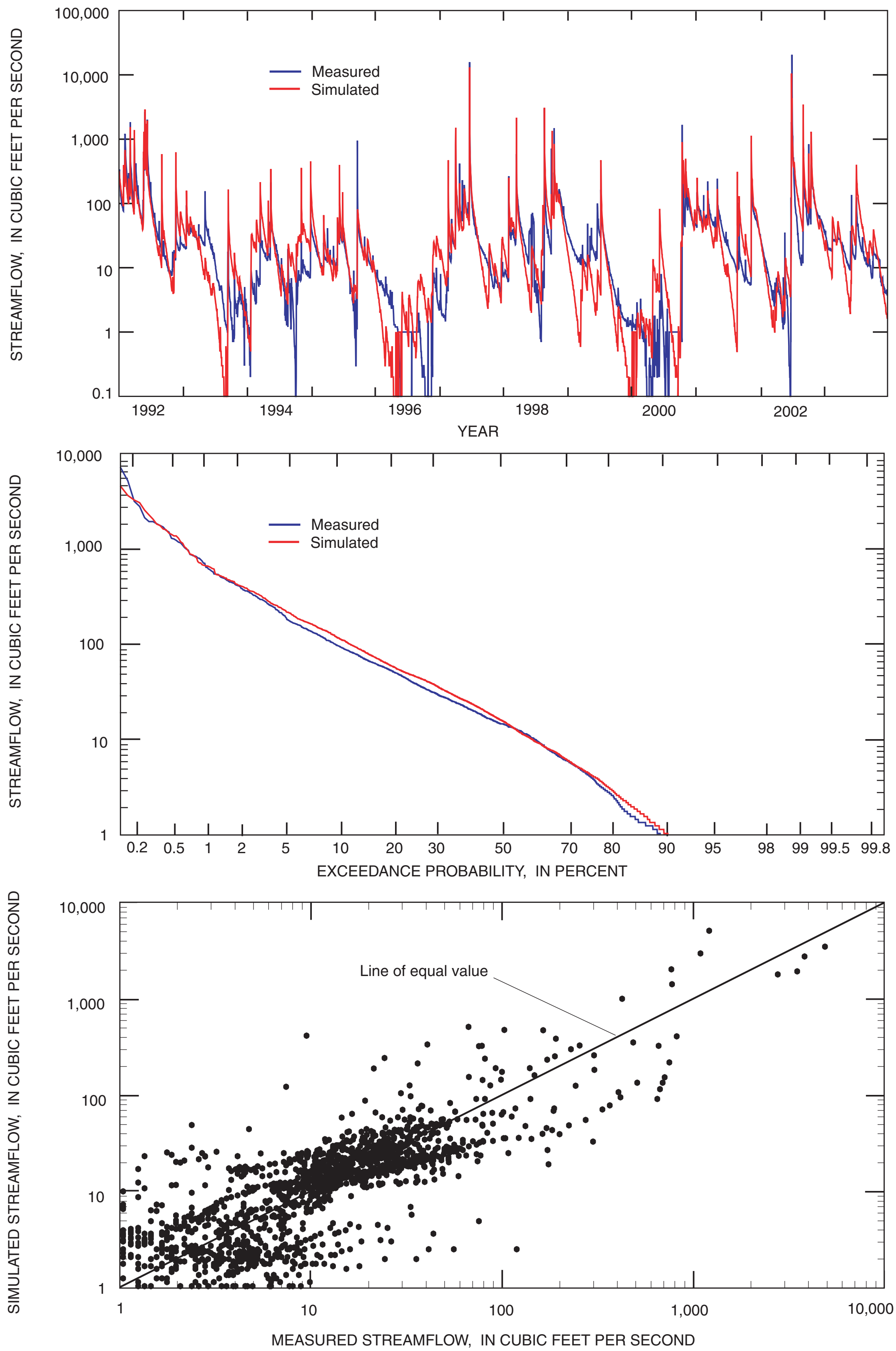

Figure 7. Measured and simulated daily mean streamflow at U.S. Geological Survey streamflow-gaging station 08200000 Hondo Creek near Tarpley, Texas, 1992–2003.

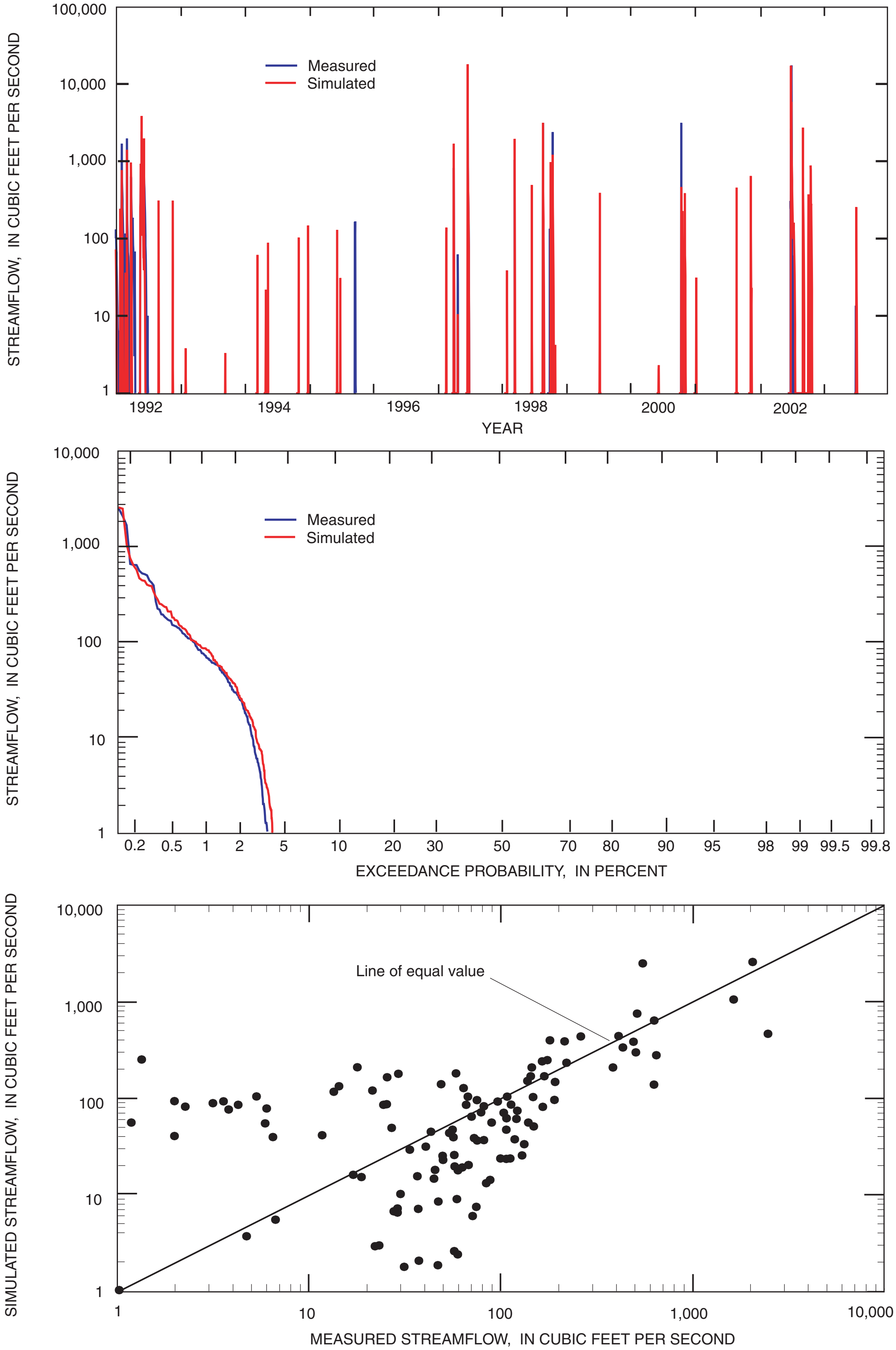

Figure 8. Measured and simulated daily mean streamflow at U.S. Geological Survey streamflow-gaging station 08200700 Hondo Creek at King Waterhole near Hondo, Texas, 1992–2003.

inflow, site 10 in fig. 4, table 3) during 1992–93. The comparison is summarized in table 7 (at end of report). Generally, simulated volumes and peak flows were higher than measured flows. Simulated flow volume (43,600 acre-ft) during 1992–93 was 31.7 percent greater than measured flow volume (33,100 acre-ft). Simulated storm peaks (three measured peaks that exceeded 1,000 ft^3/s) exceeded measured peaks by 77.9 percent.

