USGS
science for a changing world

In cooperation with the San Antonio Water System

Simulation of Runoff and Recharge and Estimation of Constituent Loads in Runoff, Edwards Aquifer Recharge Zone (Outcrop) and Catchment Area, Bexar County, Texas, 1997–2000

Water-Resources Investigations Report 02–4241

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

Cover:

Salado Creek above Loop 1604, October 17, 1998.

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

Simulation of Runoff and Recharge and Estimation of Constituent Loads in Runoff, Edwards Aquifer Recharge Zone (Outcrop) and Catchment Area, Bexar County, Texas, 1997–2000

By Darwin J. Ockerman

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 02–4241

In cooperation with the San Antonio Water System

Austin, Texas
2002

U.S. DEPARTMENT OF THE INTERIOR

Gale A. Norton, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

For additional information write to

District Chief
U.S. Geological Survey
8027 Exchange Dr.
Austin, TX 78754–4733
E-mail: dc_tx@usgs.gov

Copies of this report can be purchased from

U.S. Geological Survey
Information Services
Box 25286
Denver, CO 80225–0286
E-mail: infoservices@usgs.gov

CONTENTS

FIGURES

TABLES

Simulation of Runoff and Recharge and Estimation of Constituent Loads in Runoff, Edwards Aquifer Recharge Zone (Outcrop) and Catchment Area, Bexar County, Texas, 1997–2000

By Darwin J. Ockerman

Abstract

The U.S. Geological Survey developed a watershed model (Hydrological Simulation Program—FORTRAN) to simulate runoff and recharge and to estimate constituent loads in surface-water runoff in the Edwards aquifer recharge zone (outcrop) and catchment area in Bexar County, Texas. Rainfall and runoff data collected during 1970–98 from four gaged basins in the outcrop and catchment area were used to calibrate and test the model. The calibration parameters were applied in simulations of the four calibration basins and six ungaged basins that compose the study area to obtain runoff and recharge volumes for 4 years, 1997–2000. In 1997, simulated runoff from the study area was 5.62 inches. Simulated recharge in the study area was 7.85 inches (20 percent of rainfall). In 1998, simulated runoff was 11.05 inches; simulated recharge was 10.99 inches (25 percent of rainfall). In 1999, simulated runoff was 0.66 inch; simulated recharge was 3.03 inches (19 percent of rainfall). In 2000, simulated runoff was 5.29 inches; simulated recharge was 7.19 inches (21 percent of rainfall). During 1997–2000, direct infiltration of rainfall accounted for about 56 percent of the total Edwards aquifer recharge in Bexar County. Streamflow losses contributed about 37 percent of the recharge; flood impoundment contributed 7 percent. The simulated runoff volumes were used with event-mean-concentration data from basins in the study area and from other Bexar County basins to compute constituent loads and yields for various land uses. Annual loads for suspended solids, dissolved solids, dissolved nitrite plus nitrate nitrogen, and total lead were consistently largest from undeveloped land and smallest from commercial land or transportation corridors. Annual loads and yields varied with rainfall, with the maximum loads produced in the wettest year (1998) and the minimum loads produced in the driest year (1999).

INTRODUCTION

The Edwards aquifer is one of the most productive carbonate aquifers in the Nation and is the major source of public water supply for San Antonio, Texas, and Bexar County (fig. 1). In addition to providing public water supply for more than 1 million people in south-central Texas, 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 supply flow to downstream users and provide habitat for several threatened or endangered species.

Most recharge to the Edwards aquifer occurs west of Bexar County by direct infiltration of precipitation and by streamflow loss in the Edwards recharge zone. After entering the aquifer, water moves from west to east to points of discharge in Bexar County (mostly public supply wells) and then northeastward into Comal and Hays Counties (fig. 1), where it is discharged by withdrawals (wells) and two major springs. Additional recharge to the Edwards aquifer occurs in the recharge zone in northern Bexar County and southern Comal and Hays Counties.

In northern Bexar County, residential and commercial development in the Edwards aquifer recharge zone and catchment area is increasing. Urban development can have an appreciable influence on the quality of

Figure 1. Edwards aquifer recharge zone (outcrop), catchment area, and associated stream basins, Bexar County, Texas.

Table 1. Selected characteristics of stream basins in the Edwards aquifer recharge zone (outcrop) and catchment area, Bexar County, Texas

Basin	Total area (square miles)	Edwards aquifer outcrop area (square miles)	Estimated impervious fraction (percent)
San Geronimo Creek (within Bexar County)	24.52	3.12	0
Culebra Creek	17.38	13.55	.5
Helotes Creek	27.41	5.23	3.9
Leon Creek	65.25	16.73	7.3
Olmos/Huebner Creeks	8.48	7.38	12.5
Salado Creek	30.68	6.61	2.3
Panther Springs Creek	22.26	14.45	7.2
Mud Creek	22.73	18.14	9.7
Elm Creek	30.07	25.33	4.1
Cibolo Creek (within Bexar County)	61.62	14.56	2.1
Total	310.4	125.1	4.6

surface water and on water that recharges the aquifer. Impervious land cover in developed areas can result in increased stormwater runoff conveying contaminants from nonpoint sources to local streams or geologic features (caves, fractures) where infiltration into the aquifer can occur.

Estimates of runoff, water-quality constituent loads in runoff, and recharge to the Edwards aquifer are uncertain because of insufficient streamflow and water-quality data in the Edwards aquifer recharge zone and catchment area and the complexity of the rainfall-runoff process. The effects of commercial and residential development on runoff quantity and quality and recharge quantity are not well known. To learn more about these phenomena, the U.S. Geological Survey (USGS), in cooperation with the San Antonio Water System (SAWS), began a study in 1996 to develop a watershed model to simulate runoff and recharge and to estimate constituent loads in surface-water runoff in the Edwards aquifer recharge zone and catchment area in Bexar County.

Purpose and Scope

This report describes the calibration, testing, and use of a watershed model to simulate runoff and recharge, the results of which were used to estimate constituent loads in surface-water runoff in the Edwards aquifer recharge zone and catchment area in Bexar County for 1997–2000. The Hydrological Simulation Program—FORTRAN (HSPF) watershed model (Bicknell and others, 1997) was used for the simulations. Rainfall and runoff data collected during 1970–98 from selected gaged basins of the Edwards aquifer recharge zone and catchment area were compiled and used to calibrate and test the model. The calibration parameters then were transferred to the largely ungaged study area, and simulations were done for the entire study area to obtain runoff and recharge volumes. The simulated runoff volumes were used with event-mean-concentration data from basins in the study area and other Bexar County basins to compute constituent loads and yields for various land uses.

Description of Study Area

The study area comprises the Edwards aquifer recharge zone and the adjacent catchment area in northern Bexar County (fig. 1). The Edwards aquifer recharge zone is approximately coincident with the Edwards aquifer outcrop. (The Edwards aquifer recharge zone is hereinafter referred to as the Edwards aquifer outcrop.) The catchment area consists of drainage basins of streams that lose water to (recharge) the Edwards aquifer as they cross the outcrop. The 10 stream basins of the study area encompass about 310 square miles that include about 125 square miles of Edwards aquifer outcrop and about 185 square miles of catchment area (table 1).

Most of the land (about 72 percent) in the outcrop is undeveloped (fig. 2) (David Kruse, Alamo Area Council of Governments, written commun., 1999). In 1998, residential land use was about 10 percent of the Edwards aquifer outcrop area, although development there is increasing. A comparison of 1996–98 land use data indicates that residential land use in the study area increased by about 9 percent from 19,260 acres in 1996 to 20,970 acres in 1998.

The primary geologic formations that crop out in the study area are the Glen Rose Limestone and the Kainer, Person, and Georgetown Formations (Stein and Ozuna, 1995). The Glen Rose Limestone covers most of the catchment area, and the Kainer, Person, and Georgetown Formations cover the Edwards aquifer outcrop. The Glen Rose Limestone is less permeable than the formations of the Edwards aquifer outcrop and generates more runoff per unit area. The Glen Rose Limestone also sustains base flow (ground-water inflow to stream channels) for days or weeks after large rainfalls. In contrast, the more permeable formations of the outcrop allow streamflow losses to the aquifer, thus limiting streamflow after large rainfalls to very short duration (often only a few hours). These streamflow losses contribute recharge directly to the Edwards aquifer (Land and others, 1983).

Vegetation on the undeveloped part of the Glen Rose Limestone consists of moderate to dense stands of juniper, oak, and shrub. Vegetation on the Edwards aquifer outcrop consists of open to moderately open oak, juniper, and shrub (University of Texas, Bureau of Economic Geology, 1985). The soils in the study area consist primarily of two associations: Tarrant-Brackett and Crawford-Bexar (U.S. Department of Agriculture, Soil Conservation Service, 1966). The Tarrant-Brackett soils account for about 80 percent of the study area and overlie most of the Glen Rose Limestone. Crawford-Bexar soils are more common on the Edwards aquifer outcrop. Both soil associations are primarily clay, ranging from a few inches to about 16 inches deep.

Twelve major flood-control structures are located in the study area (San Antonio River Authority, 1996); 10 are located in the Edwards aquifer outcrop. During major runoff, the structures retain water so that it has more time to infiltrate as ground-water recharge. Figure 3 is a photograph of water behind a flood-control structure in the upper Salado Creek Basin after a rainfall in October 1998.

Description of Simulation Model and Modeling Process

The HSPF (Bicknell and others, 1997) is a continuous-simulation model using a conceptual framework to represent infiltration, evaporation, interception storage, surface runoff, interflow (water that infiltrates into the soil and moves laterally through the upper soil horizons until it returns to the surface, often in a stream), and base flow on a pervious land segment (PERLND) and to represent retention storage and surface runoff on an impervious land segment (IMPLND). Each user-defined land segment represents its own unique hydrologic response system on the basis of soil type, land cover, basin slope, or other pertinent basin characteristic. These land segments do not need to be contiguous within the model. The runoff from each land segment is moved through a system of channels or reservoir reaches (RCHRES) using storage routing.

The HSPF model uses input from three types of data: time series, basin-related model parameters, and process-related model parameters. Continuous time series of precipitation and potential evaporation are needed to run the model. Point-precipitation data, measured by rain gages, are assumed to be uniform over a land segment. Potential evaporation data can be estimated from measured pan evaporation or computed from minimum and maximum daily temperatures. Time series of measured streamflow are used for model calibration and testing.

The six basin-related model parameters (table 2) define the areal extent of each land segment (AREA), the reach length (LEN), and a table of values (FTABLE) of surface area (SAREA), volume (VOL), and discharge

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

[PERLND, pervious land segment; IMPLND, impervious land 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)

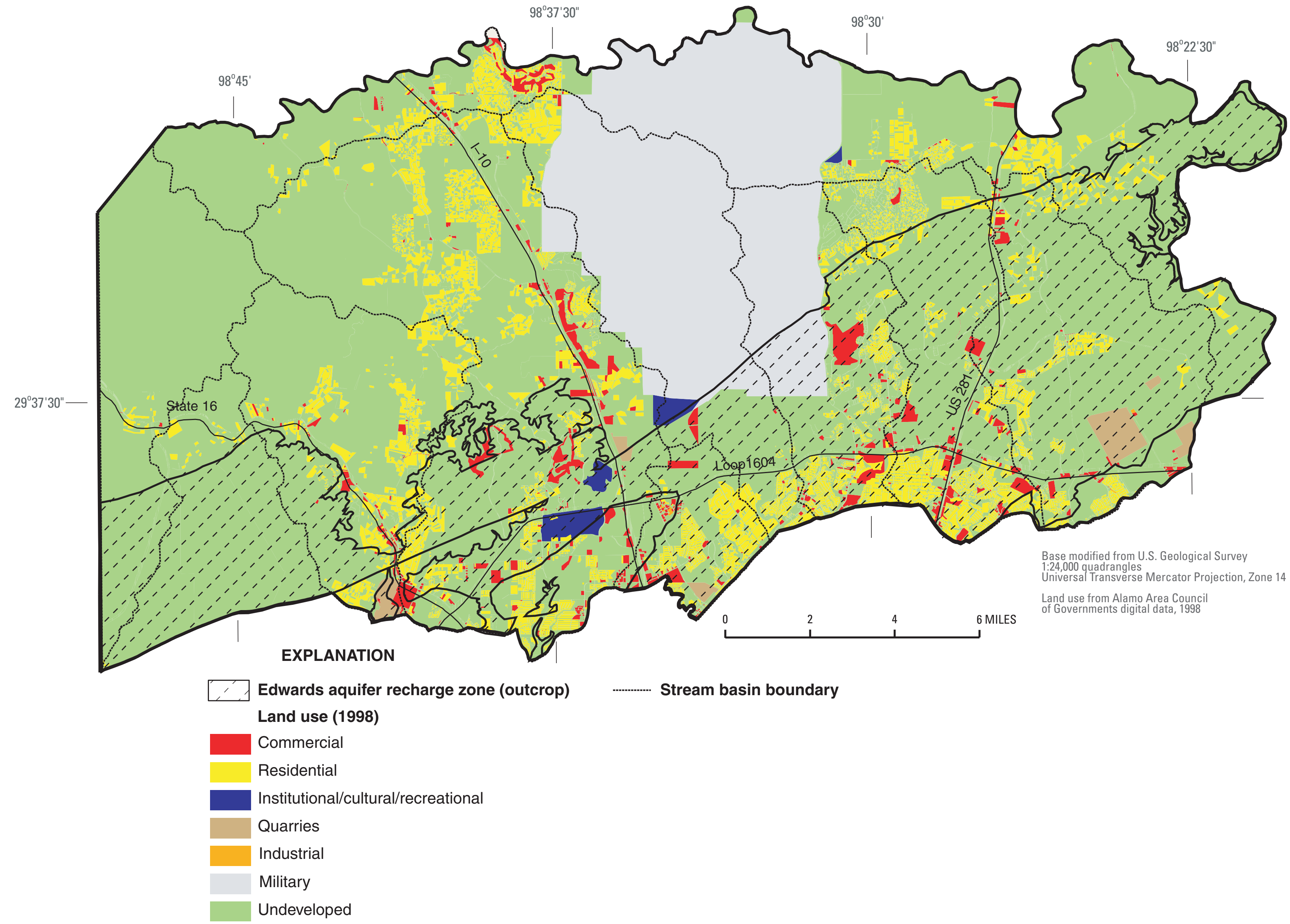

Figure 2. Land use in the Edwards aquifer recharge zone (outcrop) and catchment area, Bexar County, Texas.

