In cooperation with the San Antonio Water System

Statistical Analyses of Hydrologic System Components and Simulation of Edwards Aquifer Water-Level Response to Rainfall Using Transfer-Function Models, San Antonio Region, Texas

Scientific Investigations Report 2006–5131

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

Blank Page

Statistical Analyses of Hydrologic System Components and Simulation of Edwards Aquifer Water-Level Response to Rainfall Using Transfer-Function Models, San Antonio Region, Texas

By Lisa D. Miller and Andrew J. Long

In cooperation with the San Antonio Water System

Scientific Investigations Report 2006–5131

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

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Meyers, Director

U.S. Geological Survey, Reston, Virginia: 2006
For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

Suggested citation:

Miller, L.D., and Long, A.J., 2006, Statistical analyses of hydrologic system components and simulation of Edwards aquifer water-level response to rainfall using transfer-function models, San Antonio region, Texas: U.S. Geological Survey Scientific Investigations Report 2006–5131, 20 p., 1 appendix.

Contents

Figures

Tables

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

Statistical Analyses of Hydrologic System Components and Simulation of Edwards Aquifer Water-Level Response to Rainfall Using Transfer-Function Models, San Antonio Region, Texas

By Lisa D. Miller and Andrew J. Long

Abstract

In 2003 the U.S. Geological Survey, in cooperation with the San Antonio Water System, did a study using historical data to statistically analyze hydrologic system components in the San Antonio region of Texas and to develop transfer-function models to simulate water levels at selected sites (wells) in the Edwards aquifer on the basis of rainfall. Water levels for two wells in the confined zone in Medina County and one well in the confined zone in Bexar County were highly correlated and showed little or no lag time between water-level responses. Water levels in these wells also were highly correlated with springflow at Comal Springs. Water-level hydrographs for 35 storms showed that an individual well can respond differently to similar amounts of rainfall. Fourteen water-level-recession hydrographs for a Medina County well showed that recession rates were variable. Transfer-function models were developed to simulate water levels at one confined-zone well and two recharge-zone wells in response to rainfall. For the confined-zone well, 50 percent of the simulated water levels are within 10 feet of the measured water levels, and 80 percent of the simulated water levels are within 15 feet of the measured water levels. For one recharge-zone well, 50 percent of the simulated water levels are within 5 feet of the measured water levels, and 90 percent of the simulated water levels are within 14 feet of the measured water levels. For the other recharge-zone well, 50 percent of the simulated water levels are within 14 feet of the measured water levels, and 90 percent of the simulated water levels are within 27 feet of the measured water levels. The transfer-function models showed that (1) the Edwards aquifer in the San Antonio region responds differently to recharge (effective rainfall) at different wells; and (2) multiple flow components are present in the aquifer. If simulated long-term system response results from a change in the hydrologic budget, then water levels would be difficult to simulate accurately.

Introduction

The Edwards aquifer is the major source of water for more than 1.5 million people in the San Antonio, Texas, area and provides nearly all of the water used for industrial, military, irrigation, and public supplies. San Antonio's public water supply needs are in competition with those of farmers and ranchers west of the city. Withdrawals from the aquifer to meet the city's needs are a threat to the continuation of flows at Comal Springs, the largest spring in the southwestern United States, and San Marcos Springs. Both springs supply downstream users, sustain federally listed endangered species, and support local economies through tourism. An Edwards aquifer management plan (San Antonio Water System, 2006) has been implemented to, among several objectives, ensure continuous springflow at Comal Springs. The plan restricts water use on the basis of specific ground-water levels of the Edwards aquifer at an index well in Bexar County (Bexar County index well). To effectively manage the Edwards aquifer on a day-to-day basis, the San Antonio Water System (SAWS) would like to be able to simulate water-level response on the basis of measurable and readily available data, such as rainfall.

In 2003 the U.S. Geological Survey (USGS), in cooperation with SAWS, did a study using historical data to statistically analyze relations among Edwards aquifer water levels, springflows, rainfall, and streamflow in the San Antonio region of Texas and to develop models to simulate water levels at selected sites (wells) in the Edwards aquifer on the basis of rainfall.

Previous statistical regression analyses of hydrologic variables for the Edwards aquifer have been made by Puente

(1976), Asquith and Jennings (1993), and Tomasko and others (2001). Puente (1976) developed equations using simple linear regression to estimate daily, monthly, and annual water levels and springflow. Asquith and Jennings (1993) developed statistical models to estimate annual springflow at Comal Springs and annual water levels for the Bexar County index well. Tomasko and others (2001) examined stream-discharge, water-level, and spring-discharge response to high rainfall during October 1998. Some statistical relations developed in these previous studies might be useful in estimating missing water-level record; however, they are unable to simulate changes in water levels on the basis of readily available data.

The purpose of this report is to (1) briefly describe statistical analyses used to investigate the relations among Edwards aquifer water levels, springflows, rainfall, and streamflow in the San Antonio region of Texas, and (2) describe lumped-parameter transfer-function models developed to simulate water-level response at three wells in the Edwards aquifer on the basis of rainfall. Two of the wells, one in the recharge zone (outcrop) of the Edwards aquifer and one in the confined zone, are in Bexar County; and one well is in the recharge zone in Medina County. Hydrologic data collected by the USGS, Edwards Aquifer Authority, and National Weather Service (NWS) in Uvalde, Medina, Bexar, and Comal Counties were used in the analyses. All well (daily water-level) data used in the analyses are in the appendix (online version only, available at http://pubs.usgs.gov/sir/2006/5131/). The rainfall data are available from the National Climatic Data Center (National Climatic Data Center, 2006). The spring and stream data are available from the USGS (U.S. Geological Survey, 2001).

The Edwards aquifer in the San Antonio region (fig. 1) is composed of extensively faulted, fractured, and cavernous limestone and dolomite of Early Cretaceous age (Maclay, 1995). The Edwards aquifer in the San Antonio region consists of the Georgetown Formation and the Edwards Group or their stratigraphic equivalents. These formations crop out within the Edwards Plateau and the Balcones fault zone and underlie the Gulf Coastal Plain (fig. 2). The Del Rio Clay and overlying units form the upper confining unit of the Edwards aquifer, and the Trinity aquifer beneath the Edwards, because of its low permeability relative to that of the Edwards aquifer, acts as a lower confining unit. The Edwards aquifer ranges in thickness from about 400 to 800 feet and averages about 550 feet. The thickness increases toward the west and south (Maclay, 1995, p. 16).

Most of the recharge to the Edwards aquifer occurs west of Bexar County and is from direct infiltration of rainfall and streamflow losses in the recharge zone (fig. 1). After entering the aquifer in the recharge zone, water moves into the confined zone and then east to points of discharge in Bexar County (mostly public-supply wells) and northeast, essentially parallel to the northeast-trending faults of the Balcones fault zone into Comal and Hays Counties, where it is withdrawn from wells and discharged by springs. Additional recharge to the Edwards aquifer occurs in the recharge zone in northern Bexar County and southern Comal and Hays Counties.

Statistical Analyses of Hydrologic System Components

A brief summary of the statistical analyses used in this study to investigate the relations between ground-water-level and springflow data for parts of the Edwards aquifer, and associated rainfall and streamflow data, is discussed in this section. Techniques used consist of determination of correlation coefficients between water levels at wells, and between water levels at wells and springflows; hydrographic analyses (including storm and recession analyses); and linear regression. Table 1 lists the ground-water, rainfall, and surface-water sites used in this analysis.

Correlation Coefficients

Spearman's rho correlation coefficients (Helsel and Hirsch, 1992) were computed using long-term concurrent daily maximum water levels at selected wells in the Edwards aquifer and daily mean springflow at Comal Springs. Specifically, each time series (for example, water levels from the Bexar County index well) was lagged from 0 to 450 days in 1-day intervals against each other time series (for example, Comal Springs springflow). Correlation coefficients for daily maximum water levels at the Bexar County index well lagged from 0 to 16 days and those of selected wells and daily mean Comal Springs springflow are shown in table 2.

Daily maximum water levels at the Bexar County index, City of Castroville, and Medina County index wells were highly correlated. The highest correlations between water levels at these wells were computed using lag times of 0 to 2 days, indicating little or no time between water-level responses (table 2). Figure 3 shows daily maximum water levels for selected wells and daily mean springflow for Comal Springs relative to daily maximum water levels at the Bexar County index well. Water levels in these wells also were highly correlated with springflow at Comal Springs. Springflow at Comal Springs was most highly correlated with water levels at the Bexar County index well. The highest correlation coefficient of .9728 was obtained by lagging water levels at the Bexar County index well by 2 days (that is, water-level changes at the Bexar County index well today are most related to springflow at Comal Springs 2 days in the future). Water levels at the Medina County FM 1796 and Quihi wells also were highly correlated (correlation coefficient for zero lag = .9379).