Because a substantial part of recharge to the Edwards aquifer occurs as infiltration of flow in the stream channel, simulated streamflow that exceeds measured streamflow in San Geronimo Creek likely results in overestimation of recharge. Therefore, on the basis of 1992–93 streamflow data from the San Geronimo Creek watershed, the model was recalibrated by adjusting selected process-related parameters, primarily INFILT and LZSN (table 1). Channel-loss characteristics in the FTABLEs also were adjusted. The simulation results after recalibration are shown in figure 9 and table 7.

The resulting simulated total flow volume and the highest 10 percent (1.9 percent error) and lowest 50 percent (0 percent error) of daily flow volumes are close to measured data. Coefficients of determination and model-fit efficiency indicate an acceptable match between measured and simulated annual and monthly streamflows. However, coefficients of determination and model-fit efficiency are low (compared to those of the Hondo Creek simulations) for daily and hourly simulations. Therefore, the model calibration for daily and hourly simulations is relatively poor. One factor that affects the calibration is few available streamflow data from San Geronimo Creek. Because streamflow is intermittent at the measurement site, few discharge measurements were made during the 1992–93 data-collection period to develop and confirm the stage-discharge rating (the relation between measured water stage and computed discharge). Also, gain-loss measurements, similar to the measurements made along Hondo and Verde Creeks to estimate streamflow infiltration, have not been made along San Geronimo Creek.

Evapotranspiration

In addition to streamflow calibration, another goal of watershed-model calibration is to accurately simulate the overall water budget in the watershed, which includes recharge and evapotranspiration (ET). Model simulations of recharge cannot be compared to measured values because diffuse recharge (direct infiltration of rainfall through the soil layers to the water table), especially within the faulted karst environments of the study-area watersheds, cannot be measured directly. Estimates of recharge therefore depend on accurate model representations of the remaining water-budget components not associated with recharge (streamflow, ET, and changes in soil-water storage over the simulation period). Annual streamflow in Hondo Creek (King Waterhole streamflow-gaging station) usually is less than 10 percent of rainfall. Changes in soil-water storage (over long simulation periods) are relatively small. Therefore, ET plus recharge likely accounts for about 90 percent of rainfall. Maclay (1995, p. 31) reports that evapotranspiration in the area is about 85 to 90 percent of rainfall. Uncertainty in ET simulations can result in considerable potential error in diffuse recharge estimates.

HSPF process parameters related to ET simulation were not calibrated with actual data because very few measured ET data are available for the region, and no ET data have been collected in the study area. ET-related parameter values from other HSPF models (Brown and Raines, 2002; Ockerman, 2002) were used to guide selection of those parameters for the Hondo Creek model. Also, parameters that affect ET also affect streamflow and are adjusted during the streamflow calibration. To test the validity of the ET simulations, only general comparisons with few available data were possible. The simulated average annual ET values from several PERLND categories are listed in table 8 (at end of report).

For the three land categories listed in table 8, average 1992–2003 ET ranged from 77 to 89 percent of rainfall. Annual ET showed greater variability, ranging from 54 to 115 percent of annual rainfall.

Probably the best-available ET data for comparison were collected during 1991–95 by the Natural Resources Conservation Service in the Seco Creek watershed (site 24, fig. 4 and table 3) adjacent to the Hondo Creek watershed in northeastern Uvalde County (Dugas and others, 1998). Average ET rates in the Seco Creek watershed during March through October were 0.075 inch per day (in/d). HSPF simulations for the Hondo Creek watershed during the same time period and with similar land cover (Glen Rose Limestone, medium slope, evergreen forest) yielded an average daily ET rate of 0.079 in/d. Compared to the Seco Creek measured ET, the HSPF simulated ET is considered reasonable.

Summary of HSPF Process-Related Parameters

Through calibration and testing, sets of process-related parameters were developed for the Hondo Creek, Verde Creek, and San Geronimo Creek watershed models. The process-related annual parameters for the Hondo Creek and Verde Creek models are listed in table 9 (at end of report). The process-related annual parameters for the San Geronimo Creek model are listed in table 10 (at end of report). Values of the monthly varying lower-zone evapotranspiration parameter (LZETP) for all three models are listed in table 11 (at end of report).

Streamflow, 1951–2003

The results of streamflow simulations (average annual streamflow volumes) for each watershed model are listed in table 12 (at end of report). Total streamflow for a watershed includes all surface runoff, interflow, and base flow that originates in the watershed and reaches the stream channel. Because

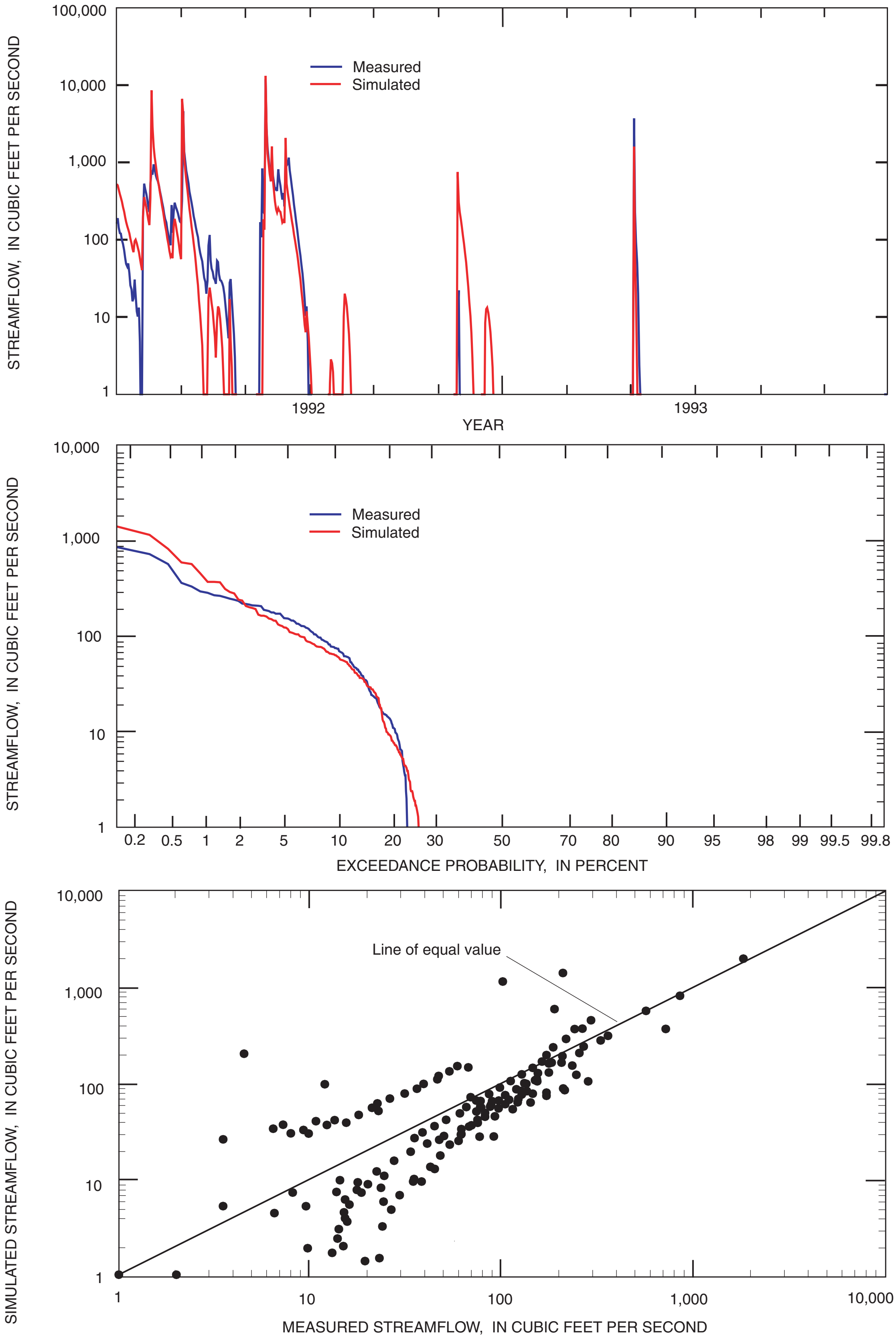

Figure 9. Measured and simulated daily mean streamflow at U.S. Geological Survey streamflow-gaging station 08180590 San Geronimo Creek Reservoir inflow near Rio Medina, Texas, 1992–93.

of streamflow channel infiltration, much of the total streamflow is lost to recharge before it reaches the watershed outlet. Simulated average annual total streamflow for 1951–2003 in the Hondo Creek, Verde Creek, and San Geronimo Creek watersheds is 45,400; 32,400; and 11,100 acre-ft; respectively. Simulated average annual streamflow at the respective watershed outlets is 13,000; 16,200; and 6,920 acre-ft; the difference between total streamflow and streamflow at the watershed outlet is streamflow lost to channel infiltration.