Figure 3. Floodwater retention behind Salado Creek structure, October 1998.

(DISCH), as a function of depth (DEPTH) for each reach or reservoir of the basin. These parameters represent the physical characteristics of each land segment or reach of a basin and generally remain unchanged during calibration and testing of the model.

Process-related model parameters (table 3) represent the physical processes of infiltration, evapotranspiration (ET), interception, interflow, groundwater recession, and surface runoff for each land segment. The process-related model parameters for each land segment are adjusted to calibrate the model. The following parameters can be varied by month to account for seasonal variations: interception storage capacity (CEPSC), interflow inflow (INTFW), interflow recession rate (IRC), lower-zone ET (LZETP), Manning's n for assumed overland flow plane (NSUR), and upper-zone nominal storage (UZSN). Because the available data were insufficient to characterize monthly variations, the parameters were not varied by month. The HSPF users manual (Bicknell and others, 1997) provides a more complete description of each parameter.

The HSPEXP (Lumb and others, 1994), a computerized expert system, was used to help adjust process-related parameters during calibration and testing. HSPEXP is a stand-alone program that incorporates HSPF. 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.

The first step in developing the HSPF model for the study area basins was to subdivide the basins into segments (RCHRES), taking into consideration the stream and reservoir (flood-control impoundment) configuration of each basin. After subdivision, each basin contained from 1 to 12 RCHRES segments—63 stream segments and 12 reservoir segments in all for the 10 major basins (fig. 4). FTABLE information for gaged stream reaches was based on discharge measurements made at USGS streamflow-gaging stations in the study area. FTABLE information for ungaged reaches was estimated from similar gaged reaches. FTABLE information for flood-control reservoirs was developed from the dam and reservoir design specifications.

Pervious land segments (PERLNDs) and impervious land segments (IMPLNDs) were configured according to geology and land use. The two geologic categories were based on the relative permeability of the rocks that compose the Edwards aquifer outcrop (relatively high permeability) and the catchment area

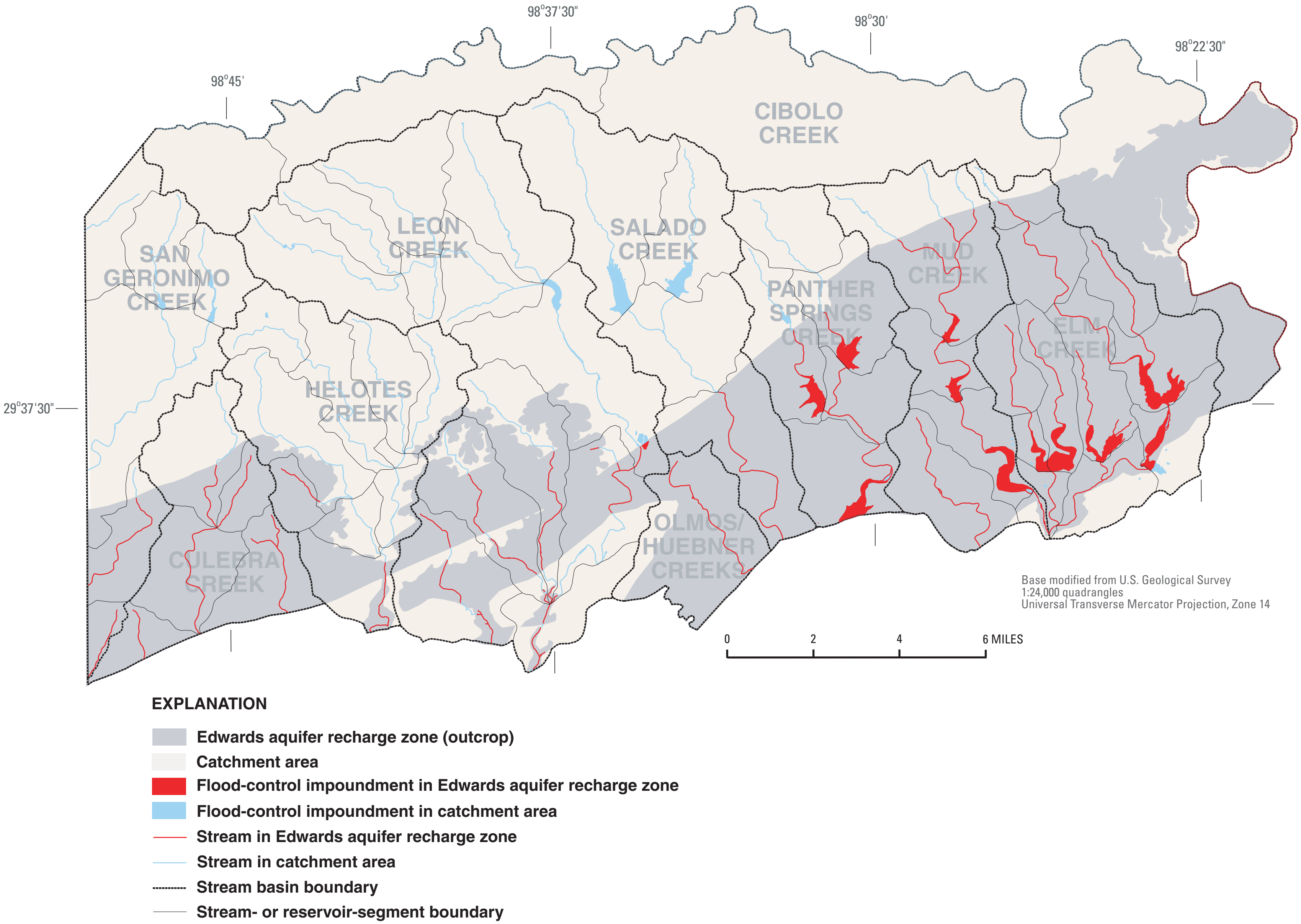

Figure 4. Stream and reservoir segments in the Edwards aquifer recharge zone (outcrop) and catchment area, Bexar County, Texas.

Table 3. Process-related model parameters for the Hydrological Simulation Program—FORTRAN

[ET, evapotranspiration; --, none]

Parameter	Description	Default value	Minimum value	Maximum value	Units
AGWS	Initial active ground-water storage	--	0	--	inches
AGWETP	Available ET satisfied by active ground water	0	0	1.0	--
AGWRC	Active ground-water recession rate	--	.001	1.0	per day
BASETP	Available ET satisfied by base flow	0	0	1.0	--
CEPSC	Interception storage capacity	0	0	1.0	inches
DEEPFR	Fraction of inflow that enters inactive ground water	0	0	1.0	--
INFEXP	Infiltration equation exponent	2.0	0	10.0	--
INFILD	Ratio of maximum to mean infiltration capacities	2.0	1.0	2.0	--
INFILT	Index to infiltration capacity of soil	--	.0001	100.0	inches per hour
INTFW	Interflow inflow	--	0	--	--
IRC	Interflow recession rate	--	0	1.0	per day
KVARY	Nonexponential ground-water recession rate	0	0	--	per inch
LSUR	Length of assumed overland flow plane	--	1.0	--	feet
LZETP	Lower-zone ET	0	0	1.0	--
LZS	Initial lower-zone storage	--	0	--	inches
LZSN	Lower-zone nominal storage	--	.01	100.0	inches
NSUR	Manning's n for assumed overland flow plane	.1	.001	1.0	--
SLSUR	Slope of assumed overland flow plane	--	.000001	10.0	feet per foot
UZS	Initial upper-zone storage	--	0	--	inches
UZSN	Upper-zone nominal storage	--	.01	10.0	inches

(relatively low permeability). Land use categories used in the model were undeveloped, residential, commercial, transportation corridor, and quarries. Military land use largely is undeveloped rangeland. The remaining land use categories (fig. 2) account for less than 5 percent of the overall land use and, therefore, were grouped with other categories that had similar hydrologic characteristics. Table 4 lists the areas, in acres, of PERLNDs and IMPLNDs for each basin.

Process-related parameters were calibrated for gaged basins. During the calibration process, parameter sets first were developed for gaged basins that were essentially undeveloped and consisted of a single geologic category—outcrop or catchment area. Because the outcrop and catchment area have substantially different rainfall-runoff characteristics, development of process-related parameters for geologically homogeneous basins facilitated the subsequent calibration of gaged basins that included both geologic categories. The transferability of calibration parameters to ungaged basins was tested by simulating gaged basins with parameter sets developed from other gaged basins.

Because uncertainty in model parameters still exists after calibration and testing, sensitivity of simulated runoff and recharge to changes in selected process-related input parameters was tested by altering values of selected parameters and evaluating the resulting changes in runoff and recharge.

After calibration, testing, and sensitivity analysis, the calibration model parameters were applied to both gaged and ungaged basins, and model simulations were done to estimate runoff and recharge. The runoff results

Table 4. Pervious and impervious land segment areas by geologic and land use categories for the 10 major basins in the study area

[In acres]

Category	San Geronimo Creek	Culebra Creek	Helotes Creek	Leon Creek	Olmos/ Huebner Creeks	Salado Creek	Panther Springs Creek	Mud Creek	Elm Creek	Cibolo Creek
	Basin									
PERLND (pervious land segment)										
Outcrop–undeveloped	2,512	8,671	3,158	7,610	2,498	3,447	6,617	7,724	13,688	8,703
Outcrop–residential	2	0	174	996	1,022	382	1,087	1,715	1,073	494
Outcrop–commercial	0	0	21	503	140	52	188	326	160	34
Outcrop–transportation	55	0	8	347	232	86	372	472	372	0
Outcrop–quarries	0	0	284	226	120	0	0	108	758	0
Catchment area–undeveloped	12,878	2,222	10,962	23,368	482	14,625	4,812	2,108	1,645	26,634
Catchment area–residential	102	140	2,017	4,332	14	562	135	672	285	2,247
Catchment area–commercial	3	0	124	564	61	12	1	17	31	280
Catchment area–transportation	34	32	94	686	41	36	6	16	106	216
Catchment area–quarries	0	0	26	87	0	0	0	0	171	0
IMPLND (impervious land segment)										
Outcrop–residential	1	0	41	174	340	128	425	469	209	55
Outcrop–commercial	0	0	24	504	139	52	191	342	159	33
Outcrop–transportation	55	0	5	345	232	86	372	472	368	0
Catchment area–residential	11	24	360	764	5	99	35	92	81	248
Catchment area–commercial	2	0	139	562	60	2	2	18	31	277
Catchment area–transportation	34	32	100	685	40	46	6	17	105	215

were used to compute constituent loads for the entire study area.

Sources of Model Calibration Data

Sources of data (data-collection stations) for model calibration and development of process-related parameter sets for the Edwards aquifer outcrop and catchment area are shown in figure 5 and listed in table 5. Some rainfall and runoff calibration data were obtained from a 1970–79 data-collection program in several undeveloped basins in the Edwards aquifer outcrop in Bexar County. Most of the stations from that program have been discontinued; land use changes, including suburban development and construction of flood-control structures, have altered the basin characteristics. The 1970s data-collection program provided the only available data for characterizing the rainfall-runoff relation in the undeveloped Edwards aquifer outcrop in the study area. The rainfall and streamflow data from undeveloped basins are required for the model calibration process, especially for selection of process-related parameters for PERLNDs associated with the Edwards aquifer outcrop.

Another important factor in the rainfall-runoff relation is streamflow losses in the outcrop area. Streamflow loss, as a function of streamflow, in Salado Creek after a major runoff during October 1998[1] is shown in figure 6. Streamflow losses are not accounted for by the HSPF process-related parameters. Instead, the channel routing process in HSPF was adjusted to incorporate streamflow losses as channel withdrawals on the basis of streamflow in a reach. The relation shown in figure 6 was used to obtain streamflow losses for the major stream reaches crossing the Edwards aquifer outcrop in the study area. The relation was linearly extrapolated to simulate streamflow losses for streamflows greater than about 200 cubic feet per second. Streamflow losses are assumed to contribute directly to ground-water recharge (Puente, 1978).

The streamflow-loss relation is appropriate for computing losses of streamflow as the water moves downstream from one RCHRES to the next RCHRES. However, water entering a RCHRES as runoff from a PERLND or IMPLND does not travel the entire length of a model RCHRES; therefore, the streamflow-loss relation must be scaled accordingly. The simplifying assumption was made that PERLND and IMPLND runoff within a RCHRES occurred at the midpoint of the RCHRES. Therefore, streamflow entering a RCHRES from an upstream RCHRES incurs streamflow losses along the entire RCHRES, and streamflow entering a RCHRES as PERLND or IMPLND runoff incurs streamflow losses over one-half the RCHRES length.

Direct infiltration to the Edwards aquifer also occurs from storm runoff detained by 10 flood-control structures. The infiltration behind these structures was estimated on the basis of data collected at Parkers Creek Reservoir in Medina County (site no. 14, fig. 5). This reservoir in the outcrop collects runoff from a 10-square-mile basin and is similar in size and design to the flood-control structures in the study area in Bexar County. The relation between reservoir impoundment surface area and infiltration at Parkers Creek was used in the model to simulate withdrawals on the basis of reservoir elevation and surface area for the Bexar County flood-control reservoirs.