Lag times between water levels at the Bexar County index well and water levels at wells in the recharge (unconfined) zone of the Edwards aquifer (Hill Country Village, Medina County FM 1796, and Quihi wells) were much longer than lag times between water levels at wells in the confined zone of the aquifer (City of Castroville, Medina County index, and Uvalde County index wells). For example, lag times between water levels at the Bexar County index well and Hill Country Village well and between the Bexar County index well and Quihi well were

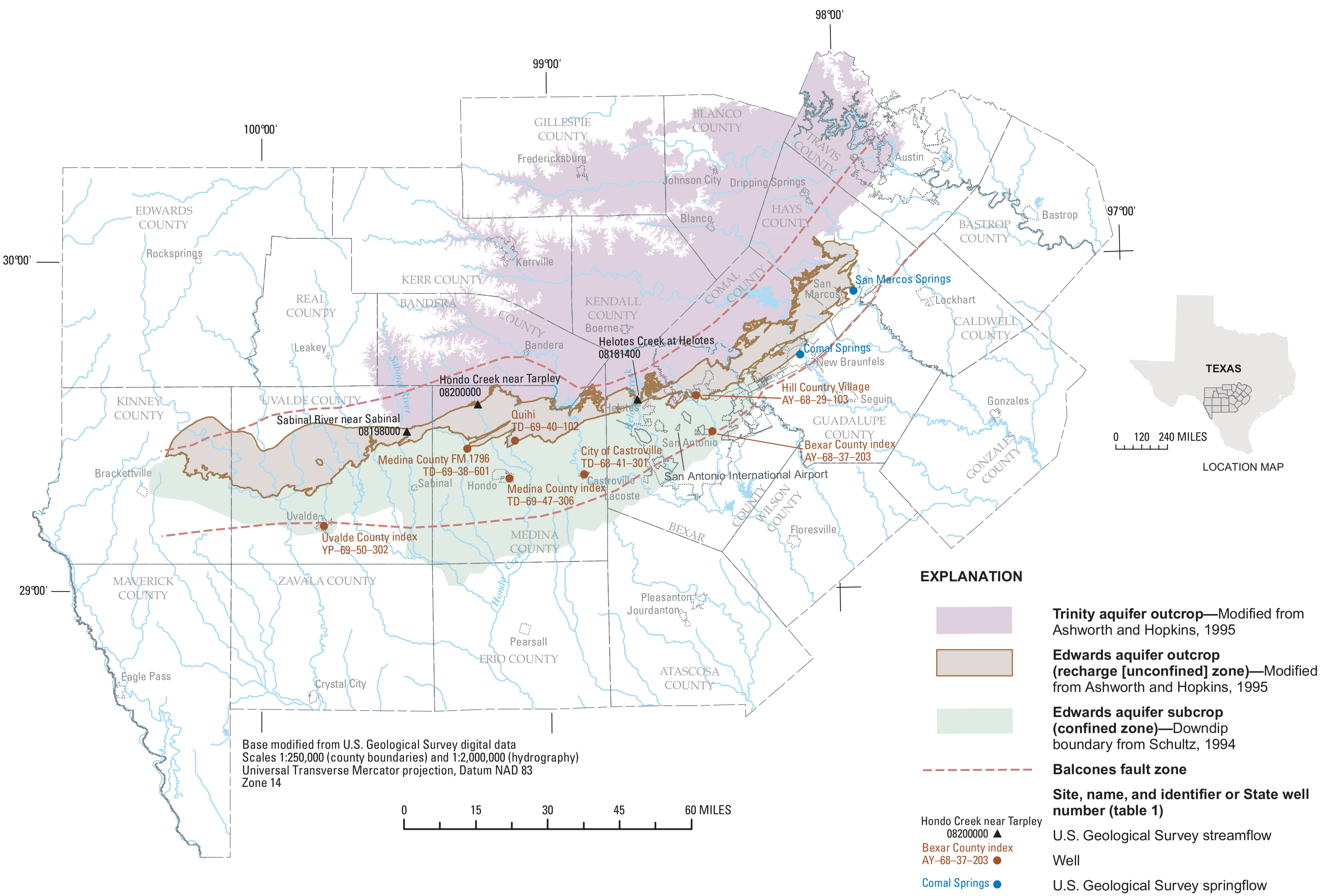


Figure 1. Trinity and Edwards aquifers and Edwards aquifer recharge zone, confined zone, and site locations in the San Antonio region, Texas.

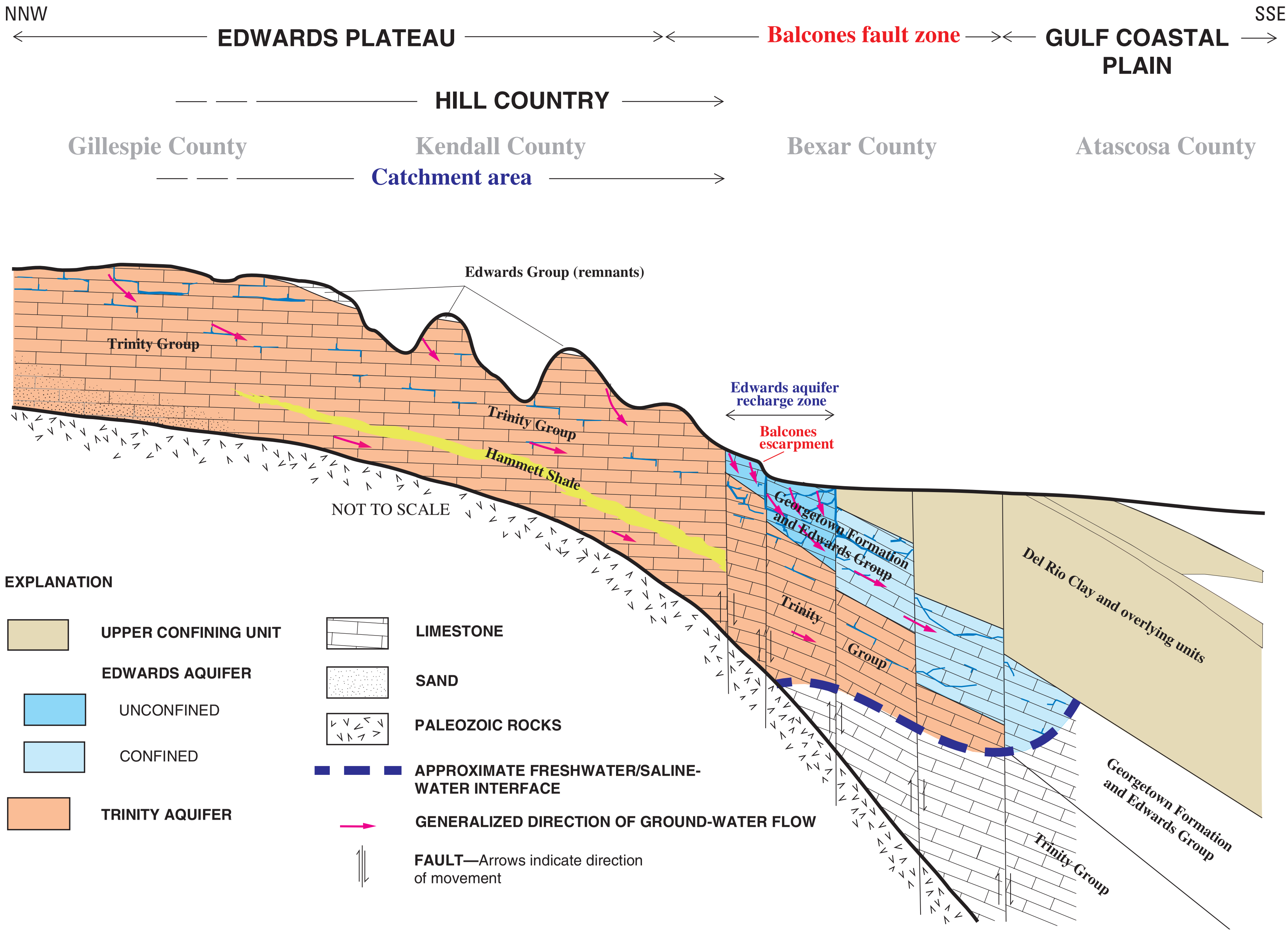


Figure 2. Diagrammatic north-northwest-to-south-southeast section showing hydrogeologic framework and generalized ground-water-flow directions, Edwards Plateau to Gulf Coastal Plain, San Antonio region, Texas (modified from Barker and Ardis, 1996, plates 1 and 3).

Table 1. Site name, site identifier, and period of record for selected well, spring, rainfall, and stream sites in or associated with the Edwards aquifer, San Antonio region, Texas.

[Most sites have periods of missing daily records. USGS, U.S. Geological Survey; EAA, Edwards Aquifer Authority; --, not available or not applicable; NWS, National Weather Service]

Site name	Site type	Agency	Site identifier	State well number	Period of record used in analysis
Bexar County index	Well	USGS/EAA	292845098255401	AY–68–37–203	June 1963–Dec. 2002
Hill Country Village	Well	USGS/EAA	293522098291201	AY–68–29–103	Nov. 1957–Dec. 2002
City of Castroville	Well	USGS/EAA	292117098524701	TD–68–41–301	May 1950–Dec. 2002
Medina County FM 1796	Well	USGS/EAA	292618099165901	TD–69–38–601	July 1957–Dec. 2002
Medina County index	Well	USGS/EAA	292045099081801	TD–69–47–306	Sept. 1986–Dec. 2002
Quihi	Well	EAA	--	TD–69–40–102	June 1994–Dec. 2002
Uvalde County index	Well	USGS/EAA	291237099471201	YP–69–50–302	Dec. 1949–Dec. 2002
Comal Springs at New Braunfels, Tex.	Spring	USGS	08168710	--	Oct. 1932–Dec. 2002
Boerne	Rainfall	NWS	410902	--	July 1897–Dec. 2002
Hondo	Rainfall	NWS	414254	--	Jan. 1900–Dec. 2002
Hondo Airport	Rainfall	NWS	414256	--	Mar. 1975–Dec. 2002
Kerrville	Rainfall	NWS	414780	--	Jan. 1897–Dec. 2002
Rio Medina	Rainfall	NWS	417628	--	Aug. 1922–Dec. 2002
Sabinal	Rainfall	NWS	417873	--	Sept. 1903–Dec. 2002
Tarpley	Rainfall	NWS	418845	--	Oct. 1937–Dec. 2002
Helotes Creek at Helotes, Tex.	Stream	USGS	08181400	--	June 1968–Dec. 2002
Hondo Creek near Tarpley, Tex.	Stream	USGS	08200000	--	Aug. 1952–Dec. 2002
Sabinal River near Sabinal, Tex.	Stream	USGS	08198000	--	Oct. 1942–Dec. 2002

about 45 and 310 days, respectively; whereas, lag times for wells in the confined zone of the aquifer (City of Castroville, Medina County index, and Uvalde County index wells) ranged from 0 to about 14 days.