Model simulations also were done to assess the effects on streamflow of recharge-enhancement structures completed for Verde Creek in April 1978 and for San Geronimo Creek in November 1979. The recharge-enhancement structures divert streamflow to recharge. Three simulations were done for each of the two watersheds: (1) for 1951–2003 for actual conditions, which means with the structures simulated in the Verde Creek watershed beginning in April 1978 and in the San Geronimo watershed beginning in November 1979; (2) for 1951–2003 without the structures simulated in either watershed for the entire period; and (3) for 1951–2003 with the structures simulated in both watersheds for the entire period.

For Verde Creek simulation (1) streamflow at the watershed outlet was 16,200 acre-ft. Simulations (2) and (3) resulted in average annual streamflow of 16,800 and 15,700 acre-ft, respectively. So, simulation with the recharge-enhancement structure in place during 1951–2003 for the entire period resulted in a reduction of streamflow exiting the watershed of about 6.5 percent.

For San Geronimo Creek simulation (1), streamflow at the watershed outlet was 6,920 acre-ft. Simulations (2) and (3) resulted in average annual runoff of 7,680 and 6,160 acre-ft, respectively. So, simulation with the recharge-enhancement structure in place during 1951–2003 for the entire period resulted in a reduction of streamflow exiting the watershed by about 20 percent. The drainage area above the San Geronimo Creek recharge-enhancement structure is about 78 percent of the watershed (compared to about 29 percent of the Verde Creek watershed upstream from the Verde Creek structure). So, as might be expected, the effect of the Verde Creek structure on streamflow at the watershed outlet is not as great as the effect of the San Geronimo Creek structure.

Recharge, 1951–2003

The HSPF models for the Hondo Creek, Verde Creek, and San Geronimo Creek watersheds were used to estimate Edwards aquifer recharge during 1951–2003. Annual recharge estimates (simulated recharge) by watershed are listed in table 13 (at end of report). Recharge comprises direct infiltration of rainfall (diffuse recharge) and infiltration of streamflow within the stream channels. Most of the simulated streamflow channel infiltration occurs in the recharge zone, but some occurs downstream from the recharge zone (about 5 percent in Hondo Creek, about 0.5 percent in Verde Creek, and about 9 percent San Geronimo Creek). The recharge estimates in table 13 do not include channel infiltration downstream from the recharge zone, and they do not include estimates of subsurface inflow to the Edwards aquifer from other aquifers.

For the Hondo Creek watershed, estimated average annual recharge for 1951–2003 is 37,900 acre-ft/yr, or 5.04 inches (in.) (about 17 percent of average annual rainfall). Most of the recharge (82 percent[2]) occurred as streamflow channel infiltration. About 18 percent occurred as diffuse recharge, or direct infiltration of rainfall to the aquifer. Annual Hondo Creek recharge is highly variable (depending on annual rainfall), ranging from 1,920 acre-ft (0.26 in.) in 1956 to 117,000 acre-ft (15.6 in.) in 1992.

For the Verde Creek watershed, estimated average annual recharge for 1951–2003 is 26,000 acre-ft/yr, or 3.36 in. (about 11 percent of average annual rainfall). About 62 percent[2] of the recharge occurred as streamflow channel infiltration. About 38 percent occurred as diffuse recharge. Annual Verde Creek recharge varied from 1,760 acre-ft (0.23 in.) in 1956 to 73,800 acre-ft (9.54 in.) in 1992.

For the San Geronimo Creek watershed, estimated average annual recharge for 1951–2003 is 5,940 acre-ft/yr, or 1.97 in. (about 6 percent of average annual rainfall). About 64 percent[2] of the recharge occurred as streamflow channel infiltration. About 36 percent occurred as diffuse recharge. Annual San Geronimo Creek recharge varied from 100 acre-ft (0.03 in.) in 1954 to 26,700 acre-ft (8.87 in.) in 1992.

Average annual recharge estimates from the San Geronimo Creek model before and after recalibration with measured streamflow data were compared to assess the sensitivity of the recharge estimation to streamflow calibration. During 1992–93 (period when streamflow calibration data were available) the simulated runoff volume exiting the San Geronimo Creek watershed before recalibration, using process-related parameters from the calibrated Hondo Creek model (43,600 acre-ft, table 7), was about 32 percent greater than after recalibration (33,100 acre-ft, table 7). Before recalibration the simulated average annual (1951–2003) recharge was 6,220 acre-ft/yr, or 2.06 in. This estimate is about 4.7 percent greater than the estimate after recalibration (5,940 acre-ft, table 13). During the period when streamflow calibration data were available (1992–93), the recharge estimate before recalibration was 5.0 percent greater than the estimate after recalibration. So, for the San Geronimo Creek watershed, the recharge estimate was not particularly sensitive to the recalibration.

HSPF 1992–2003 recharge estimates for Hondo Creek and Verde Creek were compared to USGS estimates of recharge made using the Puente method (Puente, 1978; R.N. Slattery, U.S. Geological Survey, written commun., 2003). Because the USGS recharge estimates are annual values, only annual comparisons with HSPF simulations are possible. Estimates of recharge for the San Geronimo Creek watershed by the Puente method are not available because, in the Puente

[2] Does not include streamflow channel infiltration downstream from the recharge zone.

method, recharge in that watershed is included in the recharge computation for a larger watershed. Recharge estimates for the Hondo Creek and Verde Creek watersheds for 1992–2003 computed from HSPF simulation and the Puente method are listed in table 14 (at end of report). Overall, for Hondo Creek, the HSPF recharge estimates average 40,100 acre-ft/yr compared to 51,700 acre-ft/yr estimated by the Puente method (about 22 percent less). HSPF recharge estimates for Verde Creek average 28,700 acre-ft/yr compared to 47,700 acre-ft/yr estimated by the Puente method (about 40 percent less). For years of greater-than-average rainfall in both watersheds, the HSPF recharge estimates are substantially less than the Puente recharge estimates. For years of average or less-than-average rainfall, the relation between estimates from the two methods is mixed in terms of which is greater.

Model Limitations and Assessment

Errors in model calibration can be classified either as systematic or measurement errors (Raines, 1996). Systematic errors are associated with limitations of the model to represent the hydrologic processes of the study watershed. There are possible limits on how well the model parameters and equations describe the physical characteristics of runoff and recharge. Measurement errors are introduced as a result of inaccurate or missing data. Limitations in the available rainfall data are potentially the most serious source of measurement error for the study. Runoff and recharge in the watershed are highly dependent on the occurrence of relatively extreme storms. The available network of rain gages does not always adequately represent the spatial and temporal variability of rainfall in the watershed.

HSPF model calibration for the three study-area watersheds primarily is based on calibration of HSPF process-related parameters for the Hondo Creek watershed. Process-related parameters obtained from the Hondo Creek calibration were applied directly to the other study watersheds. The Hondo Creek process parameters were applied to the Verde Creek model without recalibration because of a lack of streamflow data for calibration for the Verde Creek watershed. Therefore, the accuracy of streamflow and recharge estimations for the Verde Creek watershed is uncertain. Using Hondo Creek parameter values, the San Geronimo Creek model simulations for 1992–93 did not satisfy calibration criteria. Therefore, the San Geronimo Creek model was recalibrated on the basis of the 1992–93 streamflow data from the San Geronimo watershed.

The Hondo Creek model-fit statistics indicate that streamflow simulations compare well with measured data on an annual, monthly, and daily basis. However, the coefficient of model-fit efficiency for hourly comparisons is low. The model, therefore, is not as effective in predicting hourly streamflow values—for example, peak discharges. However, daily or monthly streamflow volume is predicted with reasonable accuracy and either daily or monthly is likely more important than hourly for estimating recharge because much of the recharge occurs as infiltration of streamflow and because recharge events and processes tend to occur on time scales substantially greater than hourly.