ET is water transpired from vegetation and evaporated from land surfaces. In the HSPF model, rainfall infiltrating into the ground is recharge or base flow that returns to the stream channel. The base-flow component can be calibrated using streamflow records. However, to estimate the fraction of infiltration that becomes ground-water recharge, ET must be estimated. To calibrate the HSPF parameters affecting ET, actual ET data are needed. Actual ET data were not available for the study area but were collected (along with rainfall and potential ET [PET]) from the Seco Creek Basin in Medina and Uvalde Counties (Dugas and others, 1998) during the months of February–September[2] from 1991 through 1995. The area of the Seco Creek Basin where the ET data were collected is undeveloped rangeland on Glen Rose Limestone, similar to that in the catchment area in Bexar County.

To use the Seco Creek ET data for model calibration, an empirical relation between measured ET, PET, and rainfall at Seco Creek was developed. A sample of the Seco Creek data is shown in figure 7. The empirical ET relation then was used with PET from the National

[1] Streamflow-loss data (unpublished) were collected by the USGS along Salado Creek after a storm during October 17–19, 1998. Flood runoff stored by flood-control structures in the upper basin (Salado structures 1 and 2) was released over 2 weeks after the storm, providing an opportunity to measure streamflow at several locations along a 5.2-mile reach of Salado Creek in the Edwards aquifer outcrop and to compute streamflow losses per mile for a range of discharges.

[2] ET data were not collected during November–February because the study area was inaccessible.

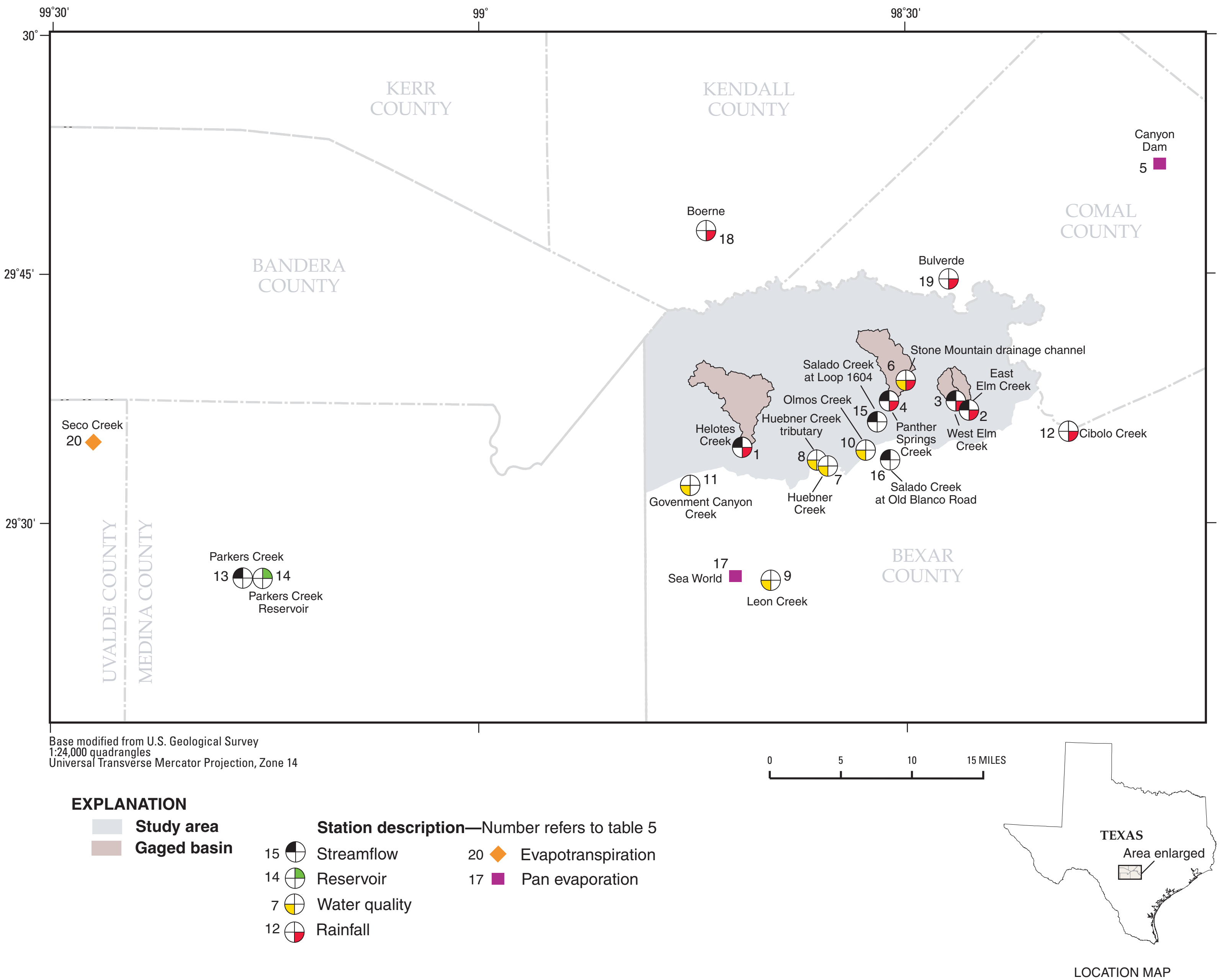

Figure 5. Data-collection stations used for Hydrological Simulation Program—FORTRAN model calibration.

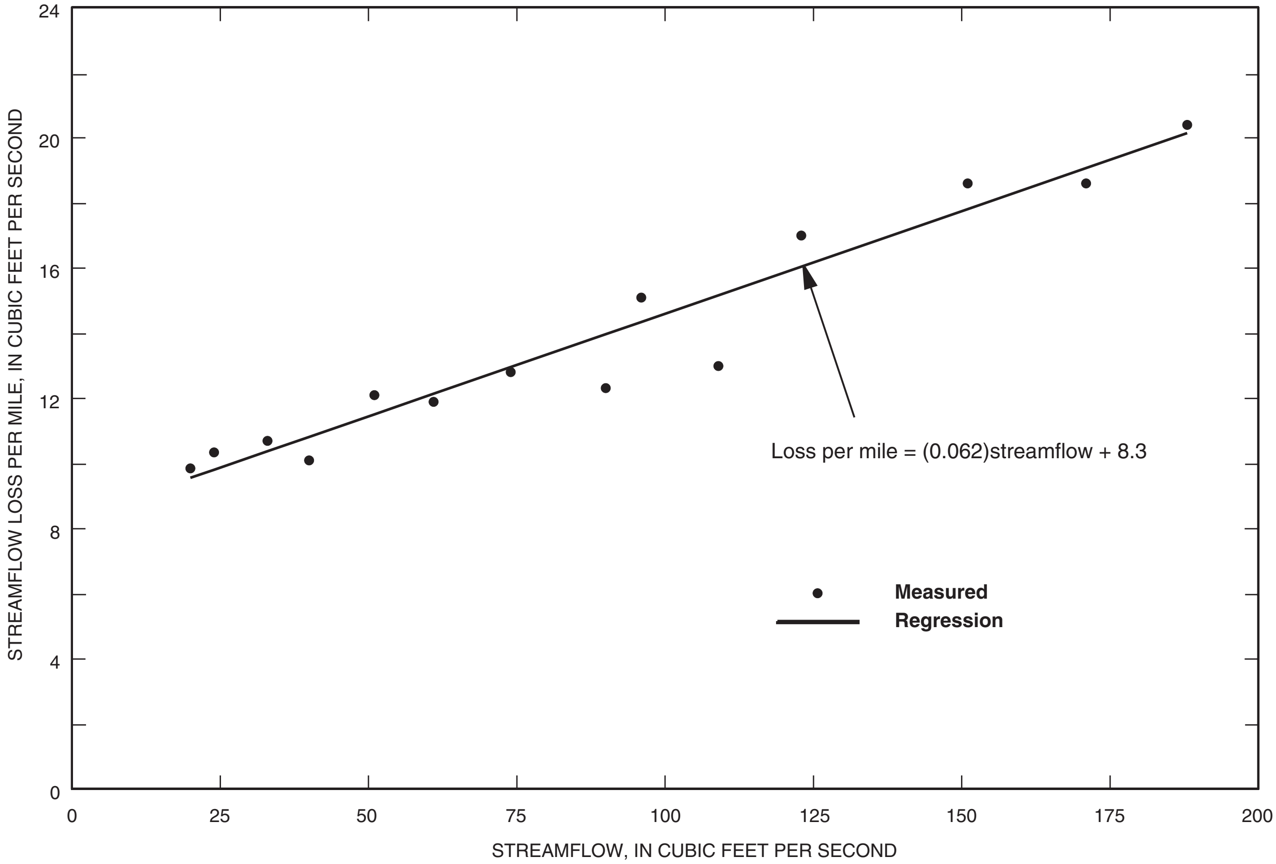

Figure 6. Salado Creek streamflow losses in the Edwards aquifer recharge zone (outcrop), Bexar County, Texas, October 1998.

Weather Service (NWS) station at Sea World of San Antonio and with rainfall data from the Helotes Creek at Helotes streamflow-gaging station to estimate actual ET for the Helotes Creek Basin during 1997–98. This estimated actual ET then was used to calibrate the HSPF parameters that influence ET.

SIMULATION OF RUNOFF AND RECHARGE

Model Calibration and Testing

Calibration and testing of process-related parameters involved four gaged basins in the study area: Helotes Creek, East Elm Creek, West Elm Creek, and Panther Springs Creek. Helotes Creek Basin primarily is in the catchment area. East Elm Creek and West Elm Creek Basins are in the Edwards aquifer outcrop. Panther Springs Creek Basin is partly in the Edwards aquifer outcrop and partly in the catchment area.

Helotes Creek Basin

About 98 percent of the gaged part (upper 9,500 acres) of the Helotes Creek Basin is undeveloped. The uppermost geologic unit is the Glen Rose Limestone. Data from six storms during April 1997–October 1998 were used for calibration of the parameters related to runoff (table 6).

Measured and simulated streamflow during the storm of Oct. 15–31, 1998, are shown in figure 8. The overall error in simulated runoff (computed as the sum of simulated runoff, minus the sum of measured runoff, divided by the sum of measured runoff, quantity times 100) for the six storms at Helotes Creek was 4.4 percent. The mean absolute error in simulated runoff for individual storms (average of the absolute values of all storm runoff percent differences) was 60 percent. This large error is heavily influenced by the 220-percent difference from the April 1997 storm. Generally, large runoffs are simulated more accurately than smaller runoffs. Therefore, mean absolute error was recomputed to weight the

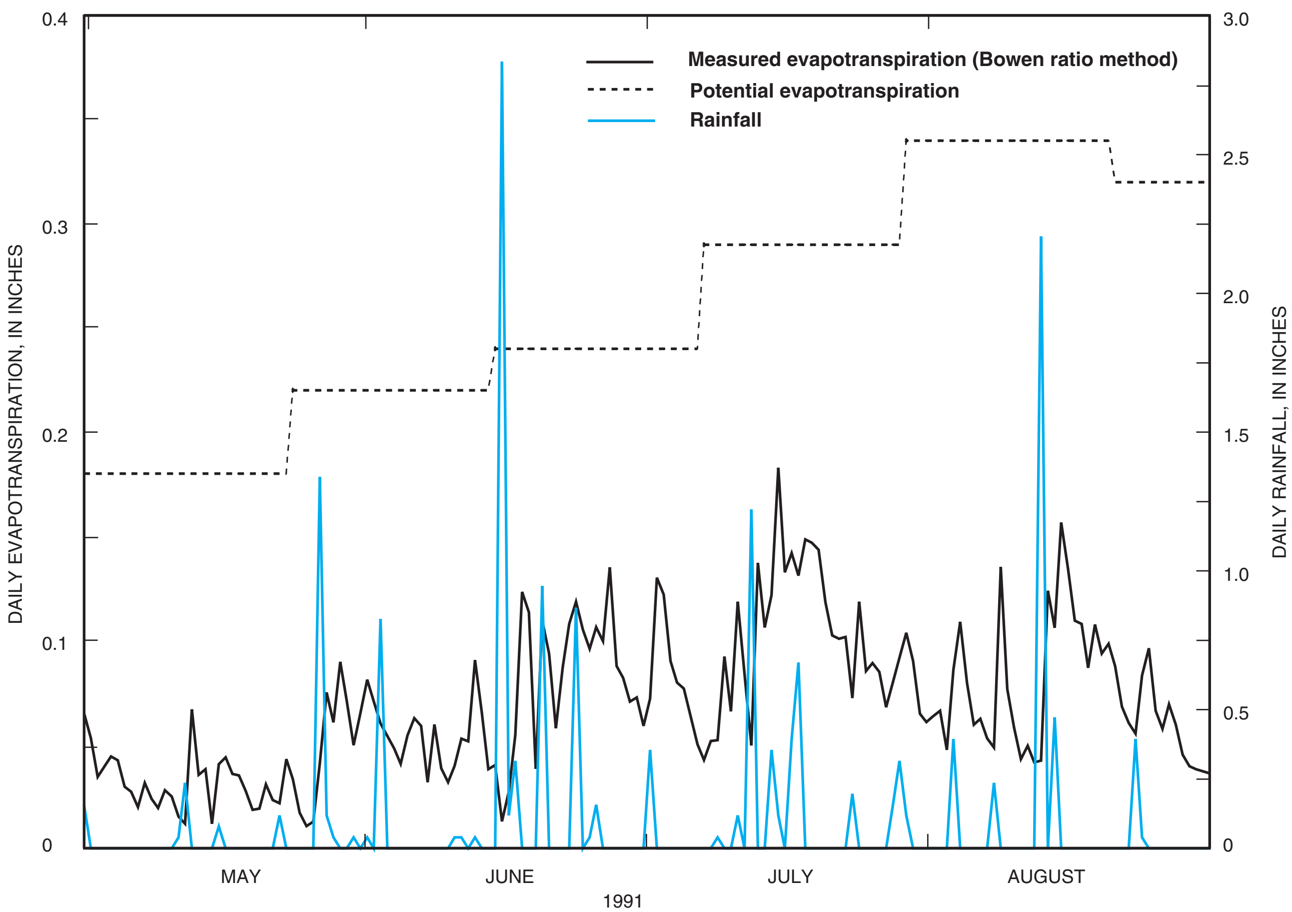

Figure 7. Hydrograph showing measured evapotranspiration, potential evapotranspiration, and rainfall, Seco Creek Basin, May 1–August 12, 1991.