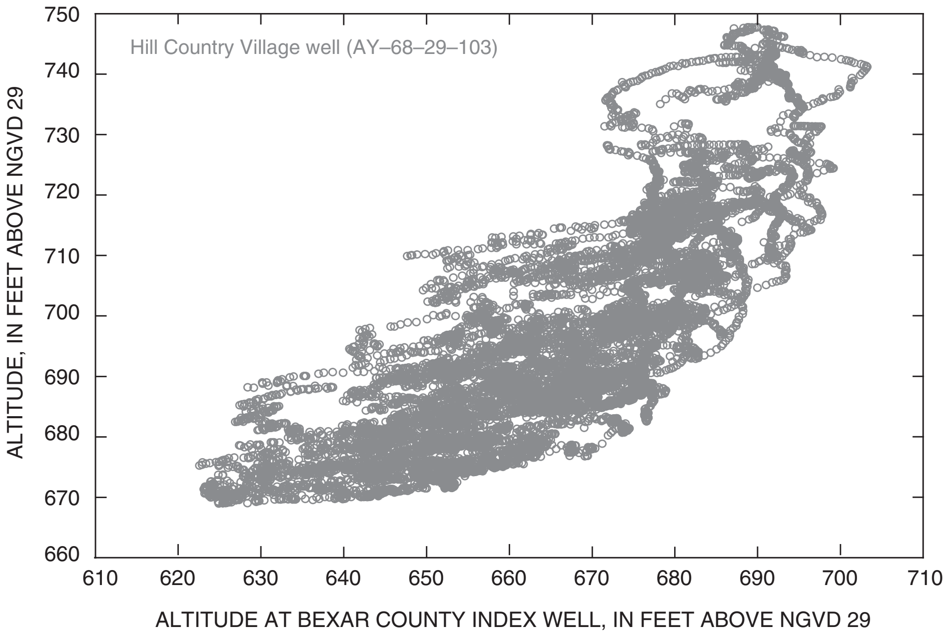
Hydrographic Analyses

Hydrographic analyses were done to obtain relations between rainfall and water-level changes and to characterize water-level-recession curves during periods of no rainfall. Water-level hydrographs were generated for 35 storms for the Bexar County index well and the City of Castroville well. Fourteen water-level-recession hydrographs were generated for the Medina County index well.

Average basinwide rainfall for the 35 storms ranged from 0.17 to 2.18 inches. The time to peak water level, the monthly Palmer drought severity index (National Weather Service Climate Prediction Center, 2005), and daily total rainfall and daily mean streamflow across the basin were recorded for each storm. The Palmer drought severity index uses temperature and rainfall information in a formula to characterize dryness. It was somewhat useful in approximating long-term antecedent conditions.

Figure 4 shows hydrographs of water levels at the Bexar County index, City of Castroville, and Medina County index wells, and springflow at Comal Springs. Long-term water levels for these wells are very similar; however, short-term fluctuations (water-level changes over days or weeks) can be quite different. In general for the 35 storms analyzed, water levels peaked sooner at the Bexar County index well than at the City of Castroville well.

Visual examination of the water-level hydrographs showed that an individual well can respond differently to similar amounts of rainfall. For example, figure 5 shows two different responses at the Bexar County index well to approximately the same amount of rainfall. The water level rose about 6 feet during one event (event 1), whereas the water level rose only 0.5 foot during another event (event 2). The Palmer drought severity index indicated below-normal moisture during event 1 (6-foot water-level rise) and above-normal moisture during event 2 (0.5-foot water-level rise). The average water level at the Bexar County index well during event 1 was 644.25 feet above NGVD 29 and during event 2 was 680.41 feet above NGVD 29. Average 7-day streamflows were computed at selected USGS streamflow sites within the well catchment area (defined later) during each event. Streamflow was lower across the basin during event 1 than during event 2. For



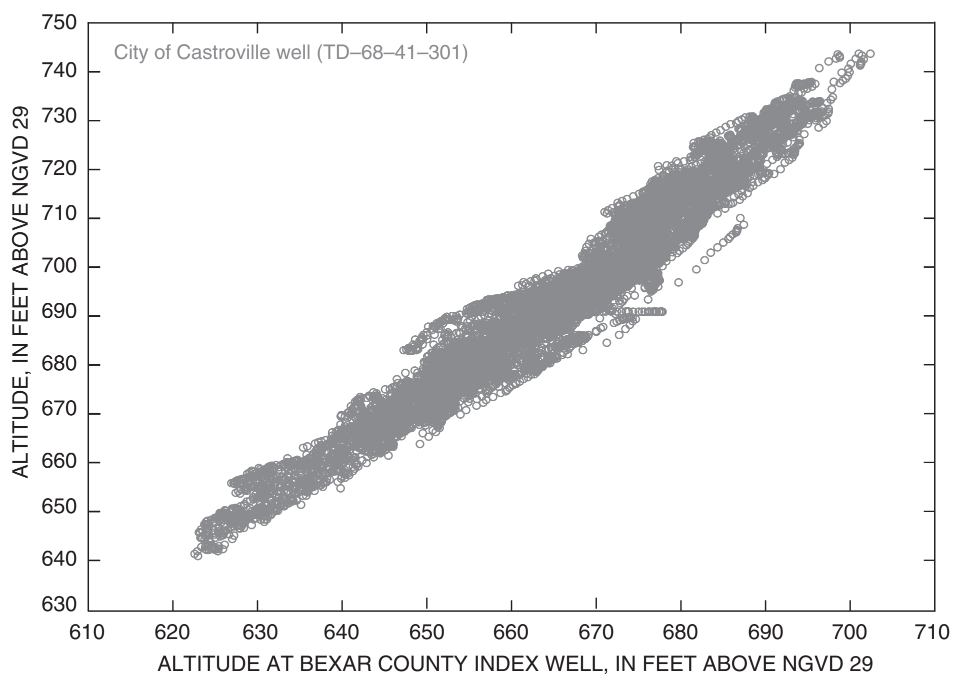
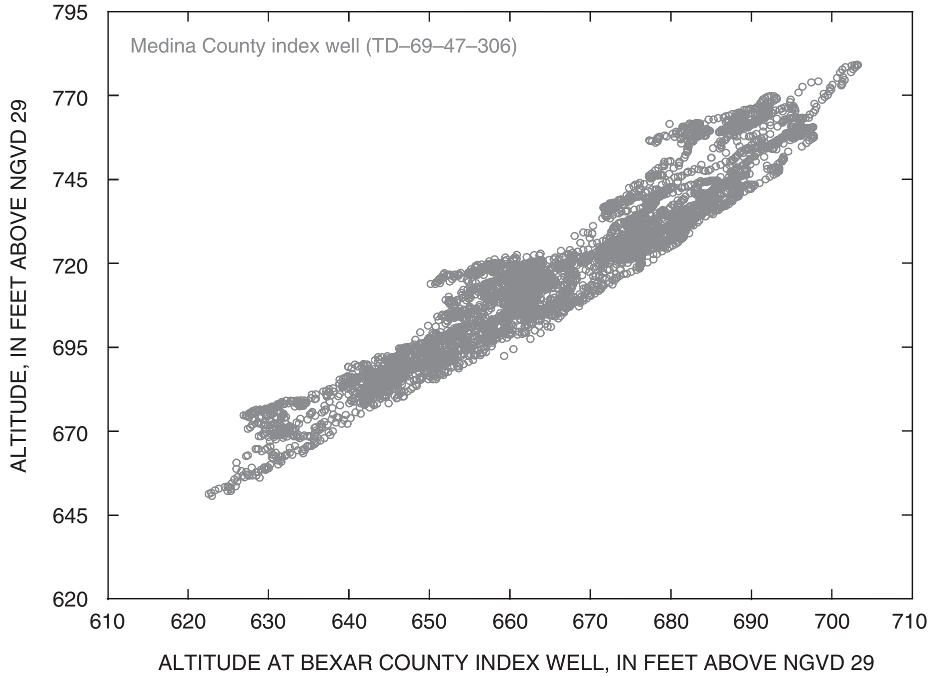


Figure 3. Daily maximum water levels at selected wells and daily mean springflow at Comal Springs relative to daily maximum water levels at Bexar County index well (AY–68–37–203), Edwards aquifer, San Antonio region, Texas, September 1986–December 2002.