The accuracy of streamflow and recharge estimates from the Verde Creek and San Geronimo Creek models is difficult to assess because of the lack of streamflow data available for model calibration. Transfer of calibrated process-related parameters from the Hondo Creek model to the San Geronimo Creek model resulted in simulations that did not compare favorably with the few measured data. Therefore, using Hondo Creek process-related parameters in the Verde Creek model also might not produce simulations that reasonably represent actual conditions.

Because most recharge to the Edwards aquifer occurs as streamflow infiltration and most of that streamflow originates in the Glen Rose Limestone outcrop upstream from the recharge zone, gaged streamflow upstream from and downstream from the Edwards aquifer recharge zone (similar to that measured in Hondo Creek) might be useful for improving the calibration of the Verde Creek and San Geronimo Creek HSPF models. Additional gain-loss measurements, especially along San Geronimo Creek, also might help improve model calibration. Because ET is a large component of the water budget in these study watersheds, additional ET data, especially in the Edwards aquifer recharge zone, might improve model calibration and estimates of recharge.

Summary

The U.S. Geological Survey (USGS), in cooperation with the San Antonio Water System, constructed HSPF watershed models to simulate streamflow (runoff) and estimate recharge to the Edwards aquifer in the Hondo Creek, Verde Creek, and San Geronimo Creek watersheds in south-central Texas. The models were calibrated and tested with available data collected during 1992–2003. Simulations of runoff and recharge to the Edwards aquifer were done for 1951–2003.

Outcropping rocks in the upper part of each watershed are Glen Rose Limestone; outcropping rocks in the central part of each watershed—the Edwards aquifer recharge zone—are Edwards Group. Glen Rose Limestone generally has low permeability compared to rocks of the Edwards Group. Edwards Group rocks are characterized by high permeability because of faults, sinkholes, and other karst features. Relatively impermeable confining units overlie the Edwards aquifer south of the recharge zone, the lower part of each watershed. Streams in the study-area watersheds originate in the topographically rugged Texas Hill Country north of the recharge zone and generally flow south, crossing the recharge zone and continuing onto Edwards aquifer confining units.

Two USGS streamflow-gaging stations on Hondo Creek provided adequate data to calibrate the HSPF model of the Hondo Creek watershed. However, suitable calibration data for the Verde Creek and San Geronimo Creek watersheds is

lacking. Verde Creek is ungaged. Data from the San Geronimo Creek watershed is limited to streamflow data from a discontinued USGS streamflow-gaging station operated during 1992–93.

The approach to develop the models was to first calibrate the Hondo Creek model (with an hourly time step) using 1992–99 data and test that model using 2000–2003 data. Then the calibrated Hondo Creek model parameters were applied to the Verde Creek and San Geronimo Creek watersheds. For the entire calibration and testing period (1993–2003), the simulated total flow volumes for Hondo Creek exceeded measured flow volumes at both USGS gages by about 1.1 percent, within limits considered acceptable for calibration. Two other measures of simulation quality, coefficients of determination and model-fit efficiency, indicate (by values of 0.9 or greater) that annual, monthly, and daily simulated streamflows for Hondo Creek adequately matched measured values, but simulated hourly streamflows did not.

The Verde Creek model, using parameters from the Hondo Creek model, remains untested. The accuracy of streamflow simulations for Verde Creek thus is uncertain.

After applying the Hondo Creek model parameters to the San Geronimo Creek model, the simulation was tested using 1992–93 streamflow data from the discontinued USGS gage. Because the simulated streamflow volumes compared poorly to the measured volumes, the San Geronimo Creek model was recalibrated using the 1992–93 data. The streamflow calibration was improved but not to the level of the Hondo Creek model calibration. The resulting simulated total flow volume and the highest 10 percent and lowest 50 percent of daily flow volumes are within 1.9 percent of measured data. Coefficients of determination and model-fit efficiency indicate an acceptable (or nearly so) match between simulated and measured annual and monthly streamflows. However, those coefficients are low (compared to those of the Hondo Creek simulations) for daily and hourly simulations. Therefore, the model calibration for daily and hourly streamflows is relatively poor compared to the Hondo Creek model calibration.

Simulated average annual total streamflow for 1951–2003 in the Hondo Creek, Verde Creek, and San Geronimo Creek watersheds is 45,400, 32,400, and 11,100 acre-ft, respectively. Simulated average annual streamflow at the respective watershed outlets is 13,000, 16,200, and 6,920 acre-ft; the difference between total streamflow and streamflow at the watershed outlet is streamflow lost to channel infiltration.

Estimated average annual Edwards aquifer recharge (direct infiltration of rainfall [diffuse recharge] and channel infiltration) for Hondo Creek, Verde Creek, and San Geronimo Creek for 1951–2003 is 37,900 acre-ft (5.04 in.), 26,000 acre-ft (3.36 in.), and 5,940 acre-ft (1.97 in.), respectively. Most of the recharge (about 77 percent for the three study watersheds together) occurs as streamflow channel infiltration. Diffuse recharge accounts for the remaining 23 percent of recharge.

HSPF 1992–2003 annual recharge estimates for the Hondo Creek and Verde Creek watersheds were compared to USGS estimates of historical annual recharge for those watersheds computed using a method documented in 1978 and referred to as the Puente method. For the Hondo Creek watershed, the HSPF recharge estimates for 1992–2003 average 40,100 acre-ft/yr compared to 51,700 acre-ft/yr estimated by the Puente method (about 22 percent less). HSPF recharge estimates for the Verde Creek watershed average 28,700 acre-ft/yr compared to 47,700 acre-ft/yr estimated by the Puente method (about 40 percent less). During years of greater-than-average rainfall in both watersheds, the HSPF recharge estimates are substantially less than the Puente recharge estimates. During years of average or less-than-average rainfall, the relation between estimates from the two methods is mixed in terms of which is greater.

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Table 6. Streamflow calibration and testing results, Hydrological Simulation Program—FORTRAN model, Hondo Creek watershed, south-central Texas, 1992–2003.

[acre-ft, acre-feet; ft^3/s, cubic feet per second; --, not applicable]

Hondo Creek near Tarpley (08200000)

Comparison of streamflow volumes and peaks	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Calibration period 1992–99				
Total flow volume, acre-ft	282,000	282,000	0	10
Total of highest 10 percent of daily flow volumes, acre-ft	192,000	183,000	-4.7	15
Total of lowest 50 percent of daily flow volumes, acre-ft	15,000	14,700	-2.0	10
Average of selected storm peaks, ft^3/s (20 storms)	9,030	7,640	-15.4	--
Testing period 2000–2003				
Total flow volume, acre-ft	186,000	191,000	2.7	10
Total of highest 10 percent of daily flow volumes, acre-ft	125,000	130,000	4.0	15
Total of lowest 50 percent of daily flow volumes, acre-ft	7,730	8,590	11.1	10
Average of selected storm peaks, ft^3/s (4 storms)	20,100	16,900	-15.9	--
Entire (calibration and testing) period 1992–2003				
Total flow volume, acre-ft	468,000	473,000	1.1	10
Total of highest 10 percent of daily flow volumes, acre-ft	317,000	313,000	1.3	15
Total of lowest 50 percent of daily flow volumes, acre-ft	22,700	23,300	2.6	10
Average of selected storm peaks, ft^3/s (24 storms)	14,000	11,900	-15.0	--

Model-fit statistics 1992–2003	Annual	Monthly	Daily mean	Hourly[3]
Number of years, months, days, or hours	12	144	4,383	104,448
Coefficient of determination	.98	.92	.94	.72
Coefficient of model-fit efficiency[4]	.96	.90	.91	.68
Percentage of time simulated within 10 percent of measured	41.7	18.0	18.4	18.7
Percentage of time simulated within 25 percent of measured	58.3	36.8	33.6	33.8

Table 6. Streamflow calibration and testing results, Hydrological Simulation Program—FORTRAN model, Hondo Creek watershed, south-central Texas, 1992–2003—Continued.