Table 5. Data-collection stations providing data for model calibration

[USGS, U.S. Geological Survey; FM, Farm Road; NWS, National Weather Service; SH, State Highway; NRCS, Natural Resources Conservation Service]

Reference no. (fig. 5)	Name and USGS no. (if applicable)	Type of data	Period of operation	Comment
1	USGS station 08181400 Helotes Creek at Helotes	Rainfall/ streamflow	1997–2000	15-square-mile basin; data used for calibration of process-related parameters for catchment area
2	USGS station 08178645 East Elm Creek at San Antonio	Rainfall/ streamflow	1976	2.33-square-mile basin; data used for calibration of process-related parameters for outcrop–undeveloped
3	USGS station 08178640 West Elm Creek at San Antonio	Rainfall/ streamflow	1976–78	2.45-square-mile basin; data used for testing of process-related parameters for outcrop–undeveloped

Table 5. Data-collection stations providing data for model calibration—Continued

Reference no. (fig. 5)	Name and USGS no. (if applicable)	Type of data	Period of operation	Comment
4	USGS station 08178600 Panther Springs Creek at FM 2696 near San Antonio	Rainfall/ streamflow	1973	9.54-square-mile basin; data used for testing process-related parameters for outcrop and catchment area
5	NWS station at Canyon Dam	Pan evaporation	1973–78	Data used for calibration simulations of West Elm Creek, East Elm Creek, and Panther Springs Creek Basins
6	USGS station 08178595 Stone Mountain drainage channel at Granite Path, San Antonio	Rainfall/water quality	1997–2000	Rainfall data used for 1997–2000 simulations; water-quality data used to characterize residential runoff
7	USGS station 08181420 Huebner Creek at De Zavala Rd., San Antonio	Water quality	1996	Data used to characterize commercial runoff
8	USGS station 08181425 Cedar Elm outfall at Huebner Creek tributary, San Antonio	Water quality	1996–97	Data used to characterize commercial runoff
9	USGS station 08181440 Leon Creek outfall at Ingram Rd. near SH 151, San Antonio	Water quality	1992–99	Data for 1997–99 used to characterize transportation runoff
10	USGS station 08177600 Olmos Creek tributary at FM 1535 at Shavano Park	Water quality	1997–98	Data used to characterize residential runoff
11	USGS station 08180940 Government Canyon Creek near Helotes	Water quality	1997–98	Data used to characterize undeveloped land runoff
12	USGS station 08185000 Cibolo Creek at Selma	Rainfall	1997–2000	Data used for 1997–2000 simulations
13	USGS station 08202790 Parkers Creek Reservoir inflow near D'Hanis	Streamflow	1992–97	Measured inflow used to estimate water balance of Parkers Creek Reservoir and, in turn, to estimate infiltration at flood-control reservoirs in Bexar County
14	USGS station 08202800 Parkers Creek Reservoir near D'Hanis	Reservoir elevation and storage	1992–97	Measured infiltration rates used to estimate infiltration at flood-control reservoirs in Bexar County
15	USGS station 08178592 Salado Creek at Loop 1604 near San Antonio	Streamflow	1998	Gain-loss measurement data used to estimate streamflow losses in outcrop
16	USGS station 08178593 Salado Creek at Old Blanco Rd. near San Antonio	Streamflow	1998	Gain-loss measurement data used to estimate streamflow losses in outcrop
17	NWS station at Sea World, San Antonio	Pan evaporation	1997–2000	Data used for 1997–2000 simulations
18	NWS station near Boerne	Rainfall	1997–2000	Data used for 1997–2000 simulations
19	NWS station near Bulverde	Rainfall	1997–2000	Data used for 1997–2000 simulations
20	NRCS station in Seco Creek Basin, Medina County	Evapotrans-piration	1992–96	Data used for calibration simulations, Helotes Creek Basin

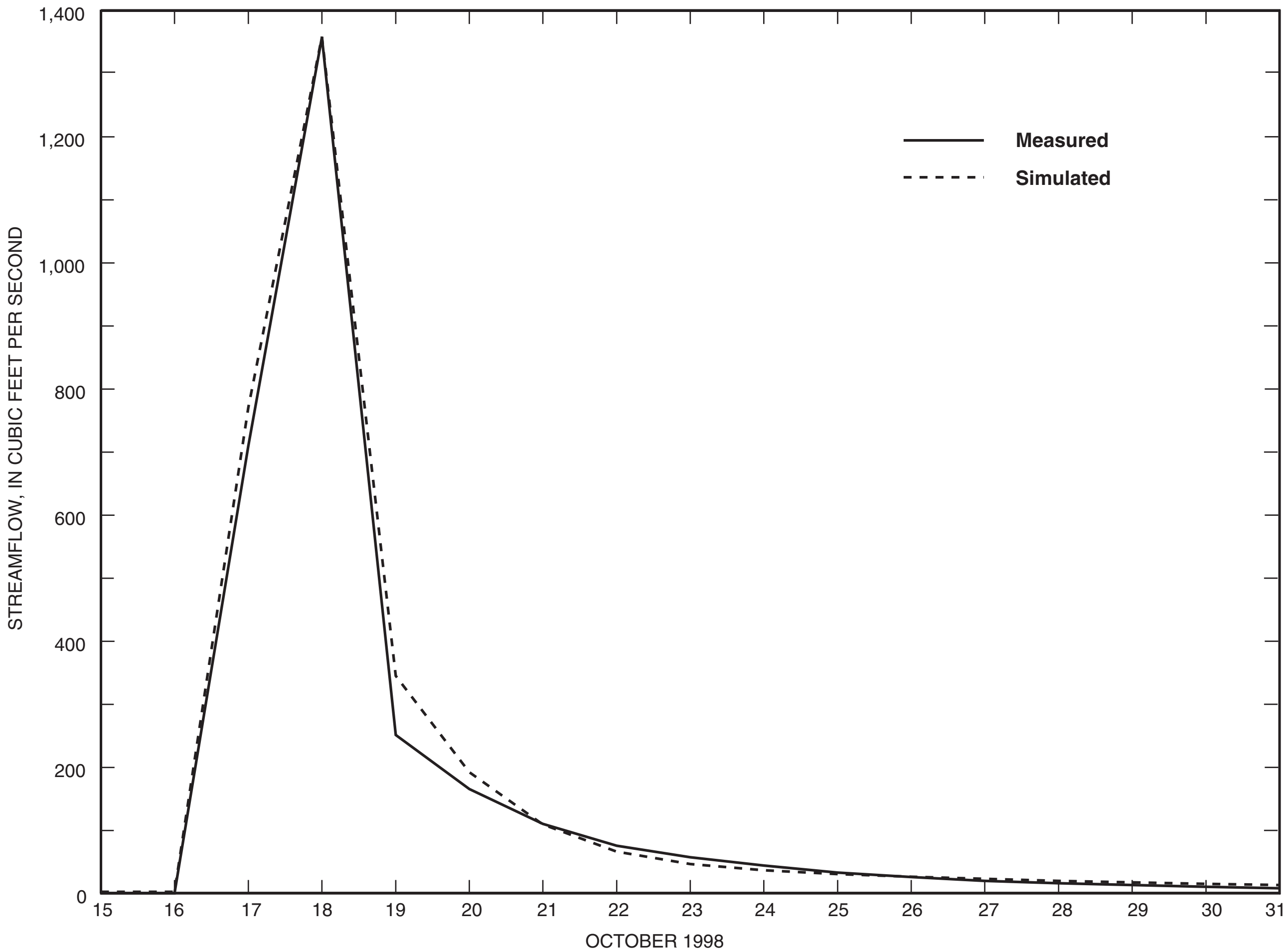

Figure 8. Hydrograph showing measured and simulated streamflow, Helotes Creek at Helotes, October 15–31, 1998.

Table 6. Summary of model calibration results for Helotes Creek Basin, 1997–98

Date	Rainfall amount (inches)	Measured runoff (inches)	Simulated runoff (inches)	Percent difference[1]
04/01–12/1997	4.16	0.29	0.93	220
05/21–31/1997	.80	.52	.08	–85
06/21–30/1997	8.38	5.79	5.65	–2.4
02/25–03/03/1998	1.15	.42	.62	48
03/16–17/1998	1.54	1.02	1.01	–1.0
10/15–31/1998	10.11	7.16	7.58	5.9
Total	26.14	15.20	15.87	4.4

[1] Percent difference between measured and simulated runoff computed as simulated minus measured, divided by measured, quantity times 100.

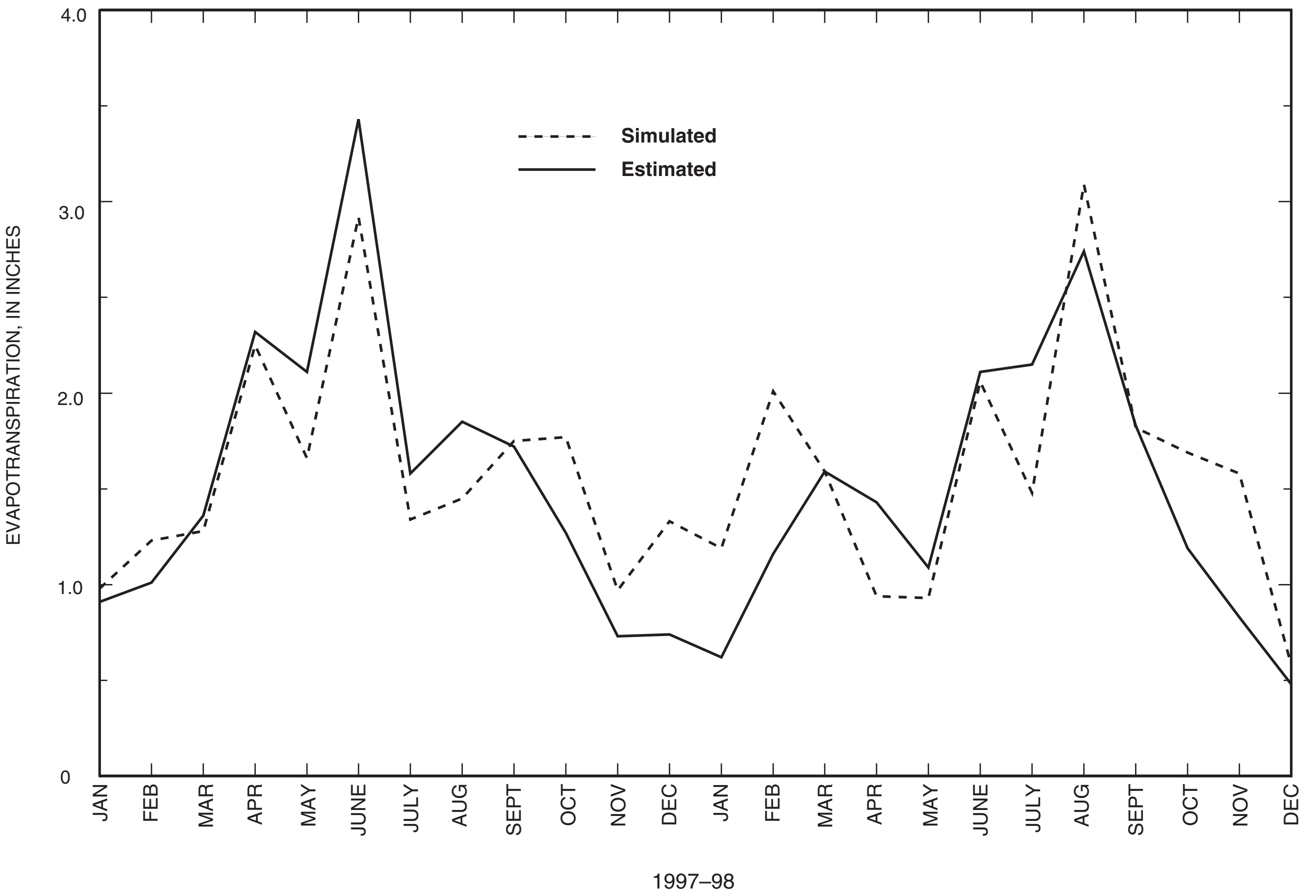

Figure 9. Hydrograph showing simulated and estimated evapotranspiration, Helotes Creek Basin, 1997–98.

error of each storm by measured (gaged) runoff. The mean absolute runoff-weighted error of the six Helotes Creek storms was 12 percent.

Along with parameters related to runoff, parameters related to ET also were calibrated. Rainfall from the Helotes Creek at Helotes gage and PET (from the Sea World NWS station) were used to estimate actual ET on undeveloped Glen Rose Limestone using the empirical relation between measured ET, PET, and rainfall from the Seco Creek Basin previously described. The model parameters (primarily UZSN, LZSN, and LZETP) were adjusted so that ET simulated by the model approximated ET estimated from the empirical relation. Monthly simulated ET compared with ET estimated from the empirical relation is shown in figure 9.