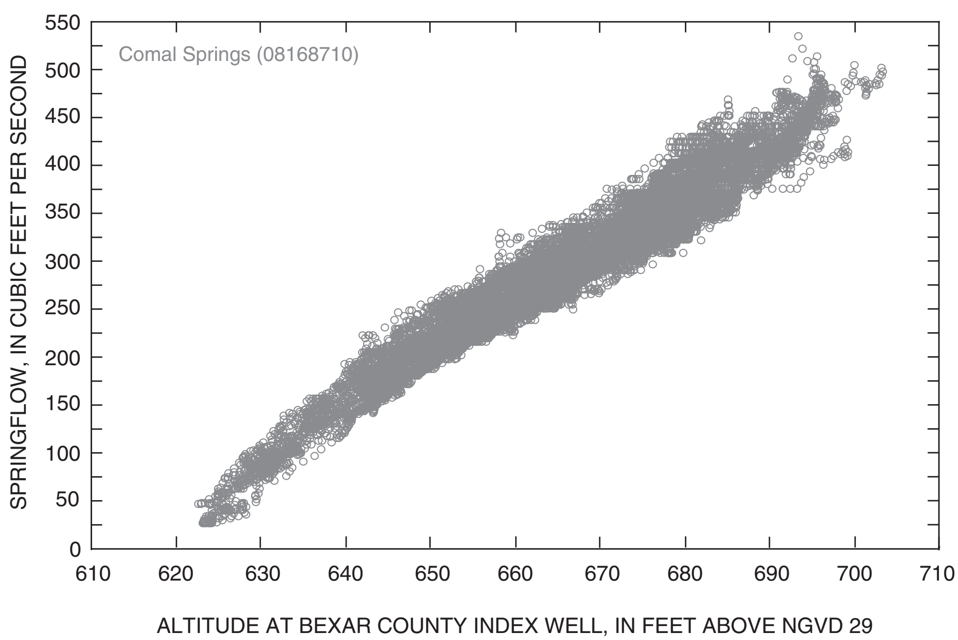


Figure 3. Continued.

Table 2. Spearman's rho correlation coefficients for daily maximum water levels at Bexar County index well (AY–68–37–203) lagged from 0 to 16 days and daily maximum water levels at selected wells and daily mean springflow at Comal Springs, Edwards aquifer, San Antonio region, Texas.

[Bexar County index well_LAG#, number of days water levels at Bexar County index well were lagged (example: LAG1 = 1-day lag); first number presented in table is Spearman's rho correlation coefficient; second number presented in table is number of x-y pairs used to compute correlation]

	City of Castroville well (TD–68–41–301)	Medina County index well (TD–69–47–306)	Uvalde County index well (YP–69–50–302)	Comal Springs (08168710)
Bexar County index well_LAG0	.9736	.9636	.8054	.9720
	13,092	5,806	10,121	14,651
Bexar County index well_LAG1	.9740	.9636	.8066	.9726
	13,091	5,806	10,120	14,650
Bexar County index well_LAG2	.9738	.9629	.8076	.9728
	13,090	5,806	10,119	14,649
Bexar County index well_LAG3	.9732	.9618	.8085	.9725
	13,089	5,806	10,118	14,648
Bexar County index well_LAG4	.9722	.9604	.8094	.9721
	13,088	5,806	10,117	14,647
Bexar County index well_LAG5	.9711	.9587	.8100	.9714
	13,087	5,806	10,116	14,646
Bexar County index well_LAG6	.9697	.9568	.8106	.9705
	13,086	5,806	10,115	14,645
Bexar County index well_LAG7	.9681	.9547	.8111	.9694
	13,085	5,806	10,114	14,644
Bexar County index well_LAG8	.9664	.9526	.8115	.9681
	13,084	5,806	10,113	14,643
Bexar County index well_LAG9	.9645	.9503	.8117	.9666
	13,083	5,806	10,112	14,642
Bexar County index well_LAG10	.9625	.9479	.8118	.9650
	13,082	5,806	10,111	14,641
Bexar County index well_LAG11	.9603	.9455	.8118	.9633
	13,081	5,806	10,110	14,640
Bexar County index well_LAG12	.958	.9432	.8119	.9615
	13,080	5,806	10,109	14,639
Bexar County index well_LAG13	.9556	.9408	.8120	.9597
	13,079	5,806	10,108	14,638
Bexar County index well_LAG14	.9532	.9383	.8121	.9578
	13,078	5,806	10,107	14,637
Bexar County index well_LAG15	.9507	.9358	.8120	.9558
	13,077	5,806	10,106	14,636
Bexar County index well_LAG16	.9482	.9333	.8118	.9537
	13,076	5,806	10,105	14,635

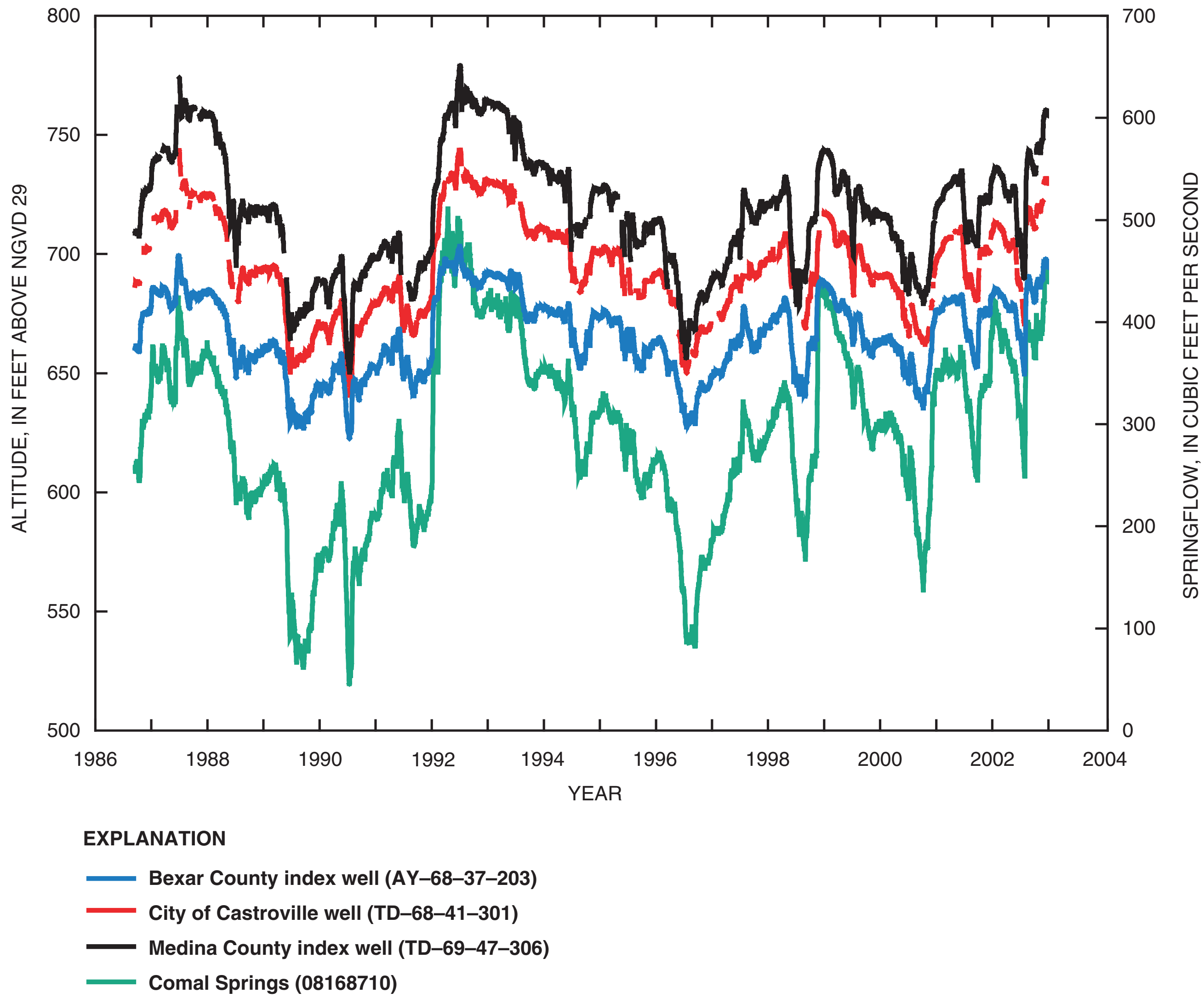


Figure 4. Daily maximum water levels at selected wells and daily mean springflow at Comal Springs, Edwards aquifer, San Antonio region, Texas, September 1986–December 2002.

example, during event 1, the streamflows at Sabinal River near Sabinal (USGS 08198000), Hondo Creek near Tarpley (USGS 08200000), and Helotes Creek at Helotes (USGS 08181400) were 13, 4, and 0.01 cubic feet per second, respectively; whereas, the average streamflows at these sites during event 2 were 54, 39, and 8 cubic feet per second, respectively.

Water-level-recession hydrographs were generated to indicate whether recession rates were similar during periods of no rainfall at a given well and whether a simple relation could be developed to simulate water-level response to no rainfall. Recession hydrographs were isolated by choosing periods with no rainfall for at least 10 to 14 days and declining water levels. Analyses of 14 recession hydrographs for the Medina County index well showed that recession rates were variable. Average recession rates ranged from about 0.11 to 1.22 feet per day. The difference in recession rates could be caused by factors such as season, antecedent condition, and aquifer depth. These hydrographic analyses underscore the need to incorporate antecedent conditions in any model to simulate water levels.