Hondo Creek at King Waterhole near Hondo (08200700)

Comparison of streamflow volumes and peaks	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Calibration period 1992–99				
Total flow volume, acre-ft	104,000	103,000	1.0	10
Total of highest 10 percent of daily flow volumes, acre-ft	104,000	103,000	1.0	15
Total of lowest 50 percent of daily flow volumes, acre-ft	0	0	0	10
Average of selected storm peaks, ft^3/s (13 storms)	10,800	8,800	-18.5	--
Testing period 2000–2003				
Total flow volume, acre-ft	81,100	84,300	3.9	10
Total of highest 10 percent of daily flow volumes, acre-ft	81,100	84,300	3.9	15
Total of lowest 50 percent of daily flow volumes, acre-ft	0	0	0	10
Average of selected storm peaks, ft^3/s (3 storms)	19,900	33,000	65.8	--
Entire (calibration and testing) period 1992–2003				
Total flow volume, acre-ft	185,000	187,000	1.1	10
Total of highest 10 percent of daily flow volumes, acre-ft	185,000	187,000	.8	15
Total of lowest 50 percent of flow volumes, acre-ft	0	0	0	10
Average of selected storm peaks, ft^3/s (16 storms)	12,500	13,300	6.4	--

Model-fit statistics 1992–2003	Annual	Monthly	Daily mean	Hourly[3]
Number of years, months, days, or hours	12	144	4,383	105,192
Coefficient of determination	.94	.94	.92	.67
Coefficient of model-fit efficiency[4]	.93	.93	.90	.66
Percentage of time simulated within 10 percent of measured	33.3	84.7	94.2	94.6
Percentage of time simulated within 25 percent of measured	41.7	85.4	94.7	95.0

[1] Error = ([simulated-measured]/measured) x 100.
[2] Default error criteria from Donigian and others (1984).
[3] Hourly statistics for 0820000 and 08200700 do not include July 2002.
[4] From Nash and Sutcliffe (1970).

Table 7. Streamflow testing and recalibration results, Hydrological Simulation Program—FORTRAN model, San Geronimo Creek watershed, south-central Texas, 1992–93.

[acre-ft, acre-feet; ft^3/s, cubic feet per second; -- not applicable]

Model testing results using process-related parameters from calibrated Hondo Creek HSPF model

Comparison of streamflow volumes and peaks	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Testing period 1992–93				
Total flow volume, acre-ft	33,100	43,600	31.7	10
Total of highest 10 percent of daily flow volumes, acre-ft	31,900	37,000	16.0	15
Total of lowest 50 percent of daily flow volumes, acre-ft	0	0	0	10
Average of selected storm peaks, ft^3/s (3 storms)	7,700	13,700	77.9	--

Model-fit statistics 1992–93	Annual	Monthly	Daily	Hourly
Number of years, months, days, or hours	2	24	731	17,544
Coefficient of determination	1.00	.87	.60	.23
Coefficient of model-fit efficiency[3]	.84	.83	.55	.23
Percentage of time simulated within 10 percent of measured	0	45.8	66.1	67.0
Percentage of time simulated within 25 percent of measured	0	58.3	69.5	70.8

Model results after recalibration with measured San Geronimo Creek streamflow[4] for 1992–93

Comparison of streamflow volumes and peaks	Measured streamflow	Simulated streamflow	Error[1] (percent)	Criteria[2] (percent)
Calibration period 1992–93				
Total flow volume, acre-ft	33,100	33,100	0	10
Total of highest 10 percent of daily flow volumes, acre-ft	31,900	32,500	1.9	15
Total of lowest 50 percent of daily flow volumes, acre-ft	0	0	0	10
Average of selected storm peaks, ft^3/s (3 storms)	7,700	6,650	-13.6	--

Model-fit statistics 1992–93	Annual	Monthly	Daily	Hourly
Number of years, months, days, or hours	2	24	731	17,544
Coefficient of determination	1.00	.88	.65	.20
Coefficient of model-fit efficiency[3]	.99	.88	.64	.13
Percentage of time simulated within 10 percent of measured	50.0	70.8	72.9	75.1
Percentage of time simulated within 25 percent of measured	50.0	70.8	75.5	75.4

[1] Error = ([simulated-measured]/measured) X 100.
[2] Default error criteria from HSPEXP (Lumb and others, 1994).
[3] From Nash and Sutcliffe, 1970.
[4] Measured at San Geronimo Creek Reservoir inflow near Rio Medina (08180590).

Table 8. Rainfall and simulated evapotranspiration, Hydrological Simulation Program—FORTRAN model, Hondo Creek watershed, south-central Texas, 1992–2003.

[In inches; ET, evapotranspiration]

Year	Land category					
	Glen Rose Limestone, evergreen forest, low slope		Edwards Group, evergreen forest, low slope		Confining units of Edwards aquifer, evergreen forest, low slope	
	Rainfall	ET	Rainfall	ET	Rainfall	ET
1992	49.74	32.40	49.74	32.48	44.56	35.49
1993	24.47	24.78	22.55	23.13	41.83	37.89
1994	37.10	28.93	23.31	21.30	16.60	19.15
1995	27.94	27.54	25.11	22.49	33.18	27.22
1996	19.33	18.51	13.50	13.49	19.12	21.65
1997	43.62	30.16	35.03	25.19	20.13	19.86
1998	39.17	28.14	32.65	23.98	59.08	42.45
1999	16.06	16.46	15.27	16.15	31.32	30.43
2000	30.94	21.46	23.06	19.07	17.94	19.67
2001	33.25	26.87	23.50	20.18	32.49	25.11
2002	51.01	27.75	35.56	21.97	42.37	34.56
2003	26.99	25.07	27.54	23.46	19.11	21.69
Average 1992–2003	33.30	25.67	27.24	21.91	31.48	27.93

Table 9. Process-related annual parameters for pervious and impervious land segments, Hydrological Simulation Program—FORTRAN models, Hondo Creek and Verde Creek watersheds, south-central Texas.

[Parameter definitions in table 1; PERLND, PERvious LaND; --, not applicable; IMPLND, IMPervious LaND]

Glen Rose Limestone (Trinity aquifer outcrop)

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0	0.96	0.001	0.27	0.09	0.24	0.90	0.75	400	2.3	0.30	--	0.04	0.22
Deciduous/mixed forest, low slope	0	.96	.001	.15	.09	.24	.90	.75	400	2.3	.30	--	.04	.22
Shrubland, low slope	0	.96	.001	.12	.09	.24	.90	.75	400	2.3	.30	--	.04	.22
Grassland, low slope	0	.96	.001	.10	.09	.24	.90	.75	400	2.3	.30	--	.04	.22
Bare/transitional, low slope	0	.96	.001	.10	.09	.24	.90	.75	400	2.3	.30	--	.04	.22
Agricultural, low slope	0	.96	.001	.10	.09	.24	.90	.75	400	2.3	.30	--	.04	.22
Developed, low slope	0	.96	.001	.10	.09	.24	.90	.75	400	2.3	.30	--	.04	.22
Evergreen forest, medium slope	0	.96	.001	.26	.09	.23	.90	.75	400	2.2	.30	--	.08	.21
Deciduous/mixed forest, medium slope	0	.96	.001	.15	.09	.23	.90	.75	400	2.2	.30	--	.08	.21
Shrubland, medium slope	0	.96	.001	.12	.09	.23	.90	.75	400	2.2	.30	--	.08	.21
Grassland, medium slope	0	.96	.001	.10	.09	.23	.90	.75	400	2.2	.30	--	.08	.21
Bare/transitional, medium slope	0	.96	.001	.10	.09	.23	.90	.75	400	2.2	.30	--	.08	.21
Agricultural, medium slope	0	.96	.001	.10	.09	.23	.90	.75	400	2.2	.30	--	.08	.21
Developed, medium slope	0	.96	.001	.10	.09	.23	.90	.75	400	2.2	.30	--	.08	.21
Evergreen forest, steep slope	0	.96	.001	.25	.09	.22	.90	.75	400	2.1	.30	--	.14	.20
Deciduous/mixed forest, steep slope	0	.96	.001	.15	.09	.22	.90	.75	400	2.1	.30	--	.14	.20
Shrubland, steep slope	0	.96	.001	.12	.09	.22	.90	.75	400	2.1	.30	--	.14	.20
Grassland, steep slope	0	.96	.001	.10	.09	.22	.90	.75	400	2.1	.30	--	.14	.20
Bare/transitional, steep slope	0	.96	.001	.10	.09	.22	.90	.75	400	2.1	.30	--	.14	.20
Agricultural, steep slope	0	.96	.001	.10	.09	.22	.90	.75	400	2.1	.30	--	.14	.20
Developed, steep slope	0	.96	.001	.10	.09	.22	.90	.75	400	2.1	.30	--	.14	.20
IMPLND segment														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	.05	.06	--

Table 9. Process-related annual parameters for pervious and impervious land segments, Hydrological Simulation Program—FORTRAN models, Hondo Creek and Verde Creek watersheds, south-central Texas—Continued.