The following table shows rainfall for the Helotes Creek Basin and simulated ET for the undeveloped Glen Rose Limestone and ET expressed as a percentage of annual rainfall. During 1997, 1998, and 2000, annual rainfall was greater than normal, and much of the rainfall occurred in a few large storms that generated considerable runoff that exited the study area and was not subject to ET. The result was low ET as a percentage of rainfall in 1997, 1998, and 2000. In contrast, 1999 was dryer than normal with no major storms; ET as a percentage of rainfall was high.

Helotes Creek annual rainfall and HSPF simulated evapotranspiration (ET), 1997–2000

Year	Rainfall (inches)	Glen Rose Limestone ET (inches)	Glen Rose Limestone ET (percent of annual rainfall)
1997	36.75	18.93	51.5
1998	41.38	18.96	45.8
1999	15.72	15.32	97.4
2000	36.30	18.22	50.2

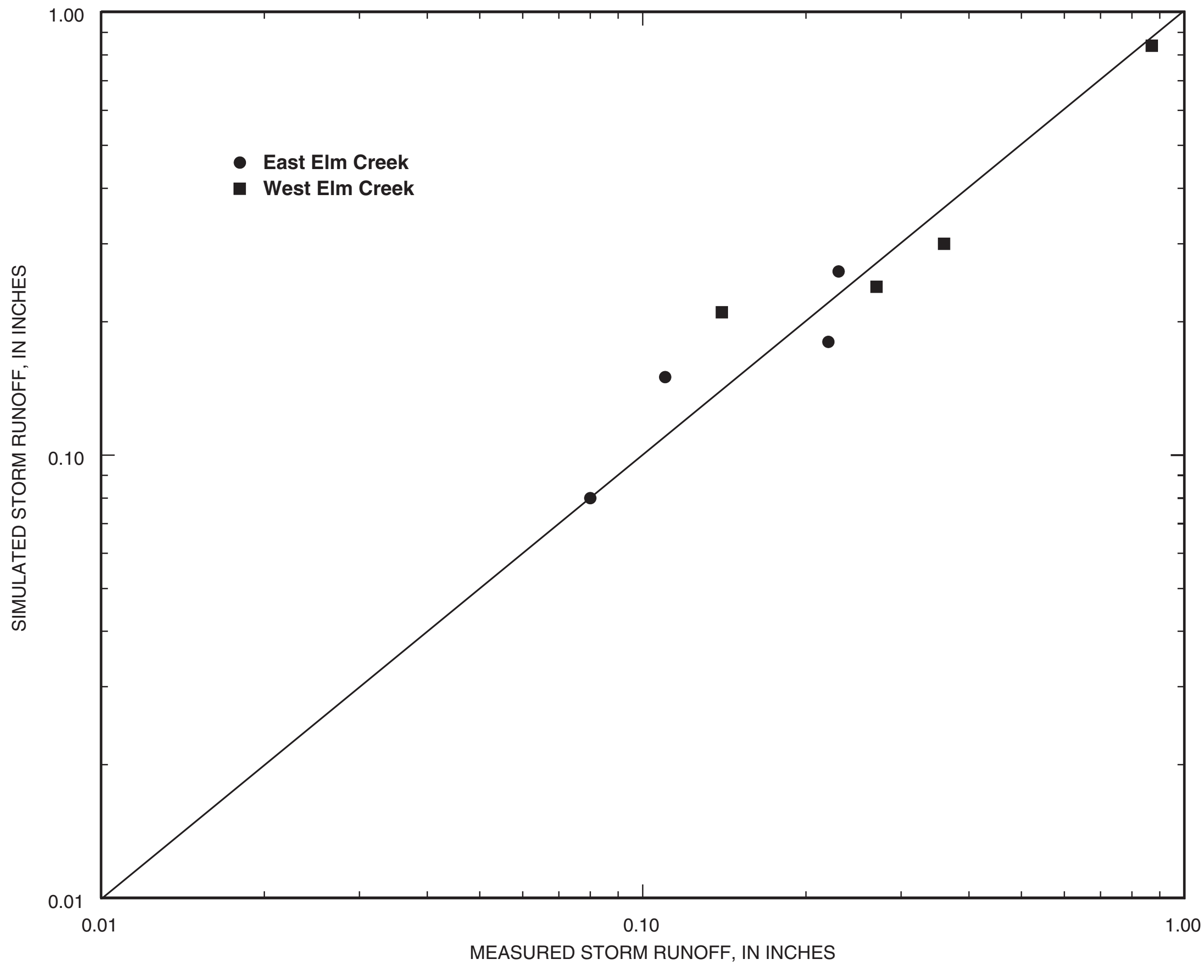

Figure 10. Measured and simulated storm runoff volumes, East Elm Creek and West Elm Creek Basins, 1976–78.

East Elm Creek and West Elm Creek Basins

Calibration and testing of East Elm Creek and West Elm Creek Basins were done to obtain process-related parameters for the undeveloped Edwards aquifer outcrop. Rainfall and runoff data during May 1976–September 1978 (when the basins were undeveloped) were used for the model calibration and testing. East Elm Creek Basin was calibrated using data from four storms during 1976. To test the calibration and also to test the transferability of model parameters to similar ungaged basins, the calibration model parameters from the East Elm Creek Basin were applied to the West Elm Creek Basin in simulations of four storms during 1976–78. Simulated runoff volumes were 4.7-percent larger than the gaged volumes for the East Elm Creek storms and 3.1-percent smaller for the West Elm Creek storms (table 7). Simulated and measured runoff volumes for the East and West Elm Creek Basins are shown in figure 10; a hydrograph showing measured and simulated streamflow for the East Elm Creek storm on September 28, 1976, is shown in figure 11.

The overall errors in simulated runoff for the four storms at East Elm Creek and the four storms at West Elm Creek were 4.7 and -3.1 percent, respectively. The mean absolute errors in simulated runoff for individual storms were 17 and 20 percent, respectively; and the mean absolute runoff-weighted errors were 17 and 12 percent, respectively.

Data to calibrate ET-related parameters in the Edwards aquifer outcrop were not available. Although the infiltration capacity and permeability of the Edwards aquifer outcrop and Glen Rose Limestone likely are different, other factors affecting ET, such as soil and vegetation, are similar. The ET-related parameters developed for the catchment area (Glen Rose Limestone) in the Helotes Creek Basin calibration

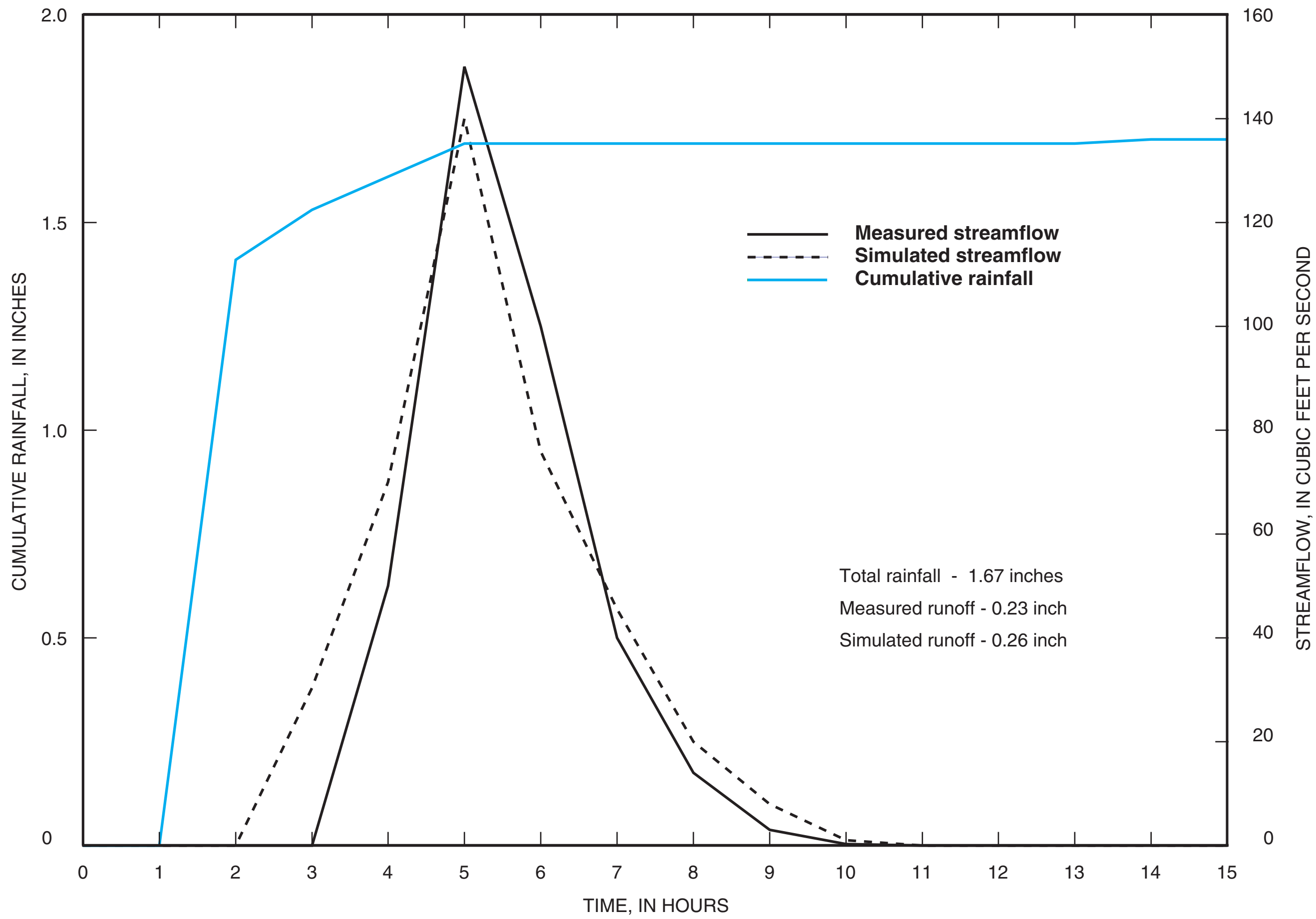

Figure 11. Hydrograph showing measured and simulated streamflow, East Elm Creek Basin, September 28, 1976.

Table 7. Summary of model calibration and testing results for East Elm Creek and West Elm Creek Basins, 1976–78

Date	Rainfall amount (inches)	Measured runoff (inches)	Simulated runoff (inches)	Percent difference[1]
East Elm Creek (calibration)				
05/26/1976	2.72	0.11	0.15	36
07/06/1976	2.08	.22	.18	-18
09/28/1976	1.67	.23	.26	13
10/23/1976	1.82	.08	.08	0
Total	8.29	.64	.67	4.7
West Elm Creek (testing)				
05/07/1976	2.38	.27	.24	-11
09/28/1976	1.70	.14	.21	50
11/01/1977	4.56	.87	.84	-3.5
09/13/1978	2.71	.36	.30	-17
Total	11.35	1.64	1.59	–3.1

[1] Percent difference between measured and simulated runoff computed as simulated minus measured, divided by measured, quantity times 100.

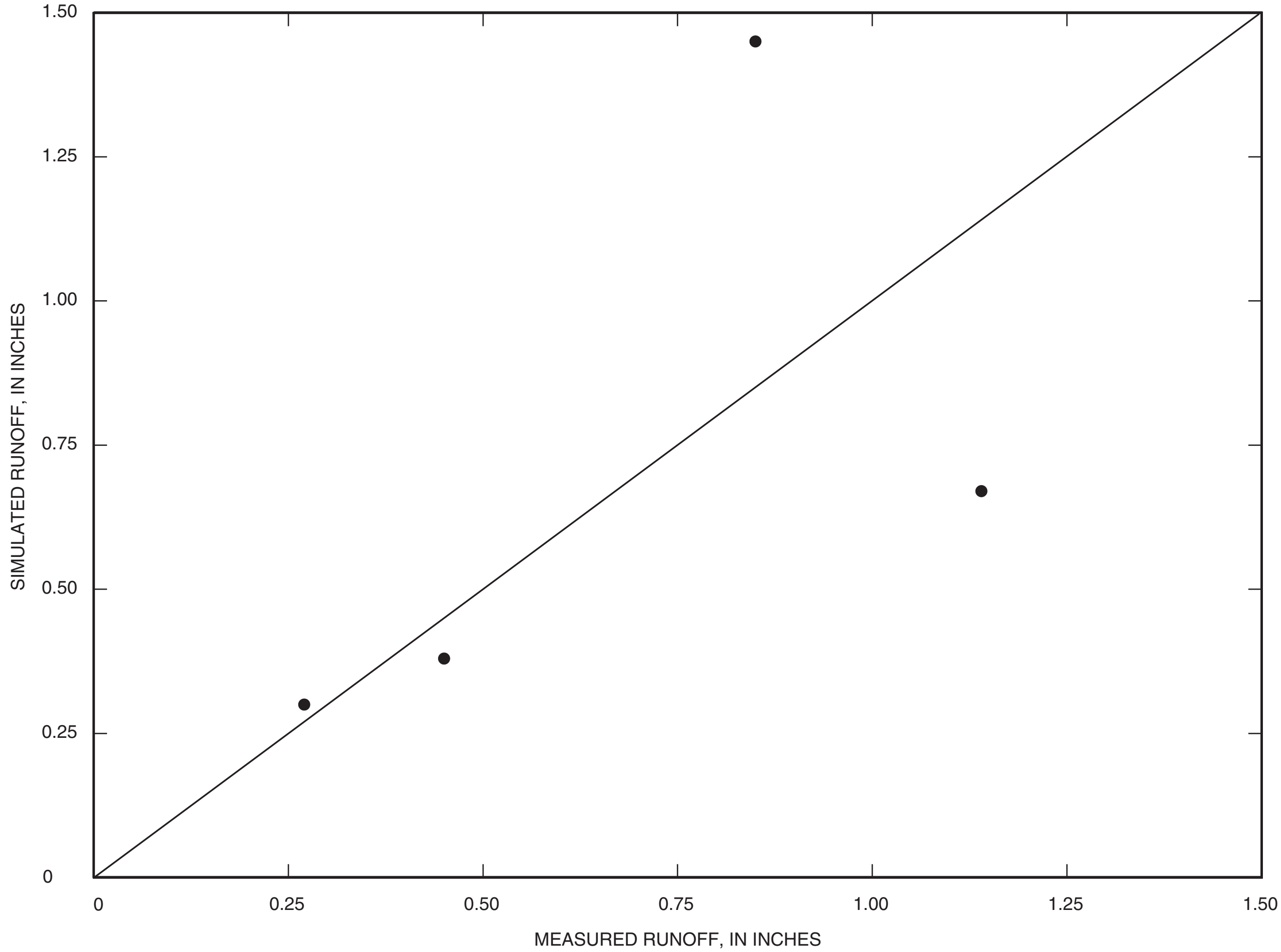

Figure 12. Measured and simulated storm runoff volumes, Panther Springs Creek Basin, 1973.