Linear Regression

Linear regression equations were developed to estimate water levels at selected wells using data available on a near real-time basis, such as water levels from nearby wells, rainfall, and streamflow. The monthly Palmer drought severity index also was used as an independent variable in the regressions. Simple linear regression was done using water levels at one well to simulate water levels at another well on the basis of lag times determined from the correlation analyses. Simple linear regression also was done using water levels at a selected well and rainfall at nearby gages or streamflow from nearby streams. Multi-

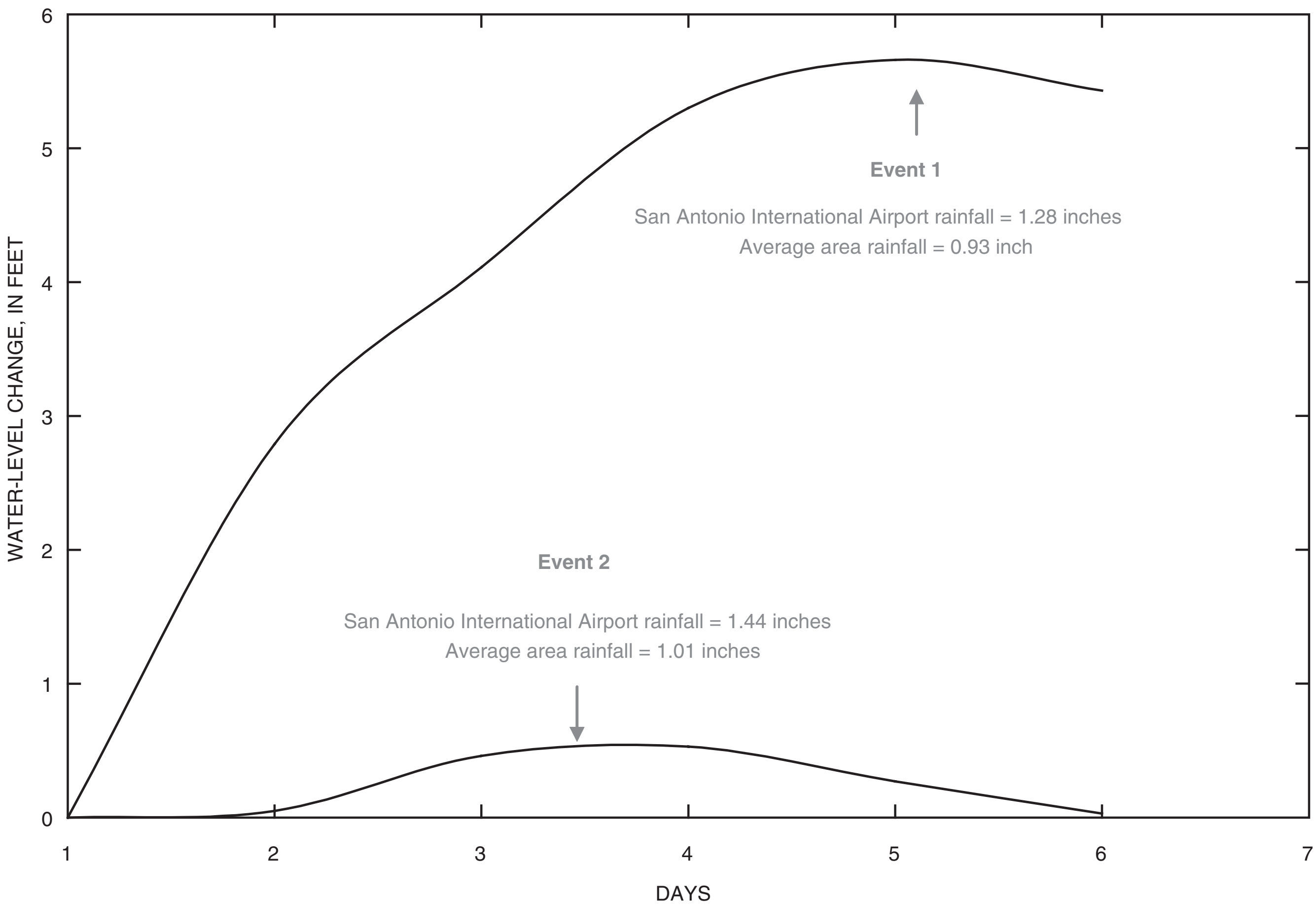


Figure 5. Water-level response to rainfall events for Bexar County index well (AY–68–37–203), Edwards aquifer, San Antonio region, Texas.

ple linear regression was used to try to improve the equations developed using one variable. Variables used in the multiple linear regressions comprise water levels at selected wells, rainfall, streamflow, and monthly Palmer drought severity index. Rainfall and streamflow were not used in the same equations because these two variables were correlated.

Water-level equations with the highest coefficients of determination (r^2) (the fraction of the variation in simulated water levels accounted for by the variation in the explanatory variables) are shown below:

$$WL_{HillCountry} = (WL_{BexarCo\_Lag45})(0.8910) + (SA\ Prec60)(0.4997) + 99.5469, \quad (1)$$

$r^2 = .7072$,

Residual standard error = 9.217 on 13,630 degrees of freedom, p-value (attained significance level) < .0001; and

$$WL_{MedinaFM} = (WL_{MedinaCo\_Lag85})(1.0437) + 131.5623, \quad (2)$$

$r^2 = .7742$,

Residual standard error = 14.74 on 4,114 degrees of freedom, p-value < .0001,

where

$WL_{HillCountry}$ is water level, in feet above NGVD 29, at the Hill Country Village well;

$WL_{BexarCo\_Lag45}$ is water level, in feet above NGVD 29, at the Bexar County index well lagged 45 days;

SA Prec60 is sum of the previous 60 days of daily total rainfall, in inches, at San Antonio International Airport;

$WL_{MedinaFM}$ is water level, in feet above NGVD 29, at the Medina County FM 1796 well;

$WL_{MedinaCo\_Lag85}$ is water level, in feet above NGVD 29, at the Medina County index well lagged 85 days.

Observed water levels in the Edwards aquifer show both short-term (hours or days) and long-term (days, weeks, or months) response to rainfall. Although there are some relatively high coefficients of determination, the regression equations might not adequately take into account both the short- and long-term variation in water levels. For this reason, transfer-function models were developed to simulate water-level response at three wells to rainfall.

Simulation of Water-Level Response to Rainfall Using Transfer-Function Models

Transfer functions, often called unit hydrographs, are commonly used in watershed modeling. The transfer-function approach requires few assumptions about the properties and boundary conditions of the system, because the properties affecting the response are lumped into a single transfer function determined on the basis of measured hydrologic time-series data. The shape of the transfer function characterizes the system response to an input signal. In this application, the system response is the water-level change and the input signal is effective rainfall; that is, the amount of rainfall passing through the root zone that recharges the aquifer.

The following sections describe the methods used to develop the transfer-function models and the results obtained. The methods comprise estimation of effective rainfall, convolution, and parameter estimation. The results are simulated water levels at three wells.

Effective Rainfall Estimation

The amount of rainfall during the last few days before a particular rainfall event partly determines the fraction of rainfall that passes through the root zone. High humidity and cool temperatures during wet periods might decrease evapotranspiration (ET) rates. The method of Jakeman and Hornberger (1993) is used to compute an antecedent rainfall index, s_i, which weights the daily rainfall by the rainfall of previous days. The weight is scaled exponentially backward in time and is computed by

$$\begin{aligned} s_i &= cr_i + (1-\kappa^{-1})s_{i-1} \\ &= c[r_i + (1-\kappa^{-1})r_{i-1} + (1-\kappa^{-1})^2 r_{i-2} + \ldots]; \\ & i = 0, 1, 2, \ldots, N; \\ & 0 > s_i > 1; \end{aligned} \qquad (3)$$

where

- i is the time step, in days;
- c is a normalizing parameter to limit s_i to values between 0 and 1; and
- κ is a coefficient that weights the influence of antecedent conditions.

Effective daily rainfall, u_i, is then estimated by

$$u_i = r_i s_i, \qquad (4)$$

where

- r_i is the total daily rainfall, in inches.

When discussing the hydraulic-head (water-level) response, the term “effective rainfall” is used in this report to describe the fraction of total rainfall that recharges an aquifer by direct infiltration. For this analysis, it is assumed that most rainfall on the recharge zone of the Edwards aquifer recharges the aquifer by direct infiltration.

Convolution

A transfer-function model also can be called a linear system. In this approach, the water-level response to effective rainfall is described by the convolution integral,

$$y(t) = \int_o^i h(t-\tau)x(\tau)d\tau, \qquad (5)$$

where

- $y(t)$ is the time series of water level (response function);
- $x(\tau)$ is the time series of recharge (forcing function or signal);
- $h(t-\tau)$ is a transfer function;
- $(t-\tau)$ is the delay time from forcing function to response; and
- d_t is the derivative of time (Dooge, 1973; Singh, 1988).

If time steps of equal duration are used, the discrete form of equation 5 is

$$y_i = \sum_{j=0}^{i} h_{i-j}x_j \qquad i = 0, 1, 2, \ldots, N \qquad (6)$$

The transfer function (h_{i-j}) represents the component of the response function (y_i) that results from a single pulse of the forcing function x_j. Thus, the transfer function can be thought of as the superposition of multiple transfer functions resulting from multiple pulses of the forcing function, where each of the transfer functions is scaled by the magnitude of the corresponding pulse. The transfer function also represents the statistical distribution of response travel times for a single point in space for any single pulse of the forcing function, the peak of which establishes the travel time for the peak response. The total length of time of the transfer function establishes the length of time that the effects of a pulse remain.

The transfer function is assumed to be stationary in time at any single point in space. If transfer functions are estimated along a series of points in space, each located a farther distance from the forcing function’s location, then that series of transfer functions will begin with a short duration and high peak and progressively acquire longer durations with lower peaks. This series would be similar to the propagation of a wave.