Edwards Group outcrop (Edwards aquifer recharge zone)

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0	0.70	0	0.27	0.90	0.42	0.80	0.60	400	2.2	0.30	--	0.04	0.30
Deciduous/mixed forest, low slope	0	.70	0	.15	.90	.42	.80	.60	400	2.2	.30	--	.04	.30
Shrubland, low slope	0	.70	0	.12	.90	.42	.80	.60	400	2.2	.30	--	.04	.30
Grassland, low slope	0	.70	0	.10	.90	.42	.80	.60	400	2.2	.30	--	.04	.30
Bare/transitional, low slope	0	.70	0	.10	.90	.42	.80	.60	400	2.2	.30	--	.04	.30
Agricultural, low slope	0	.70	0	.10	.90	.42	.80	.60	400	2.2	.30	--	.04	.30
Developed, low slope	0	.70	0	.10	.90	.42	.80	.60	400	2.2	.30	--	.04	.30
Evergreen forest, medium slope	0	.70	0	.26	.90	.42	.80	.60	400	2.1	.30	--	.08	.30
Deciduous/mixed forest, medium slope	0	.70	0	.15	.90	.42	.80	.60	400	2.1	.30	--	.08	.30
Shrubland, medium slope	0	.70	0	.12	.90	.42	.80	.60	400	2.1	.30	--	.08	.30
Grassland, medium slope	0	.70	0	.10	.90	.42	.80	.60	400	2.1	.30	--	.08	.30
Bare/transitional, medium slope	0	.70	0	.10	.90	.42	.80	.60	400	2.1	.30	--	.08	.30
Agricultural, medium slope	0	.70	0	.10	.90	.42	.80	.60	400	2.1	.30	--	.08	.30
Developed, medium slope	0	.70	0	.10	.90	.42	.80	.60	400	2.1	.30	--	.08	.30
Evergreen forest, steep slope	0	.70	0	.25	.90	.40	.80	.60	400	2.0	.30	--	.14	.30
Deciduous/mixed forest, steep slope	0	.70	0	.15	.90	.40	.80	.60	400	2.0	.30	--	.14	.30
Shrubland, steep slope	0	.70	0	.12	.90	.40	.80	.60	400	2.0	.30	--	.14	.30
Grassland, steep slope	0	.70	0	.10	.90	.40	.80	.60	400	2.0	.30	--	.14	.30
Bare/transitional, steep slope	0	.70	0	.10	.90	.40	.80	.60	400	2.0	.30	--	.14	.30
Agricultural, steep slope	0	.70	0	.10	.90	.40	.80	.60	400	2.0	.30	--	.14	.30
Developed, steep slope	0	.70	0	.10	.90	.40	.80	.60	400	2.0	.30	--	.14	.30
IMPLND segment														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.04	--

Table 9. Process-related annual parameters for pervious and impervious land segments, Hydrological Simulation Program—FORTRAN models, Hondo Creek and Verde Creek watersheds, south-central Texas—Continued.

Edwards Group remnants (hilltops) overlying Glen Rose Limestone

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0.001	0.94	0.001	0.27	0.09	0.30	0.90	0.65	400	2.3	0.30	--	0.04	0.22
Deciduous/mixed forest, low slope	.001	.94	.001	.15	.09	.30	.90	.65	400	2.3	.30	--	.04	.22
Shrubland, low slope	.001	.94	.001	.12	.09	.30	.90	.65	400	2.3	.30	--	.04	.22
Grassland, low slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.3	.30	--	.04	.22
Bare/transitional, low slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.3	.30	--	.04	.22
Agricultural, low slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.3	.30	--	.04	.22
Developed, low slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.3	.30	--	.04	.21
Evergreen forest, medium slope	.001	.94	.001	.26	.09	.30	.90	.65	400	2.2	.30	--	.08	.21
Deciduous/mixed forest, medium slope	.001	.94	.001	.15	.09	.30	.90	.65	400	2.2	.30	--	.08	.21
Shrubland, medium slope	.001	.94	.001	.12	.09	.30	.90	.65	400	2.2	.30	--	.08	.21
Grassland, medium slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.2	.30	--	.08	.21
Bare/transitional, medium slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.2	.30	--	.08	.21
Agricultural, medium slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.2	.30	--	.08	.21
Developed, medium slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.2	.30	--	.08	.21
Evergreen forest, steep slope	.001	.94	.001	.25	.09	.30	.90	.65	400	2.1	.30	--	.14	.20
Deciduous/mixed forest, steep slope	.001	.94	.001	.15	.09	.30	.90	.65	400	2.1	.30	--	.14	.20
Shrubland, steep slope	.001	.94	.001	.12	.09	.30	.90	.65	400	2.1	.30	--	.14	.20
Grassland, steep slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.1	.30	--	.14	.20
Bare/transitional, steep slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.1	.30	--	.14	.20
Agricultural, steep slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.1	.30	--	.14	.20
Developed, steep slope	.001	.94	.001	.10	.09	.30	.90	.65	400	2.1	.30	--	.14	.20
IMPLND segment														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.04	--

Table 9. Process-related annual parameters for pervious and impervious land segments, Hydrological Simulation Program—FORTRAN models, Hondo Creek and Verde Creek watersheds, south-central Texas—Continued.

Edwards aquifer confining units

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0.001	0.75	0.001	0.27	0.20	0.35	0.40	0.70	400	5.0	0.30	--	0.04	0.50
Deciduous/mixed forest, low slope	.001	.75	.001	.15	.20	.35	.40	.70	400	5.0	.30	--	.04	.50
Shrubland, low slope	.001	.75	.001	.12	.20	.35	.40	.70	400	5.0	.30	--	.04	.50
Grassland, low slope	.001	.75	.001	.10	.20	.35	.40	.70	400	5.0	.30	--	.04	.50
Bare/transitional, low slope	.001	.75	.001	.10	.20	.35	.40	.70	400	5.0	.30	--	.04	.50
Agricultural, low slope	.001	.75	.001	.10	.20	.35	.40	.70	400	5.0	.30	--	.04	.50
Developed, low slope	.001	.75	.001	.10	.20	.35	.40	.70	400	5.0	.30	--	.04	.50
Evergreen forest, medium slope	.001	.75	.001	.26	.20	.35	.40	.70	400	5.0	.30	--	.08	.50
Deciduous/mixed forest, medium slope	.001	.75	.001	.15	.20	.35	.40	.70	400	5.0	.30	--	.08	.50
Shrubland, medium slope	.001	.75	.001	.12	.20	.35	.40	.70	400	5.0	.30	--	.08	.50
Grassland, medium slope	.001	.75	.001	.10	.20	.35	.40	.70	400	5.0	.30	--	.08	.50
Bare/transitional, medium slope	.001	.75	.001	.10	.20	.35	.40	.70	400	5.0	.30	--	.08	.50
Agricultural, medium slope	.001	.75	.001	.10	.20	.35	.40	.70	400	5.0	.30	--	.08	.50
Developed, medium slope	.001	.75	.001	.10	.20	.35	.40	.70	400	5.0	.30	--	.08	.50
IMPLND segment														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.04	--

Alluvial deposits

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0.001	0.85	0.001	0.27	0.45	0.35	1.50	0.70	400	3.0	0.30	--	0.04	0.60
Deciduous/mixed forest, low slope	.001	.85	.001	.15	.45	.35	1.50	.70	400	3.0	.30	--	.04	.60
Shrubland, low slope	.001	.85	.001	.12	.45	.35	1.50	.70	400	3.0	.30	--	.04	.60
Grassland, low slope	.001	.85	.001	.10	.45	.35	1.50	.70	400	3.0	.30	--	.04	.60
Bare/transitional, low slope	.001	.85	.001	.10	.45	.35	1.50	.70	400	3.0	.30	--	.04	.60
Agricultural, low slope	.001	.85	.001	.10	.45	.35	1.50	.70	400	3.0	.30	--	.04	.60
Developed, low slope	.001	.85	.001	.10	.45	.35	1.50	.70	400	3.0	.30	--	.04	.60
IMPLND segment														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.04	--

Table 10. Process-related annual parameters for pervious and impervious land segments, Hydrological Simulation Program—FORTRAN model, San Geronimo Creek watershed, south-central Texas.