Table 8. Summary of model testing results for Panther Springs Creek Basin, 1973

Date	Rainfall amount (inches)	Measured runoff (inches)	Simulated runoff (inches)	Percent difference[1]
06/11–12/1973	4.96	0.45	0.38	–16
07/16/1973	3.29	1.14	.67	–41
09/26–27/1973	4.05	.85	1.45	71
10/11/1973	1.94	.27	.30	11
Total	14.24	2.71	2.80	3.3

[1] Percent difference between measured and simulated runoff computed as simulated minus measured, divided by measured, quantity times 100.

were used for calibration, testing, and simulations of basins in the Edwards aquifer outcrop.

Panther Springs Creek Basin

The calibration parameters from Helotes Creek, East Elm Creek, and West Elm Creek Basins were further tested by applying them in simulations of the Panther Springs Creek Basin. The gaged area of the basin in the 1970s (about 6,100 acres) was about equally divided between catchment area and Edwards aquifer outcrop. The gaged area was largely undeveloped in 1973 when rainfall and runoff data were collected during four storms (table 8). Simulated runoff during these storms is compared to measured runoff in figure 12.

Table 9. Errors, mean absolute errors, and mean absolute runoff-weighted errors for storm runoff volumes used in model calibrations

[In percent]

Watershed	Number of storm events	Error	Mean absolute error	Mean absolute runoff-weighted error
Helotes Creek	6	4.4	60	12
East Elm Creek	4	4.7	17	17
West Elm Creek	4	–3.1	20	12
Panther Springs Creek	4	3.3	35	43

The simulations of the four storms for the Panther Springs Creek Basin yielded an overall error in runoff volumes of 3.3 percent. The mean absolute error for the individual storms was 35 percent, and the mean absolute runoff-weighted error was 43 percent. Unlike the simulations for the other three basins, weighting the errors by runoff volume did not result in a smaller mean error.

The simulation errors for all four basins are summarized in table 9. As a result of model calibration and testing with data for the four basins, a set of process-related model parameters for simulation of all of the basins in the study area was obtained; those parameters are summarized in table 10.

Error Analysis

The types of error from the model calibration and testing can be classified as measurement errors or systematic errors (Raines, 1996). Measurement errors are introduced as a result of missing data or of inaccurate data used in calibration or testing. For example, measured or gaged streamflow is subject to potential error in rating tables of stage and discharge; insufficient data also contribute to potential error. For example, relatively few gaged storms (from only four of the 10 basins) were available for calibration, and the results (calibration parameters) were transferred to ungaged basins. Possible seasonal hydrologic factors could not be investigated because of the small number of storms. ET is a substantial component of the hydrologic cycle, yet ET data were not available for the Edwards aquifer outcrop. Also, streamflow-loss data from one stream (Salado Creek) was used to characterize losses for most of the major streams in the study area. Finally, the spatial variability of rainfall in a basin might not be adequately represented by the available network of rain gages.

Systematic errors are associated with limited ability of the simulation model to represent the hydrologic processes of the basins in the study area. Limits exist on

Table 10. Selected process-related calibration parameters used for basin simulations

[Parameter definitions in table 3; --, not applicable]

Parameter	Value	Unit
AGWRC–outcrop	0.50	per day
AGWRC–catchment area	.98	per day
AGWETP	0	--
BASETP	0	--
CEPSC	.1	inches
DEEPFR–outcrop	.95	--
DEEPFR–catchment area	.05	--
INFEXP	2.0	--
INFILD	2.0	--
INFILT–outcrop	.40	inches per hour
INFILT–catchment area	.15	inches per hour
INTFW–outcrop	.2	--
INTFW–catchment area	2.0	--
IRC–outcrop	.1	per day
IRC–catchment area	.4	per day
LZETP	.1	--
LZSN–outcrop	4.0	inches
LZSN–catchment area	5.0	inches
NSUR	.15	--
UZSN–outcrop	.20	inches
UZSN–catchment area	.25	inches

[1] The users manual for Hydrological Simulation Program—FORTRAN (Bicknell and others, 1997) provides a more complete description of each parameter.

Table 11. Sensitivity of selected process-related parameters, Panther Springs Creek Basin

[Parameter definitions in table 3]

Parameter	Initial value	Adjusted value	Change in parameter (percent)	Change in surface runoff (percent)	Change in Edwards aquifer recharge (percent)	Change in stream-flow exiting basin (percent)
CEPSC	0.10	0.15	50	–0.40	–4.9	–1.7
DEEPFR–outcrop	.95	.85	10.5	0	–1.6	5.9
DEEPFR–catchment area	.05	.10	100	0	–4.4	8.0
INFILT–outcrop	.40	.30	–25	1.4	–4.2	8.0
INFILT–catchment area	.10	.15	50	–.60	–2.6	–2.4
INTFW–catchment area	1.0	.8	20	.90	–.30	1.0
IRC–catchment area	.50	.40	20	0	–.10	.30
LZETP	.10	.15	50	–1.4	–9.1	–6.2
LZSN–outcrop	2.5	3.0	20	–.30	–.40	–1.8
UZSN–outcrop	.50	.60	20	–.60	–.40	–3.5

how well the model parameters and equations describe the physical properties of runoff. Also, the configuration of the model segments (PERLNDs, IMPLNDs, and RCHRESs) and the selection of simulation time step (in this case, hourly) can only approximate the actual physical configuration and hydrologic response of the basins.

Despite incomplete data, the HSPF model provides reasonable simulations of runoff volumes compared with observed data. For each of the calibration basins, total simulated runoff was within 5 percent of measured runoff. For individual storms, mean absolute runoff-weighted errors were within 20 percent for Helotes Creek, East Elm Creek, and West Elm Creek Basins.

Figures 8 and 11 show how the model simulations represent the peak flow and runoff response of the basins. There is a characteristic difference in runoff response between basins in the catchment area and those in the Edwards aquifer outcrop. Runoff for Helotes Creek (catchment area) lasted weeks, whereas runoff at East Elm Creek (outcrop) ceased within hours. Although the Panther Springs Creek storms exhibited the highest mean absolute error in runoff volumes, the HSPF model was able to account for differences in rainfall intensity and antecedent conditions in runoff simulation. For example, the June 1973 rainfall (4.96 inches) occurred after a relatively dry month (0.16 inch in May). The June 1973 measured runoff of 0.45 inch is less than the runoff that occurred during the July and September storms (table 8), which featured less, but more intense, rainfall.

Sensitivity Analysis

Panther Springs Creek Basin parameters were used in a sensitivity analysis of selected HSPF model parameters to determine the effects of changes in the values of selected parameters on simulated runoff, recharge, and streamflow exiting the basin. (Streamflow exiting the basin is runoff minus streamflow losses and water lost to infiltration behind recharge dams.) Each parameter was changed by a hydrologically reasonable amount while keeping other parameters unchanged, and simulations were run. The resulting changes in surface runoff (surface plus interflow runoff), recharge, and streamflow exiting the basin are listed in table 11.

The parameters to which simulated model outputs were most sensitive were lower-zone ET (LZETP) and index to soil infiltration capacity (INFILT). A 50-percent increase in LZETP resulted in a 9.1-percent decrease in recharge, a 1.4-percent decrease in surface runoff, and a 6.2-percent decrease in streamflow exiting the basin. Also, recharge was somewhat sensitive to interception storage capacity (CEPSC). A 50-percent increase in CEPSC resulted in a 4.9-percent decrease in recharge.

In addition to the process parameters, the percentage of impervious area in residential and commercial land use categories is subject to some uncertainty. The effect of a percentage change in the effective impervious cover for residential land use was simulated.

The overall, effective impervious cover for residential land use in the Panther Springs Creek Basin in 1998 was estimated to be 29 percent. A model simulation was done with a residential impervious cover of 32 percent (10-percent increase). The increase in overall basin impervious cover was from 7.2 to 7.6 percent. The resulting percentage changes in runoff and recharge are listed in the following table:

Results of sensitivity analysis of change in percentage of residential land use effective impervious cover

[In percent]

Scenario	Change in residential surface runoff	Change in Edwards aquifer recharge	Change in volume of streamflow exiting basin
10-percent increase in residential effective impervious cover	5.6	0.04	1.1

Increasing the residential effective impervious cover from 29 percent to 32 percent resulted in a negligible increase in recharge of 0.04 percent. Although recharge from direct infiltration decreased because of pervious area loss, recharge occurring from streamflow losses increased, and the two changes effectively canceled one another.

Runoff From and Recharge to the Major Basins

The process-related model parameters calibrated and tested in the Helotes Creek, East Elm Creek, West Elm Creek, and Panther Springs Creek Basins were applied to the 10 major basins in the study area to simulate runoff from (streamflow exiting) the basins and recharge to the basins during 1997–2000 (table 12). During 1997, 39.23 inches of rain (area-weighted average of rain-gage data used for the simulations) fell on the study area—about 35 percent above normal. In June 1997, a major rainfall occurred in the western part of the study area where as much as 10 inches of rain fell during a 2-day period. Rainfall in 1998 was 44.06 in, about 50 percent above normal. Some areas in the northeastern part of the study area received more than 20 inches of rainfall in October 1998. In contrast, rainfall in 1999 was 15.85 inches, about 45 percent below normal; rainfall in 2000 was 34.66 inches, about 20 percent above normal.

In 1997, simulated streamflow exiting the 10 major basins (and thus runoff from the study area) was 5.62 inches. Simulated recharge to the 10 major basins (essentially in the Edwards aquifer outcrop in the study area) was 7.85 inches (20 percent of rainfall). In 1998, simulated streamflow exiting was 11.05 inches, and simulated recharge was 10.99 inches (25 percent of rainfall). In 1999, simulated streamflow exiting was 0.66 inch, and simulated recharge was 3.03 inches (19 percent of rainfall). In 2000, simulated streamflow exiting was 5.29 inches; simulated recharge was 7.19 inches (21 percent of rainfall).

During 1997–2000, simulated recharge in the study area (essentially in the Edwards aquifer outcrop) was about 22 percent of rainfall, simulated runoff from the study area was about 17 percent of rainfall, and simulated ET in the study area was about 51 percent of rainfall. The remaining 10 percent of rainfall during 1997–2000 was accounted for by simulated changes in soil and unsaturated-zone storages and by a small amount of simulated recharge in the catchment area. Figure 13 shows simulated monthly runoff from and recharge to the study area during 1997–2000. About 37 percent of the recharge (177,000 acre-ft) and about 66 percent of the runoff (248,000 acre-ft) occurred during four months—June 1997, October 1998, and October and November 2000. Thus the proportions of rainfall accounted for by recharge, runoff, and ET during 1997–2000 might not reflect the proportions characteristic of long-term average hydrologic conditions

Simulated recharge and runoff during 1997–2000 varied widely among the 10 basins. The Leon Creek Basin (mostly Glen Rose Limestone) had 20.60 inches of recharge; the Elm Creek Basin (mostly Edwards aquifer outcrop; includes four flood-control structures) had 49.30 inches of recharge. For the study area as a whole, recharge during 1997–2000 was 29.06 inches The Helotes Creek Basin had the least amount of runoff (6.60 inches compared with 22.62 inches for the entire study area) mostly because of relatively large streamflow losses in a stream reach that passes through a quarry near the exit of the basin. Cibolo Creek had the largest amount of runoff (36.18 inches); it also received the largest amount of rainfall (150.86 inches compared with the area-weighted average of 133.80 inches for the entire study area).

Primary sources of recharge to the Edwards aquifer are direct infiltration of rainfall in interstream areas, streamflow losses in the outcrop, and infiltration of impounded runoff behind flood-control structures.