The transfer function is propagated through the system similarly to the propagation of a wave and thus can change as it moves through the system, depending on the distance traveled and media heterogeneity. One unique advantage of transfer-function models is that multiple flow components can be detected by using multiple transfer functions. In this approach, each transfer function is assumed to represent a distinct component of flow. Long and Putnam (2004) used this method to simulate transport in a karst aquifer using oxygen-18 (^{18}O) data and concluded that there were three distinct components of flow—conduit flow, diffuse flow, and delayed flow. The conduit-flow component responded quickest, followed by the diffuse-flow component, and then the delayed-flow component. White and White (2001) indicate that the Edwards aquifer also has three distinct components of flow.

A lognormal distribution is similar to karst springflow hydrographs in response to storms and is therefore assumed to approximate the true transfer function of a karst hydraulic response. The lognormal distribution also is computationally efficient and is defined by only two parameters: the mean and variance.

Parameter Estimation

Effective rainfall and measured daily maximum water levels were input into the parameter estimation program PEST (Doherty, 2002). Parameters comprising the mean (μ), variance (σ^2), and scalar component (α) of each transfer function and the effective rainfall coefficient (κ) were estimated using PEST. The scalar component represents the relative fraction of flow for each of the three distinct components—conduit, diffuse, and delayed flow. PEST minimizes the sum of the squared weighted residuals between measured and computed values by adjusting model parameters in an iterative process. Parameter sensitivities are determined by calculating the derivatives of all observations with respect to all parameters.

Simulated Water Levels at Three Wells

Transfer-function models were determined for three wells in the Edwards aquifer: the Bexar County index well, Hill Country Village well, and Medina County FM 1796 well. These transfer-function models were developed using daily maximum water levels and effective rainfall (estimated recharge). Daily maximum water levels were used to develop the models because long-term records were available. Effective rainfall was estimated from daily total rainfall recorded at an NWS rainfall site located within or near each well catchment area. Figure 6 shows the well catchment areas for Bexar County index, Hill Country Village, and Medina County FM 1796 wells. A well catchment area is assumed to be one of four flow units (or part of a flow unit) of the Edwards aquifer in the San Antonio region, as defined by Maclay and Land (1988, fig. 22, table 4), in which the well is located. The water-level datum used in the models was the base of the aquifer, which is better suited to transfer-function models than is NGVD 29. Water levels, however, are reported here in terms of feet above NGVD 29. The approximate altitude of the base of the aquifer at each well was estimated from well logs.

Bexar County Index Well (AY–68–37–203)

The Bexar County index well (AY–68–37–203) is within the city of San Antonio in the confined zone of the Edwards aquifer. Transfer-function models were developed using daily maximum water levels from June 4, 1963, to December 31, 2002, at the Bexar County index well and daily total rainfall from January 1, 1920, to December 31, 2002, at the NWS rainfall site at Hondo (414254) (fig. 6). During the period, water levels at the well ranged from 622.66 to 703.31 feet above NGVD 29 and daily total rainfall at Hondo ranged from 0 to 9.15 inches. Missing daily total rainfall at Hondo was estimated directly from daily total rainfall at NWS rainfall site Hondo Airport (414256). If daily total rainfall was missing at both Hondo and Hondo Airport, daily total rainfalls at NWS sites Sabinal (417873), Tarpley (418845), and Rio Medina (417628) were averaged to estimate daily total rainfall at Hondo.

Three transfer-function models were used to simulate water-level response to effective rainfall at the Bexar County index well. Table 3 shows the estimated parameters for the transfer-function models. The first function peaks at about 2 months, the second function peaks at about 9 years, and the third function peaks at about 27 years (fig. 7). Measured and simulated water levels at the Bexar County index well (fig. 8) were compared. Fifty percent of the simulated water levels are within 10 feet of the measured water levels, and 80 percent of the simulated water levels are within 15 feet of the measured water levels.

Hill Country Village Well (AY–68–29–103)

The Hill Country Village well is in northern Bexar County in the recharge zone of the Edwards aquifer. Transfer-function models were developed using daily maximum water levels from November 15, 1957, to December 31, 2002, at the Hill Country Village well and daily total rainfall at the NWS rainfall site Boerne (410902) (fig. 6) from January 1, 1920, to December 31, 2002. During the period, water levels at the well ranged from 668.32 to 747.67 feet above NGVD 29 and daily total rainfall at Boerne ranged from 0 to 8.93 inches. Missing daily total rainfall at Boerne was estimated directly from daily total rainfall at either NWS rainfall sites Kerrville (414780), Bulverde (411215), or Fair Oaks Ranch (413038).

Two transfer-function models were used to simulate water-level response to effective rainfall at the Hill Country Village well. Table 3 lists the estimated parameters for transfer-function models. The first function peaks at about 6 months, and the second function peaks at about 16 years (fig. 9). Because the relation between effective rainfall and water-level response at the Hill Country Village well appeared to change over time, a

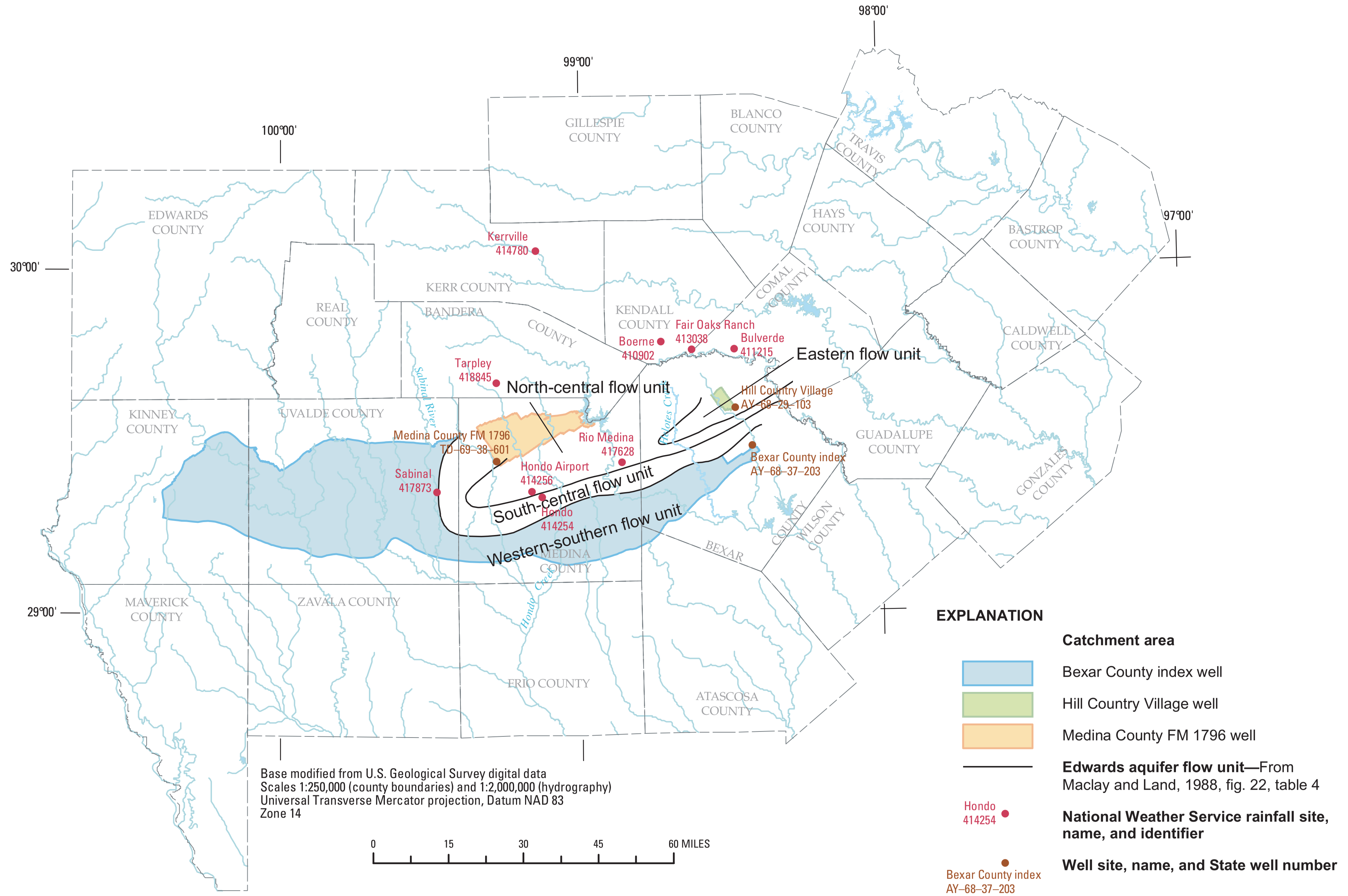


Figure 6. Flow units of the Edwards aquifer, San Antonio region, Texas, and well catchment areas for Bexar County index well, Hill Country Village well, and Medina County FM 1796 well.