[Parameter definitions in table 1; PERLND, PERvious LaND; --, not applicable; IMPLND, IMPervious LaND]

Glen Rose Limestone (Trinity aquifer outcrop)

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0.001	0.95	0.001	0.27	0.22	0.3	1.0	0.8	400	3.6	0.3	--	0.04	0.24
Deciduous/mixed forest, low slope	.001	.95	.001	.15	.22	.3	1.0	.8	400	3.6	.3	--	.04	.24
Shrubland, low slope	.001	.95	.001	.12	.22	.3	1.0	.8	400	3.6	.3	--	.04	.24
Grassland, low slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.04	.24
Bare/transitional, low slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.04	.24
Agricultural, low slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.04	.24
Developed, low slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.04	.24
Evergreen forest, medium slope	.001	.95	.001	.26	.22	.3	1.0	.8	400	3.6	.3	--	.08	.24
Deciduous/mixed forest, medium slope	.001	.95	.001	.15	.22	.3	1.0	.8	400	3.6	.3	--	.08	.24
Shrubland, medium slope	.001	.95	.001	.12	.22	.3	1.0	.8	400	3.6	.3	--	.08	.24
Grassland, medium slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.08	.24
Bare/transitional, medium slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.08	.24
Agricultural, medium slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.08	.24
Developed, medium slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.08	.24
Evergreen forest, steep slope	.001	.95	.001	.25	.22	.3	1.0	.8	400	3.6	.3	--	.14	.22
Deciduous/mixed forest, steep slope	.001	.95	.001	.15	.22	.3	1.0	.8	400	3.6	.3	--	.14	.22
Shrubland, steep slope	.001	.95	.001	.12	.22	.3	1.0	.8	400	3.6	.3	--	.14	.22
Grassland, steep slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.14	.22
Bare/transitional, steep slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.14	.22
Agricultural, steep slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.14	.22
Developed, steep slope	.001	.95	.001	.10	.22	.3	1.0	.8	400	3.6	.3	--	.14	.22
IMPLND segment														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.06	--

Table 10. Process-related annual parameters for pervious and impervious land segments, Hydrological Simulation Program—FORTRAN model, San Geronimo Creek watershed, south-central Texas—Continued.

Edwards Group outcrop (Edwards aquifer recharge zone)

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0	0.75	0	0.27	0.9	0.4	0.8	0.6	500	2.8	0.3	--	0.04	0.4
Deciduous/mixed forest, low slope	0	.75	0	.15	.9	.4	.8	.6	500	2.8	.3	--	.04	.4
Shrubland, low slope	0	.75	0	.12	.9	.4	.8	.6	500	2.8	.3	--	.04	.4
Grassland, low slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.04	.4
Bare/transitional, low slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.04	.4
Agricultural, low slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.04	.4
Developed, low slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.04	.4
Evergreen forest, medium slope	0	.75	0	.26	.9	.4	.8	.6	500	2.8	.3	--	.08	.4
Deciduous/mixed forest, medium slope	0	.75	0	.15	.9	.4	.8	.6	500	2.8	.3	--	.08	.4
Shrubland, medium slope	0	.75	0	.12	.9	.4	.8	.6	500	2.8	.3	--	.08	.4
Grassland, medium slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.08	.4
Bare/transitional, medium slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.08	.4
Agricultural, medium slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.08	.4
Developed, medium slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.08	.4
Evergreen forest, steep slope	0	.75	0	.25	.9	.4	.8	.6	500	2.8	.3	--	.13	.4
Deciduous/mixed forest, steep slope	0	.75	0	.15	.9	.4	.8	.6	500	2.8	.3	--	.13	.4
Shrubland, steep slope	0	.75	0	.12	.9	.4	.8	.6	500	2.8	.3	--	.13	.4
Grassland, steep slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.13	.4
Bare/transitional, steep slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.13	.4
Agricultural, steep slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.13	.4
Developed, steep slope	0	.75	0	.10	.9	.4	.8	.6	500	2.8	.3	--	.13	.4
IMPLND segment														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.04	--

Table 10. Process-related annual parameters for pervious and impervious land segments, Hydrological Simulation Program—FORTRAN model, San Geronimo Creek watershed, south-central Texas—Continued.

Edwards Group remnants (hilltops) overlying Glen Rose Limestone

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0.001	0.94	0.001	0.27	0.2	0.35	0.9	0.7	400	3.6	0.3	--	0.04	0.4
Deciduous/mixed forest, low slope	.001	.94	.001	.15	.2	.35	.9	.7	400	3.6	.3	--	.04	.4
Shrubland, low slope	.001	.94	.001	.12	.2	.35	.9	.7	400	3.6	.3	--	.04	.4
Grassland, low slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.04	.4
Bare/transitional, low slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.04	.4
Agricultural, low slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.04	.4
Developed, low slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.04	.4
Evergreen forest, medium slope	.001	.94	.001	.26	.2	.35	.9	.7	400	3.6	.3	--	.08	.4
Deciduous/mixed forest, medium slope	.001	.94	.001	.15	.2	.35	.9	.7	400	3.6	.3	--	.08	.4
Shrubland, medium slope	.001	.94	.001	.12	.2	.35	.9	.7	400	3.6	.3	--	.08	.4
Grassland, medium slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.08	.4
Bare/transitional, medium slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.08	.4
Agricultural, medium slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.08	.4
Developed, medium slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.08	.4
Evergreen forest, steep slope	.001	.94	.001	.25	.2	.35	.9	.7	400	3.6	.3	--	.14	.4
Deciduous/mixed forest, steep slope	.001	.94	.001	.15	.2	.35	.9	.7	400	3.6	.3	--	.14	.4
Shrubland, steep slope	.001	.94	.001	.12	.2	.35	.9	.7	400	3.6	.3	--	.14	.4
Grassland, steep slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.14	.4
Bare/transitional, steep slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.14	.4
Agricultural, steep slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.14	.4
Developed, steep slope	.001	.94	.001	.10	.2	.35	.9	.7	400	3.6	.3	--	.14	.4
IMPLND segment														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.04	--

Table 10. Process-related annual parameters for pervious and impervious land segments, Hydrological Simulation Program—FORTRAN model, San Geronimo Creek watershed, south-central Texas—Continued.

Edwards aquifer confining units

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0.001	0.75	0.001	0.27	0.2	0.35	0.4	0.7	400	5.0	0.3	--	0.04	0.5
Deciduous/mixed forest, low slope	.001	.75	.001	.15	.2	.35	.4	.7	400	5.0	.3	--	.04	.5
Shrubland, low slope	.001	.75	.001	.12	.2	.35	.4	.7	400	5.0	.3	--	.04	.5
Grassland, low slope	.001	.75	.001	.10	.2	.35	.4	.7	400	5.0	.3	--	.04	.5
Bare/transitional, low slope	.001	.75	.001	.10	.2	.35	.4	.7	400	5.0	.3	--	.04	.5
Agricultural, low slope	.001	.75	.001	.10	.2	.35	.4	.7	400	5.0	.3	--	.04	.5
Developed, low slope	.001	.75	.001	.10	.2	.35	.4	.7	400	5.0	.3	--	.04	.5
Evergreen forest, medium slope	.001	.75	.001	.26	.2	.35	.4	.7	400	5.0	.3	--	.08	.5
Deciduous/mixed forest, medium slope	.001	.75	.001	.15	.2	.35	.4	.7	400	5.0	.3	--	.08	.5
Shrubland, medium slope	.001	.75	.001	.12	.2	.35	.4	.7	400	5.0	.3	--	.08	.5
Grassland, medium slope	.001	.75	.001	.10	.2	.35	.4	.7	400	5.0	.3	--	.08	.5
Bare/transitional, medium slope	.001	.75	.001	.10	.2	.35	.4	.7	400	5.0	.3	--	.08	.5
Agricultural, medium slope	.001	.75	.001	.10	.2	.35	.4	.7	400	5.0	.3	--	.08	.5
Developed, medium slope	.001	.75	.001	.10	.2	.35	.4	.7	400	5.0	.3	--	.08	.5
IMPLND														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.04	--