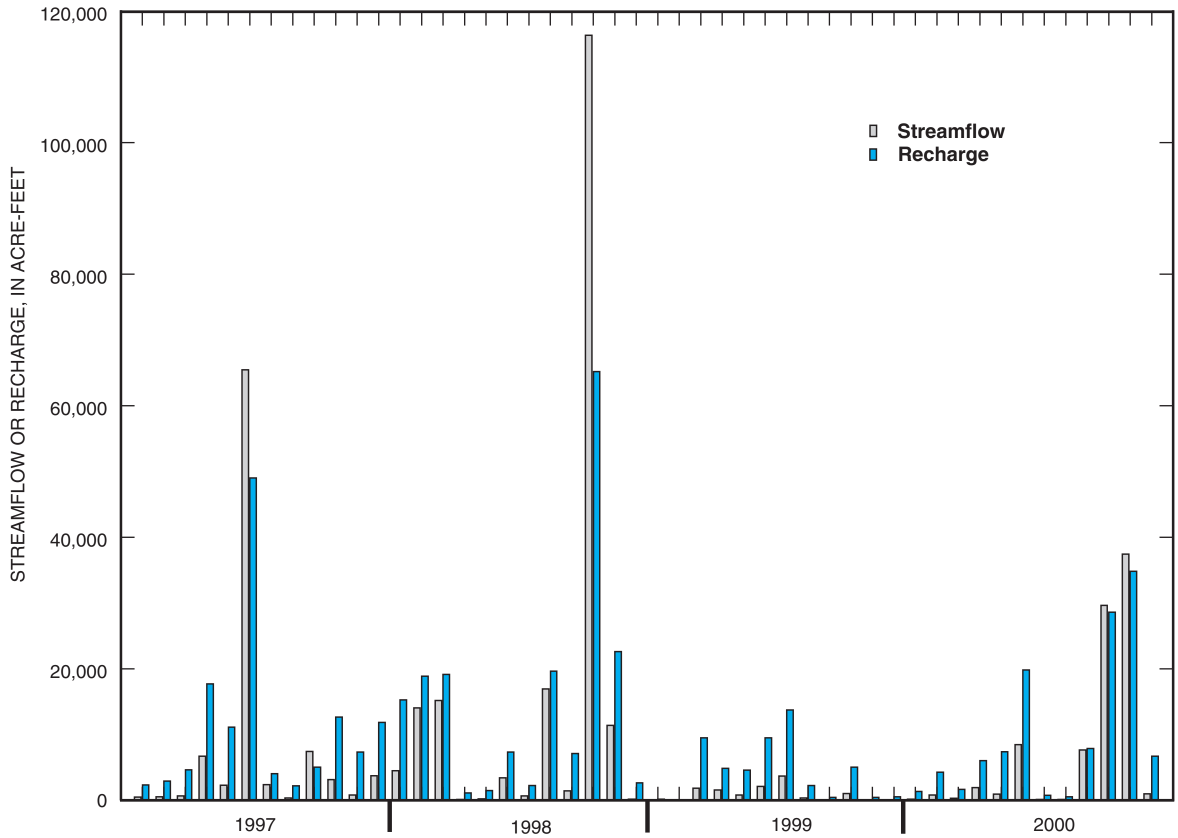

Figure 13. Simulated monthly runoff from (streamflow exiting) and recharge to the study area, 1997–2000.

Simulated recharges, by primary sources, are listed in table 13. During 1997–2000, direct infiltration of rainfall accounted for about 56 percent of the total Edwards aquifer recharge in Bexar County. Streamflow losses contributed about 37 percent of the recharge; flood impoundment contributed 7 percent.

ESTIMATION OF CONSTITUENT LOADS IN RUNOFF

In this report a constituent load is the mass of a constituent moved past a point by water in a specified time. Loads for suspended solids, dissolved solids, dissolved nitrite plus nitrate nitrogen, and total lead in runoff were computed using the equation

$$L = R \times EMC \times Cf, \qquad (1)$$

where

L = constituent load, in pounds;

R = runoff volume, in acre-feet;

EMC = median event-mean concentration during runoff, in milligrams per liter or micrograms per liter; and

Cf = conversion factor, 2.718 for concentrations in milligrams per liter or 0.00272 for concentrations in micrograms per liter.

Constituent yield, a measure of the load-producing characteristics of a basin, is computed by the equation

$$Y = L/DA, \qquad (2)$$

where

Y = constituent yield, in pounds per acre;

L = constituent load, in pounds; and

DA = contributing drainage area of the basin, in acres.

Table 12. Annual rainfall and estimates of runoff from (streamflow exiting) and recharge to the 10 major basins in the study area, 1997–2000

	San Geronimo Creek	Culebra Creek	Helotes Creek	Leon Creek	Olmos/ Huebner Creeks	Salado Creek	Panther Springs Creek	Mud Creek	Elm Creek	Cibolo Creek	Total
1997											
Basin area, acres	15,690	11,121	17,540	41,759	5,426	19,637	14,245	14,546	19,244	39,438	198,646
Annual rainfall, inches	36.75	36.75	36.75	40.05	34.73	40.00	33.08	33.08	36.31	47.29	39.23
Exiting streamflow, acre-feet	9,410	2,940	2,560	29,600	1,690	6,750	2,120	2,450	2,350	33,100	93,000
Exiting streamflow, inches	7.20	3.17	1.75	8.51	3.74	4.12	1.79	2.02	1.47	10.07	5.62
Edwards recharge, acre-feet	3,110	11,600	9,960	18,800	5,390	7,720	12,200	13,400	21,200	26,400	130,000
Edwards recharge, inches	2.38	12.52	6.81	5.40	11.93	4.72	10.27	11.08	13.24	8.04	7.85
1998											
Basin area, acres	15,690	11,121	17,540	41,759	5,426	19,637	14,245	14,546	19,244	39,438	198,646
Annual rainfall, inches	40.33	40.33	40.33	42.46	41.28	45.06	41.19	41.19	45.94	51.01	44.06
Exiting streamflow, acre-feet	16,800	5,600	4,840	50,300	4,440	15,300	7,540	7,410	12,200	59,000	183,000
Exiting streamflow, inches	12.82	6.04	3.31	14.45	9.82	9.35	6.35	6.11	7.59	17.96	11.05
Edwards recharge, acre-feet	3,810	14,900	13,000	24,500	7,060	10,000	21,200	22,500	32,700	32,000	182,000
Edwards recharge, inches	2.91	16.08	8.89	7.04	15.60	6.12	17.86	18.53	20.38	9.73	10.99
1999											
Basin area, acres	15,690	11,121	17,540	41,759	5,426	19,637	14,245	14,546	19,244	39,438	198,646
Annual rainfall, inches	15.72	15.72	15.72	16.24	15.80	15.87	15.87	15.87	14.74	16.10	15.85
Exiting streamflow, acre-feet	935	26	20	4,690	440	150	510	730	1,260	2,090	10,900
Exiting streamflow, inches	.71	.03	.01	1.33	.97	.09	.43	.60	.78	.64	.66
Edwards recharge, acre-feet	1,210	4,160	4,040	7,900	2,300	2,500	5,440	6,120	9,170	7,300	50,100
Edwards recharge, inches	.93	4.49	2.76	2.27	5.08	1.53	4.58	5.05	5.72	2.22	3.03
2000											
Basin area, acres	15,690	11,121	17,540	41,759	5,426	19,637	14,245	14,546	19,244	39,438	198,646
Annual rainfall, inches	36.30	36.30	36.30	36.30	37.03	37.03	29.00	29.00	29.03	36.46	34.66
Exiting streamflow, acre-feet	10,900	2,700	2,240	33,800	2,720	8,240	1,190	1,510	1,320	23,000	87,600
Exiting streamflow, inches	8.33	2.91	1.53	9.71	6.01	5.03	1.00	1.24	.83	6.99	5.29
Edwards recharge, acre-feet	3,310	12,500	11,200	20,500	6,100	7,630	11,200	12,200	16,000	18,300	119,000
Edwards recharge, inches	2.53	13.49	7.66	5.89	13.50	4.66	9.44	10.07	9.96	5.57	7.19

Table 13. Simulated recharge to Edwards aquifer in the study area by source, 1997–2000

[In acre-feet]

Source of recharge	1997	1998	1999	2000	Total, 1997–2000
Direct infiltration	75,400	94,200	31,400	68,500	270,000
Streamflow losses	48,200	67,300	15,500	45,300	176,000
Flood-control impoundment	6,140	20,000	3,240	5,040	34,400
Annual total	130,000	182,000	50,100	119,000	[1]481,000

[1] Annual total does not equal 1997–2000 total because of rounding.

Table 14. Median event-mean concentrations[1], by land use category, used to compute constituent loads

Constituent	Undeveloped	Residential	Commercial	Transportation corridor
Suspended solids (milligrams per liter)	48	53	114	76
Dissolved solids (milligrams per liter)	119	54	52	42
Nitrite + nitrate nitrogen, dissolved (milligrams per liter)	.56	.28	.32	.31
Total lead (micrograms per liter)	2.2	4.1	8.9	9.5

[1] From Ockerman and others (1999) and B.L. Petri (U.S. Geological Survey, written commun., 2000).

Event-mean concentration (EMC) (Charbeneau and Barrett, 1998) represents a discharge-weighted average constituent concentration during storm runoff. Two sources of EMCs for Bexar County were available for this study: (1) Data collected during 1996–98 for a water-quality study of five basins with specific land uses in the Edwards aquifer outcrop, Bexar County (Ockerman and others, 1999); and (2) data obtained from a study of the San Antonio National Pollutant Discharge Elimination System (B.L. Petri, U.S. Geological Survey, written commun., 2000). Median EMCs from the two sources (table 14) were used to compute loads.

The computed constituent loads in surface-water runoff are estimates of annual total loads originating from pervious and impervious surfaces and transported to streams in the study area. The transport and fate of these constituent loads are not considered. For example, some of the load will be retained behind flood-control structures; some of the load infiltrates the aquifer with streamflow lost to the aquifer; and some of the load is transported from the study area in streamflow exiting the study area. Constituents transported to streams by interflow or base flow are not included in the load estimates. Also, basin protection ordinances in Bexar County require detention, sedimentation, and filtration structures for commercial land use in the Edwards aquifer outcrop designed to capture and isolate the first 0.5 inch of runoff during a storm to minimize pollutants entering the aquifer (San Antonio Water System, 2000). The estimates of constituent loads in runoff do not consider the effects of these pollution-control structures.

Estimates of annual loads and yields by land use for suspended solids, dissolved solids, dissolved nitrite plus nitrate nitrogen, and total lead during 1997–2000 for each of the 10 major basins are listed in tables 15–18. Annual loads for the four constituents were consistently largest from undeveloped land and smallest from commercial land or transportation corridors. Annual loads varied with rainfall (table 12), with the maximum loads for the study area produced in 1998 (wettest year) and the minimum loads produced in 1999 (driest year). For example, in 1998 when rainfall was about 50 percent above normal, nitrite plus nitrate nitrogen load from undeveloped areas was 134 tons; in 1999, when rainfall was about 45 percent below normal, nitrite plus nitrate nitrogen load from undeveloped areas was 7.5 tons (table 17).

Because they are computed from loads, annual yields for the four constituents also varied with rainfall.

Table 15. Estimates of annual loads, by land use, and yields for suspended solids in surface-water runoff for the 10 major basins in the study area, 1997–2000

	San Geronimo Creek	Culebra Creek	Helotes Creek	Leon Creek	Olmos/ Huebner Creeks	Salado Creek	Panther Springs Creek	Mud Creek	Elm Creek	Cibolo Creek	Total
1997											
Load (undeveloped), tons	540	280	500	1,000	38	490	180	140	180	1,600	5,000
Load (residential), tons	6.2	10	170	380	72	69	95	130	71	260	1,300
Load (commercial), tons	1.0	0	79	530	81	29	74	81	78	210	1,200
Load (transportation corridor), tons	25	11	35	340	73	41	98	127	130	120	1,000
Yield, pounds per acre	73	54	90	110	97	64	63	66	48	110	85
1998											
Load (undeveloped), tons	1,000	540	950	2,000	140	1,300	720	570	980	3,200	11,000
Load (residential), tons	11	16	260	590	130	120	180	280	170	360	2,200
Load (commercial), tons	2	0	100	660	120	41	120	130	130	210	1,500
Load (transportation corridor), tons	36	14	44	430	110	58	150	200	220	130	1,400
Yield, pounds per acre	140	100	150	170	180	160	160	160	160	200	160
1999											
Load (undeveloped), tons	59	11	60	110	4	39	75	53	130	100	640
Load (residential), tons	2	3	45	100	28	18	44	61	33	43	380
Load (commercial), tons	.4	0	29	190	34	10	35	39	32	60	430
Load (transportation corridor), tons	11	4	13	130	31	14	47	60	53	35	400
Yield, pounds per acre	9.1	3	17	25	36	8	28	29	26	12	20
2000											
Load (undeveloped), tons	620	290	580	1,200	79	680	130	92	130	1,200	5,000
Load (residential), tons	11	18	180	410	200	150	79	110	57	180	1,400
Load (commercial), tons	2.5	0	80	530	220	70	63	70	64	140	1,200
Load (transportation corridor), tons	68	24	36	350	200	98	84	110	110	86	1,200
Yield, pounds per acre	89	60	100	120	260	100	50	52	37	81	88

Table 16. Estimates of annual loads, by land use, and yields for dissolved solids in surface-water runoff for the 10 major basins in the study area, 1997–2000

	San Geronimo Creek	Culebra Creek	Helotes Creek	Leon Creek	Olmos/ Huebner Creeks	Salado Creek	Panther Springs Creek	Mud Creek	Elm Creek	Cibolo Creek	Total
1997											
Load (undeveloped), tons	1,300	690	1,200	2,600	94	1,200	450	350	450	4,000	12,000
Load (residential), tons	6.3	11	170	390	73	70	97	130	72	260	1,300
Load (commercial), tons	.5	0	36	240	37	13	34	37	36	96	530
Load (transportation corridor), tons	14	6	19	190	40	23	54	70	72	66	550
Yield, pounds per acre	170	130	170	160	90	130	89	81	65	230	150
1998											
Load (undeveloped), tons	2,500	1,300	2,400	4,900	360	3,300	1,800	1,400	2,400	8,000	28,000
Load (residential), tons	11	16	260	600	130	120	180	290	170	370	2,200
Load (commercial), tons	.7	0	46	300	55	19	55	59	59	96	690
Load (transportation corridor), tons	20	8	24	240	60	32	83	110	120	69	770
Yield, pounds per acre	330	240	310	290	220	350	300	260	290	430	320
1999											
Load (undeveloped), tons	150	27	150	270	10	97	180	130	320	250	1,600
Load (residential), tons	2.0	3.1	46	100	29	18	45	62	58	44	410
Load (commercial), tons	.2	0	13	87	16	4.6	16	18	29	27	210
Load (transportation corridor), tons	6	2	7	72	17	8	26	33	29	19	220
Yield, pounds per acre	20	6	25	26	26	13	38	34	46	17	24
2000											
Load (undeveloped), tons	1,500	720	1,400	3,000	200	1,700	320	230	320	3,000	12,000
Load (residential), tons	11	18	180	420	200	150	80	110	33	180	1,400
Load (commercial), tons	1.1	0	36	240	100	32	29	32	15	64	550
Load (transportation corridor), tons	38	13	20	190	110	54	46	59	29	48	610
Yield, pounds per acre	200	140	190	180	220	200	67	59	41	170	150