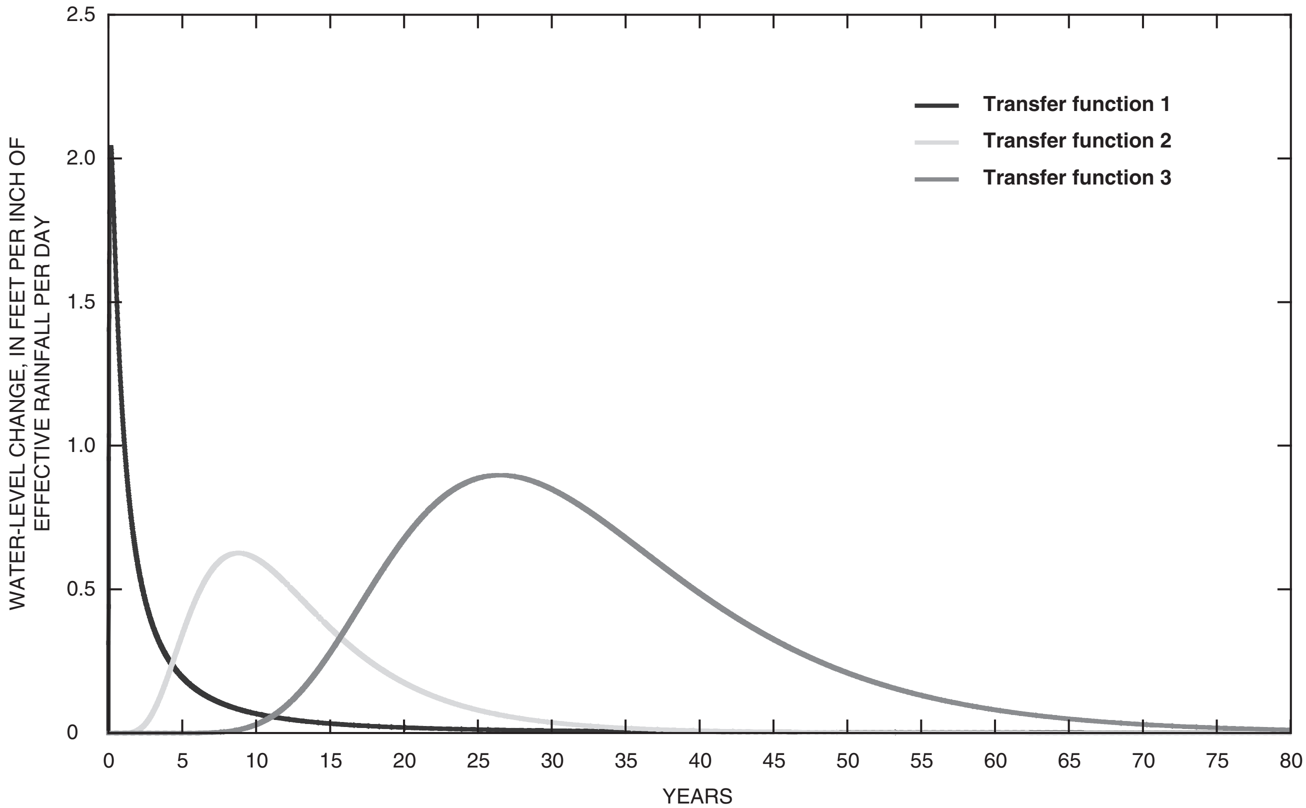


Figure 7. Calibrated transfer-function models for Bexar County index well (AY–68–37–203), Edwards aquifer, San Antonio region, Texas.

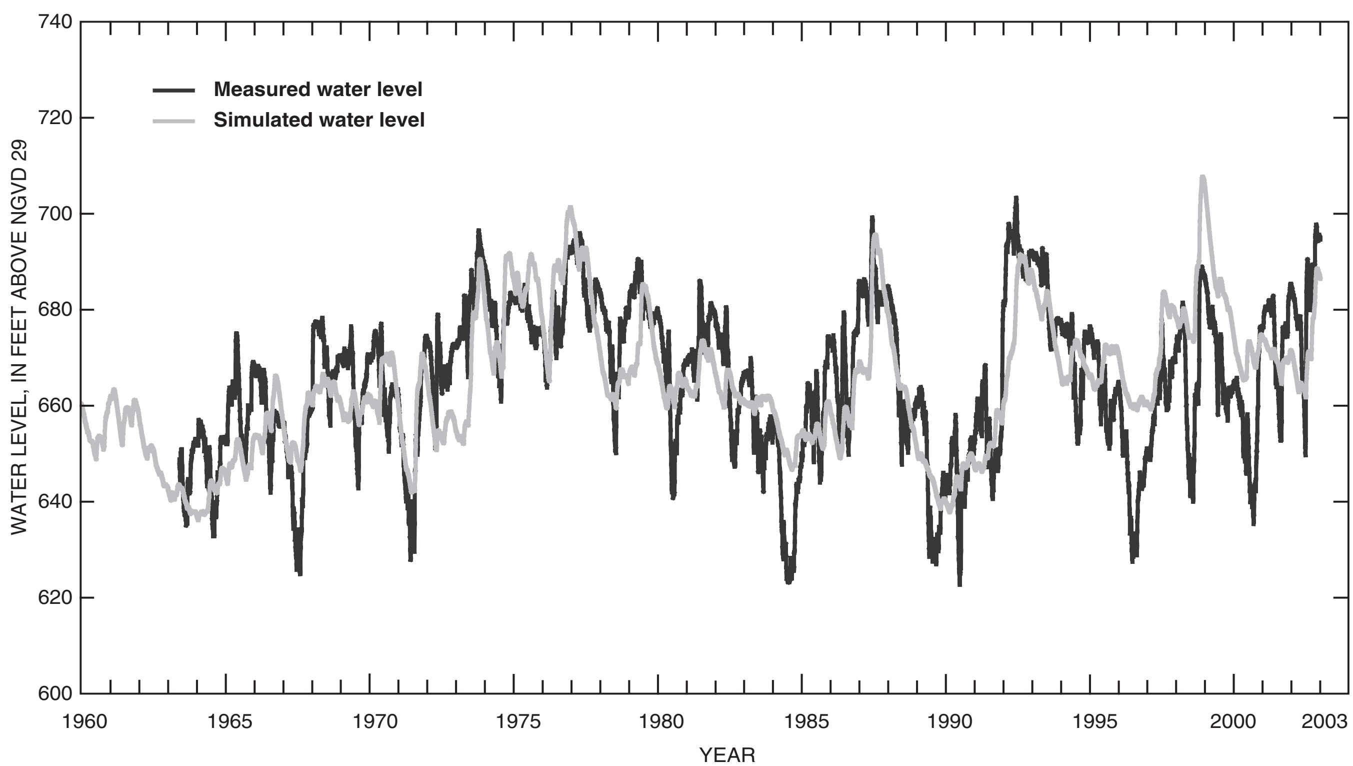


Figure 8. Measured and simulated water level for Bexar County index well (AY–68–37–203), Edwards aquifer, San Antonio region, Texas.

Table 3. Estimated parameters for transfer-function models developed for selected wells in the Edwards aquifer, San Antonio region, Texas.

[μ_i, mean; σ^2_i, standard deviation; α_i, function scale coefficient; κ, effective rainfall coefficient; *c*, normalizing factor to limit the antecedent rainfall index between 0 and 1; --, not applicable]

Parameter	Description	Transfer function number[1]	Value	Estimated 95-percent confidence limits[2]		Sensitivity	Relative sensitivity
				Lower limit	Upper limit		
Bexar County index well AY–68–37–203 (292845098255401)							
	Effective rainfall						
μ_1	Conduit response	1	6.56	6.43	6.70	1.36	1.11
σ^2_1			2.44	2.29	2.60	.19	.07
α_1			1,667.1	1,499.2	1,853.7	1.91	6.14
μ_2	Diffuse response	2	8.34	8.30	8.38	4.95	4.56
σ^2_2			.27	.24	.29	.19	.11
α_2			2,963.9	2,349.2	3,739.5	3.12	10.85
μ_3	Delayed response	3	9.32	9.30	9.33	17.63	17.09
σ^2_3			.14	.14	.14	.74	.63
α_3			8,689.3	7,331.2	10,298.9	10.50	41.35
κ	**Effective rainfall coefficient**		1,245.4	1,044.8	1,484.6	15.06	46.61
c	**Normalizing factor**		.008	--	--	--	--
Hill Country Village well AY–68–29–103 (293522098291201)							
	Effective rainfall						
μ_1	Conduit response	1	6.08	6.05	6.11	1.38	1.08
σ^2_1			.92	.9	.95	.12	.004
α_1			1,091.1	1,020.3	1,166.9	1.35	4.09
μ_2	Diffuse response	2	9.40	9.34	9.45	7.65	7.45
σ^2_2			.73	.66	.82	.24	.03
α_2			1,986.6	1,730.5	2,280.5	1.72	5.69
μ_3	Delayed response	--	--	--	--	--	--
σ^2_3			--	--	--	--	--
α_3			--	--	--	--	--
κ	**Effective rainfall coefficient**		1,002.6	919.0	1,093.8	2.90	8.70
c	**Normalizing factor**		.0091	--	--	--	--
Medina County FM 1796 well TD-69-38-601 (292618099165901							
	Effective rainfall						
μ_1	Conduit response	1	6.28	6.20	6.36	4.86	3.88
σ^2_1			1.30	1.22	1.39	.48	.05
α_1			2,634.0	2,358.0	2,942.4	4.05	13.84
μ_2	Diffuse response	2	8.03	8.01	8.04	8.55	7.73
σ^2_2			.39	.37	.41	.35	.14
α_2			3,698.8	3,368.8	4,061.3	5.27	18.80
μ_3	Delayed response	3	9.95	9.95	9.95	65.0	64.9
σ^2_3			.01	.01	.01	.24	.46
α_3			2,359.5	2,164.9	2,571.7	2.44	8.23
κ	**Effective rainfall coefficient**		273.2	247.5	301.7	5.46	13.40
c	**Normalizing factor**		.025	--	--	--	--

[1] See figure 7 for Bexar County index well; figure 9 for Hill Country Village well; figure 11 for Medina County FM 1796 well.