Alluvial deposits

Land cover and slope	AGWETP	AGWRC	BASETP	CEPSC	DEEPFR	INFILT	INTFW	IRC	LSUR	LZSN	NSUR	RETSC	SLSUR	UZSN
PERLND segment														
Evergreen forest, low slope	0.001	0.85	0.001	0.27	0.45	0.35	1.5	0.7	400	3.5	0.3	--	0.04	0.6
Deciduous/mixed forest, low slope	.001	.85	.001	.15	.45	.35	1.5	.7	400	3.5	.3	--	.04	.6
Shrubland, low slope	.001	.85	.001	.12	.45	.35	1.5	.7	400	3.5	.3	--	.04	.6
Grassland, low slope	.001	.85	.001	.10	.45	.35	1.5	.7	400	3.5	.3	--	.04	.6
Bare/transitional, low slope	.001	.85	.001	.10	.45	.35	1.5	.7	400	3.5	.3	--	.04	.6
Agricultural, low slope	.001	.85	.001	.10	.45	.35	1.5	.7	400	3.5	.3	--	.04	.6
Developed, low slope	.001	.85	.001	.10	.45	.35	1.5	.7	400	3.5	.3	--	.04	.6
IMPLND														
All impervious	--	--	--	--	--	--	--	--	400	--	.10	0.05	.04.	--

Table 11. Monthly values of lower-zone evapotranspiration (LZETP) parameter, Hydrological Simulation Program—FORTRAN models, Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas.

[PERLND, PERvious LaND]

All geology-slope combinations

Land cover	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
PERLND segment												
Evergreen forest	0.4	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.4	0.4
Deciduous/mixed forest	.2	.2	.4	.6	.7	.7	.7	.7	.6	.5	.4	.3
Shrubland	.2	.2	.4	.6	.7	.7	.7	.7	.6	.5	.4	.3
Grassland	.2	.2	.4	.6	.7	.7	.7	.7	.6	.5	.4	.3
Bare/transitional	.2	.2	.4	.6	.7	.7	.7	.7	.6	.5	.4	.3
Agriculture	.2	.2	.4	.5	.5	.5	.5	.5	.4	.3	.2	.2
Developed	.2	.2	.4	.6	.7	.7	.7	.7	.6	.6	.5	.3

Table 12. Simulated average annual streamflow volumes for Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas, 1951–2003.

[Total streamflow for a watershed includes all surface runoff, interflow, and base flow that originates in the watershed and reaches the stream channel. Streamflow at watershed outlet is difference between total streamflow and streamflow lost to channel infiltration.]

	Hondo Creek	Verde Creek	San Geronimo Creek
Watershed area, acres	102,702	140,088	43,889
Approximate area of Edwards aquifer recharge zone and contributing drainage area upstream from the recharge zone, acres	90,200	92,800	36,120
Average annual rainfall, inches	30.40	29.72	32.09
Average annual total streamflow, acre-feet	45,400	32,400	11,100
Average annual total streamflow, inches	5.30	2.78	3.03
Average annual streamflow at watershed outlet, acre-feet	13,000	16,200	6,920
Average annual streamflow at watershed outlet, inches	1.52	1.39	1.89

Table 13. Estimated annual rainfall and Edwards aquifer recharge, Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas, 1951–2003.

Calendar year	Hondo Creek		Verde Creek		San Geronimo Creek[1]	
	Rainfall (inches)	Recharge (acre-feet)	Rainfall (inches)	Recharge (acre-feet)	Rainfall (inches)	Recharge (acre-feet)
1951	18.69	9,760	20.72	8,750	19.81	230
1952	25.17	14,200	26.56	10,500	34.11	3,930
1953	19.27	21,800	18.97	14,400	19.99	1,580
1954	14.59	5,840	13.60	3,960	11.44	100
1955	19.44	4,170	18.58	4,090	17.83	210
1956	10.95	1,920	11.90	1,760	12.14	150
1957	38.65	58,500	38.16	38,800	46.61	11,400
1958	43.17	73,200	42.55	48,500	41.44	9,750
1959	29.36	21,500	32.91	14,500	37.30	4,190
1960	34.87	36,700	33.86	24,800	32.76	2,870
1961	28.29	40,600	26.79	26,800	24.92	2,810
1962	20.57	6,360	21.61	4,850	25.16	1,600
1963	20.47	9,450	19.19	6,840	19.24	700
1964	21.90	20,800	24.66	14,200	27.23	2,780
1965	30.51	30,100	31.92	22,000	39.03	7,720
1966	19.37	9,040	25.11	9,170	30.20	5,230
1967	28.32	41,900	28.56	27,800	27.39	3,980
1968	45.45	85,800	35.21	53,800	29.02	4,420
1969	36.81	52,500	36.63	35,300	38.26	6,830
1970	27.02	33,300	23.60	22,500	22.11	2,910
1971	43.08	71,300	37.58	43,900	38.46	8,460
1972	36.44	55,900	32.66	33,700	33.05	3,530
1973	41.43	46,900	45.65	33,300	50.96	12,800
1974	40.85	57,600	37.69	38,800	37.08	5,260
1975	32.34	40,500	30.09	28,700	30.13	5,130
1976	40.60	68,700	42.30	48,200	44.46	10,600
1977	28.96	40,500	25.37	26,800	28.26	3,530
1978	34.08	37,500	32.71	25,100	35.09	5,990
1979	28.46	39,900	28.28	28,200	34.49	8,720
1980	30.00	34,900	26.20	24,100	26.33	1,890
1981	41.49	69,000	37.14	44,700	38.56	10,600
1982	22.68	15,400	22.77	11,700	25.82	2,380
1983	32.13	40,000	28.94	26,800	31.00	2,230
1984	28.84	20,500	24.64	16,200	22.47	1,660
1985	36.77	65,800	35.70	44,200	39.24	9,720
1986	30.84	36,300	34.26	28,800	40.16	12,800
1987	46.42	68,600	43.17	44,600	39.82	11,300
1988	20.64	22,500	17.00	13,800	16.56	180
1989	21.14	21,000	19.50	13,700	22.33	700
1990	28.01	36,700	25.73	24,900	34.19	7,750
1991	44.08	60,000	41.95	40,900	47.36	7,260
1992	48.98	117,000	46.67	73,800	55.65	26,700
1993	26.29	17,100	26.87	16,000	22.13	2,500
1994	28.95	26,000	28.57	20,400	37.54	6,640
1995	27.65	23,300	27.99	17,900	28.31	2,160
1996	17.12	3,800	18.17	3,780	22.12	730
1997	36.97	44,800	34.66	30,500	46.58	10,800
1998	39.64	62,200	43.10	46,900	40.69	11,600
1999	18.01	9,050	21.01	9,180	18.83	1,130
2000	26.09	30,800	27.52	21,200	36.85	10,100
2001	29.49	40,500	30.94	31,700	39.23	13,800
2002	43.97	73,600	44.34	51,900	53.60	18,400
2003	26.04	32,600	24.86	21,600	27.41	4,160
Average	30.40	37,900	29.72	26,000	32.09	5,940
Minimum	10.63	1,920	11.38	1,760	11.14	100
Maximum	51.71	117,000	52.71	73,800	58.61	26,700

[1] Recalibrated values.

Table 14. Comparison of Edwards aquifer recharge estimates from Hydrological Simulation Program—FORTRAN (HSPF) with historical (Puente method) U.S. Geological Survey recharge estimates for Hondo Creek and Verde Creek watersheds, south-central Texas, 1992–2003.

Year	Hondo Creek watershed		Verde Creek watershed	
	HSPF-simulated recharge (acre-feet)	Puente method recharge (acre-feet)	HSPF-simulated recharge (acre-feet)	Puente method recharge (acre-feet)
[1]1992	117,000	209,000	73,800	133,000
1993	17,100	17,900	16,000	18,200
1994	26,000	15,500	20,400	16,300
1995	23,300	18,100	17,900	22,200
1996	3,800	1,530	3,780	5,570
[1]1997	44,800	61,600	30,500	55,800
[1]1998	62,200	64,500	46,900	62,600
1999	9,050	20,400	9,180	19,900
2000	30,800	14,600	21,200	21,000
2001	40,500	39,800	31,700	39,300
[1]2002	73,600	135,000	51,900	156,000
2003	32,600	22,800	21,600	22,100
Average	40,100	51,700	28,700	47,700

[1] Years of greater-than-average rainfall in both watersheds.

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