Table 17. Estimates of annual loads, by land use, and yields for dissolved nitrite plus nitrate nitrogen in surface-water runoff for the 10 major basins in the study area, 1997–2000

	San Geronimo Creek	Culebra Creek	Helotes Creek	Leon Creek	Olmos/ Huebner Creeks	Salado Creek	Panther Springs Creek	Mud Creek	Elm Creek	Cibolo Creek	Total
1997											
Load (undeveloped), tons	6.3	3.3	5.8	12	0.4	5.7	2.1	1.6	2.1	19	58
Load (residential), tons	.03	.06	.90	2.0	.38	.36	.50	.69	.38	1.4	6.7
Load (commercial), tons	0	0	.22	1.5	.23	.08	.21	.23	.22	.59	3.3
Load (transportation corridor), tons	.10	.04	.14	1.4	.30	.17	.40	.52	.53	.49	4.1
Yield, pounds per acre	.82	.61	.81	.81	.50	.64	.45	.42	.34	1.1	.73
1998											
Load (undeveloped), tons	12	6.3	11	23	1.7	15	8.4	6.7	11	38	134
Load (residential), tons	.06	.08	1.4	3.1	.68	.63	.95	1.5	.90	1.9	11
Load (commercial), tons	0	0	.28	1.9	.34	.12	.34	.36	.36	.59	4.2
Load (transportation corridor), tons	.15	.06	.18	1.8	.44	.24	.61	.82	.90	.51	5.6
Yield, pounds per acre	1.5	1.2	1.5	1.4	1.2	1.7	1.4	1.3	1.4	2.1	1.6
1999											
Load (undeveloped), tons	.69	.13	.70	1.3	.05	.46	.86	.62	1.5	1.2	7.5
Load (residential), tons	.01	.02	.24	.53	.15	.10	.23	.32	.30	.23	2.1
Load (commercial), tons	0	0	.08	.53	.10	.03	.10	.11	.18	.17	1.3
Load (transportation corridor), tons	.04	.02	.05	.53	.13	.06	.19	.24	.22	.14	1.6
Yield, pounds per acre	.09	.03	.12	.14	.15	.06	.19	.18	.23	.09	.13
2000											
Load (undeveloped), tons	7.2	3.4	6.8	14	.92	7.9	1.5	1.1	1.5	14	58
Load (residential), tons	.06	.10	.95	2.2	1.1	.77	.42	.58	.17	.95	7.2
Load (commercial), tons	.01	0	.22	1.5	.62	.20	.18	.20	.09	.39	3.4
Load (transportation corridor), tons	.28	.10	.15	1.4	.82	.40	.34	.44	.22	.35	4.5
Yield, pounds per acre	.97	.64	.92	.91	1.3	.95	.34	.31	.21	.80	.74

Table 18. Estimates of annual loads, by land use, and yields for total lead in surface-water runoff for the 10 major basins in the study area, 1997–2000

	San Geronimo Creek	Culebra Creek	Helotes Creek	Leon Creek	Olmos/ Huebner Creeks	Salado Creek	Panther Springs Creek	Mud Creek	Elm Creek	Cibolo Creek	Total
1997											
Load (undeveloped), tons	50	26	46	94	3.5	45	17	13	17	150	460
Load (residential), tons	.96	1.6	26	59	11	11	15	20	11	40	200
Load (commercial), tons	.16	0	12	83	13	4.5	12	13	12	33	180
Load (transportation corridor), tons	2.0	.90	2.9	28	6.0	3.3	8.0	10	11	10	82
Yield, pounds per acre	.003	.002	.006	.017	.002	.004	.003	.004	.003	.015	.005
1998											
Load (undeveloped), tons	94	50	87	180	13	120	66	52	90	300	1,000
Load (residential), tons	1.7	2.5	40	91	20	19	28	43	26	56	330
Load (commercial), tons	.23	0	16	100	19	6.4	19	20	20	33	240
Load (transportation corridor), tons	2.9	1.1	3.6	35	8.9	4.7	12	16	18	10	110
Yield, pounds per acre	.006	.003	.009	.03	.004	.01	.008	.008	.01	.025	.008
1999											
Load (undeveloped), tons	5	1.0	5.5	10	.37	3.4	6.8	4.9	12	9.2	59
Load (residential), tons	.31	.46	7.0	15	4.3	2.8	6.8	9.4	8.8	6.6	62
Load (commercial), tons	.06	0	4.5	30	5.3	1.6	5.5	6.1	10	9.4	72
Load (transportation corridor), tons	.90	.33	1.1	11	2.5	1.1	3.8	4.9	4.3	2.9	32
Yield, pounds per acre	.0004	.0001	.001	.004	.0008	.0006	.002	.002	.002	.002	.001
2000											
Load (undeveloped), tons	57	27	53	110	7.2	62	12	8.4	12	110	460
Load (residential), tons	1.7	2.8	28	63	31	22	12	17	5.1	28	210
Load (commercial), tons	.39	0	12	83	34	11	10	11	5.0	22	190
Load (transportation corridor), tons	5.6	2.0	2.9	29	16	8.0	6.8	8.7	4.4	7.0	90
Yield, pounds per acre	.004	.002	.006	.018	.006	.007	.003	.003	.002	.011	.005

Annual yields for suspended solids (table 15) ranged from 20 pounds per acre 1999 (driest year) to 160 pounds per acre in 1998 (wettest year). Among basins, the average annual yield for suspended solids in 1999 ranged from 3 pounds per acre in the Culebra Creek Basin (mostly Edwards aquifer outcrop and one of the least developed basins) to 36 pounds per acre in the Olmos/Huebner Creeks Basin (the basin with the highest estimated percentage of impervious area [table 1], primarily related to residential development).

Annual yields for dissolved solids (table 16) and dissolved nitrite plus nitrate nitrogen (table 17) showed variations with rainfall similar to those for suspended solids—generally smallest in 1999 and largest in 1998. Yields of these constituents among basins, as with suspended solids, varied widely.

The annual yield for total lead (table 18) was about eight times greater in 1998, the wettest year (0.008 pound per acre) than in 1999, the driest year (0.001 pound per acre). The Culebra Creek Basin had the smallest annual yield of total lead (0.0001 pound per acre in 1999), and the Leon Creek watershed (mostly Glen Rose Limestone and relatively greater residential and commercial development) had the largest annual yield (0.018 pound per acre in 2000, a relatively wet year).

SUMMARY

The USGS developed an HSPF watershed model to simulate runoff and recharge and to estimate constituent loads in surface-water runoff in the Edwards aquifer outcrop and catchment area in Bexar County. Rainfall and runoff data collected during 1970–98 from four gaged basins in the Edwards aquifer outcrop and catchment area were used to calibrate and test the model. The calibration parameters were applied in simulations of the four calibration basins and six ungaged basins of the study area to obtain runoff and recharge volumes for 4 years, 1997–2000. The simulated runoff volumes were used with EMC data from basins in the study area and from other Bexar County basins to compute constituent loads and yields for various land uses.

Calibration and testing of process-related model parameters (those that represent the physical processes of infiltration, ET, interception, interflow, ground-water recession, and surface runoff) involved four gaged basins in the study area: Helotes Creek, East Elm Creek, West Elm Creek, and Panther Springs Creek. Helotes Creek Basin primarily is in the catchment area. East Elm and West Elm Creek basins are in the Edwards aquifer outcrop. Panther Springs Creek Basin is partly in the Edwards aquifer outcrop and partly in the catchment area. A computerized expert system was used to guide the adjustment of process-related parameters during calibration and testing.

For the Helotes Creek Basin, data from six storms were used for calibration of the parameters related to runoff. The mean absolute runoff-weighted error for calibration simulations of the six Helotes Creek storms was 12 percent. East Elm Creek Basin was calibrated using data from four storms. To test the calibration and also to test the transferability of model parameters to similar ungaged basins, the calibration parameters from the East Elm Creek Basin were applied to the West Elm Creek Basin in simulations of four storms. The mean absolute runoff-weighted errors for the calibration (East Elm) and testing (West Elm) simulations were 17 and 12 percent, respectively. The calibration parameters from Helotes Creek, East Elm Creek, and West Elm Creek Basins were further tested by applying them in simulations of the Panther Springs Creek Basin. The mean absolute runoff-weighted error for the Panther Creek testing simulations was 43 percent.

The process-related model parameters calibrated and tested in the Helotes Creek, East Elm Creek, West Elm Creek, and Panther Springs Creek Basins were applied to the 10 major basins in the study area to simulate streamflow exiting and recharge to the basins during 1997–2000. In 1997, simulated streamflow exiting the 10 major basins (and thus runoff from the study area) was 5.62 inches; simulated recharge to the 10 major basins (essentially in the recharge zone in the study area) was 7.85 inches (20 percent of rainfall). In 1998, simulated streamflow exiting was 11.05 inches; simulated recharge was 10.99 inches (25 percent of rainfall). In 1999, simulated streamflow exiting was 0.66 inch; simulated recharge was 3.03 inches (19 percent of rainfall). In 2000, simulated streamflow exiting was 5.29 inches; simulated recharge was 7.19 inches (21 percent of rainfall).

Primary sources of recharge to the Edwards aquifer are direct infiltration of rainfall in interstream areas, streamflow losses in the outcrop, and infiltration of impounded runoff behind flood-control structures. During 1997–2000, direct infiltration of rainfall accounted for about 56 percent of the total Edwards aquifer recharge in Bexar County. Streamflow losses contributed about 37 percent of the recharge; flood impoundment contributed 7 percent.

Annual loads for suspended solids, dissolved solids, dissolved nitrite plus nitrate nitrogen, and total lead were consistently largest from undeveloped land and smallest from commercial land or transportation corridors. Annual loads varied with rainfall, with the maximum loads produced in the wettest year (1998) and the minimum loads produced in the driest year (1999).

Because they are computed from loads, annual yields for the four constituents also varied with rainfall. Annual yields for suspended solids ranged from 20 pounds per acre in 1999 (driest year) to 160 pounds per acre in 1998 (wettest year). Annual yields for dissolved solids and dissolved nitrite plus nitrate nitrogen showed variations with rainfall similar to those for suspended solids—generally smallest in 1999 and largest in 1998. The annual yield for total lead was about eight times greater in 1998 (0.008 pound per acre) than in 1999 (0.001 pound per acre).

REFERENCES

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Donigian, A.S., Jr., and Johanson, R.C., 1997, Hydrological Simulation Program—FORTRAN, user's manual for version 11: Athens, Ga., U.S. Environmental Protection Agency, National Exposure Research Laboratory, EPA/600/R–97–080, 755 p.

Charbeneau, R.J., and Barrett, M.E., 1998, Evaluation of methods for estimating stormwater pollutant loads: Water Environment Research, v. 70, no. 7, p. 1,295–1,302.

Dugas, W.A., Hicks, R.A., and Wright, P.W., 1998, Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed: Water Resources Research, v. 34, no. 6, p. 1,499–1,506.

Land, L.F., Boning, C.W., Harmsen, Lynn, and Reeves, R.D., 1983, Streamflow losses along the Balcones fault zone, Nueces River Basin, Texas: U.S. Geological Survey Water-Resources Investigations Report 83–4168, 72 p.

Lumb, A.M., McCammon, R.B., and Kittle, J.L., Jr., 1994, Users manual for an expert system (HSPEXP) for calibration of the Hydrological Simulation Program—FORTRAN: U.S. Geological Survey Water-Resources Investigations Report 94–4168, 102 p.

Ockerman, D.J., Petri, B.L., and Slattery, R.N., 1999, Stormwater runoff for selected watersheds in the Edwards aquifer recharge zone, Bexar County, Texas, 1996–98: U.S. Geological Survey Fact Sheet FS–172–98, 6 p.

Puente, Celso, 1978, Method of estimating natural recharge to the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Water-Resources Investigations Report 78–10, 34 p.

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

San Antonio River Authority, 1996, Salado Creek watershed protection and flood prevention project: San Antonio River Authority Fact Sheet, 2 p.

San Antonio Water System, 2000, Outline of ordinance #81491, aquifer recharge zone and watershed protection, San Antonio Texas, approved January 12, 1995: Accessed January 10, 2000, at URL http:www.saws.org/our_water/Source_Water_Watershed_Protection/aquifer_protection/documents/4outline.pdf

Stein, W.G., and Ozuna, G.B., 1995, Geologic framework and hydrogeologic characteristics of the Edwards aquifer recharge zone, Bexar County, Texas: U.S. Geological Survey Water-Resources Investigations Report 95–4030, 8 p.

U.S. Department of Agriculture, Soil Conservation Service, 1966, Soil survey of Bexar County, Texas: 126 p., 88 sheets.

University of Texas, Bureau of Economic Geology, 1985, The Guadalupe-Lavaca-San Antonio-Nueces River Basins regional study, San Antonio East-Llano East sheets: Austin, Tex., scale 1:250,000, 5 sheets.