[2] Confidence limits provide only an indication of parameter uncertainty—they rely on a linearity assumption, which might not extend as far in parameter space as the confidence limits themselves—see PEST manual (Doherty, 2002).

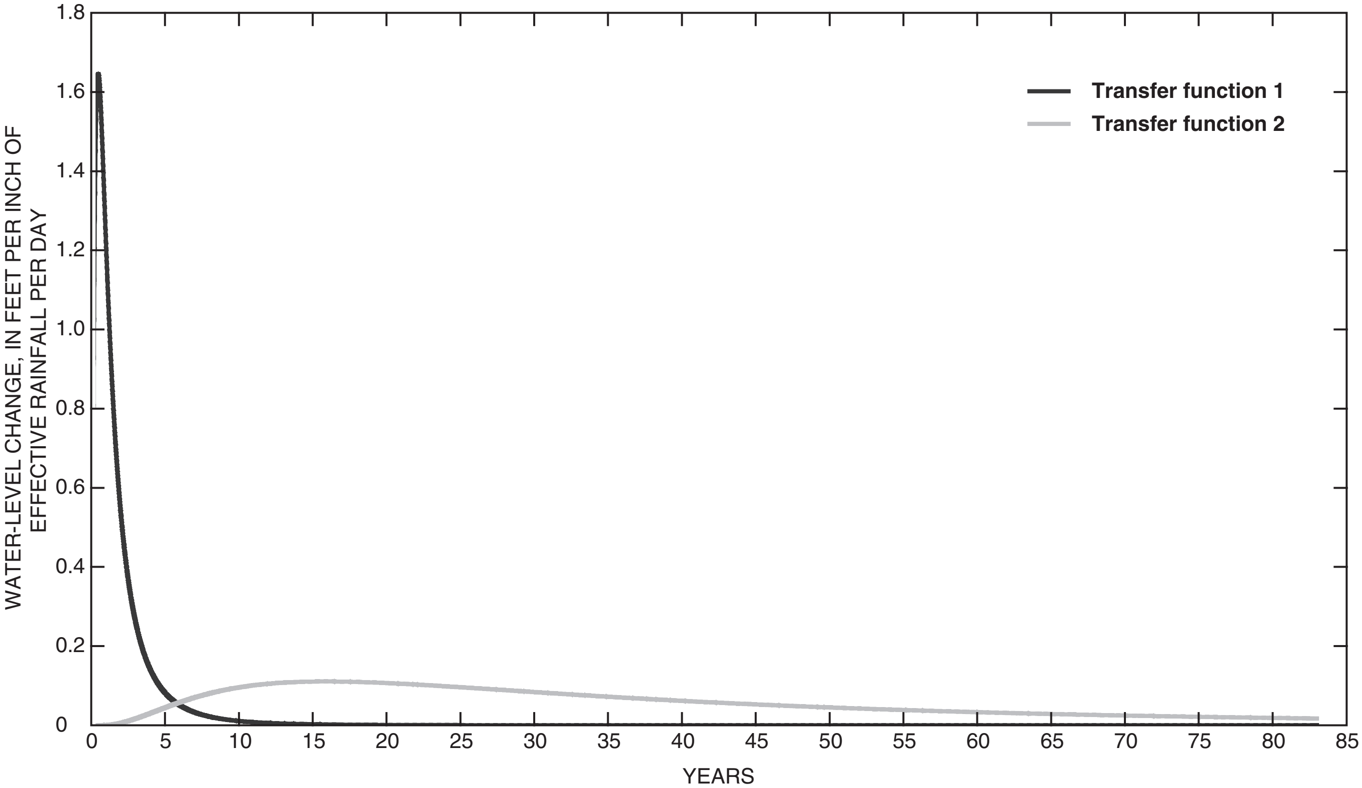


Figure 9. Calibrated transfer-function models for Hill Country Village well (AY–68–29–103), Edwards aquifer, San Antonio region, Texas.

multiplication factor was used to obtain a better match between measured and simulated water levels. As a result, effective rainfall was decreased at a constant rate starting on January 1, 1940. The multiplication factor on that day was 1.0 and decreased linearly until January 1, 2003, at which time the factor was 0.64. The cause of this change in the relation between effective rainfall and water-level response is not known. It might be related to land- or water-use changes within the catchment area or nonlinearities in the aquifer such as changes in aquifer properties with depth in the aquifer. Measured and simulated water levels at the Hill Country Village well (fig. 10) were compared. Fifty percent of the simulated water levels are within 5 feet of the measured water levels, and 90 percent of the simulated water levels are within 14 feet of the measured water levels.

Medina County FM 1796 Well (TD–69–38–601)

The Medina County FM 1796 well is in northwestern Medina County in the recharge zone of the Edwards aquifer. Transfer-function models were developed using daily maximum water levels from July 8, 1957, to December 31, 2002, at the Medina County FM 1796 well and daily total rainfall from January 1, 1920, to December 31, 2002, at the NWS rainfall site Hondo (414254) (fig. 6). During the period, water levels at the well ranged from 733.70 to 942.00 feet above NGVD 29, and daily total rainfall at Hondo ranged from 0 to 9.15 inches. Missing daily total rainfall at Hondo was estimated directly from daily total rainfall at NWS rainfall site Hondo Airport (414256). If daily total rainfall was missing at both Hondo and Hondo Airport, daily total rainfalls at NWS sites Sabinal (417873), Tarpley (418845), and Rio Medina (417628) were averaged to estimate daily total rainfall at Hondo.

Three transfer-function models were used to simulate water-level response to effective rainfall at the Medina County FM 1796 well. Table 3 lists the estimated parameters for transfer-function models. The first function peaks at about 5 months, the second function peaks at about 6 years, and the third function peaks at about 57 years (fig. 11). Measured and simulated water levels at the Medina County FM 1796 well were compared (fig. 12). Fifty percent of the simulated water levels are within 14 feet of the measured water levels, and 90 percent of the simulated water levels are within 27 feet of the measured water levels.

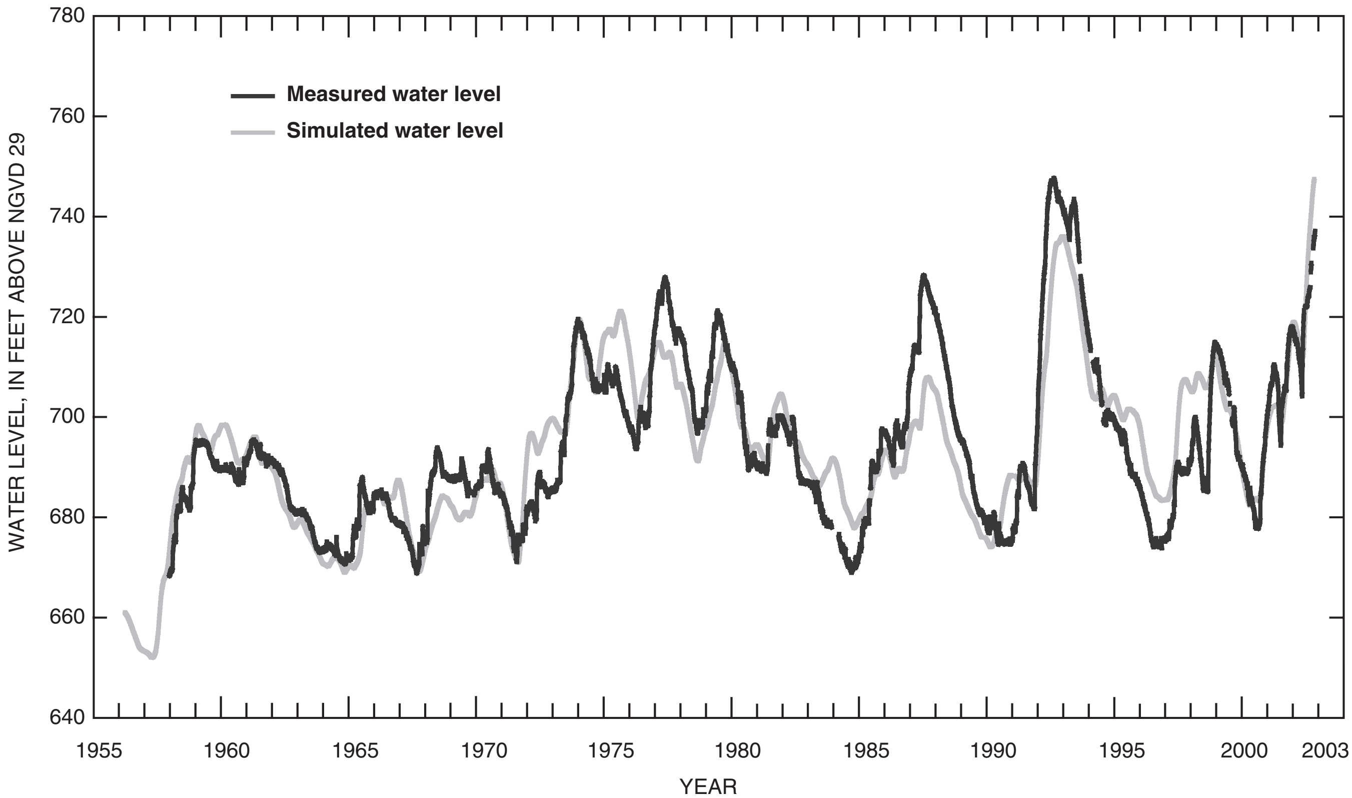


Figure 10. Measured and simulated water level for Hill Country Village well (AY–68–29–103), Edwards aquifer, San Antonio region, Texas.

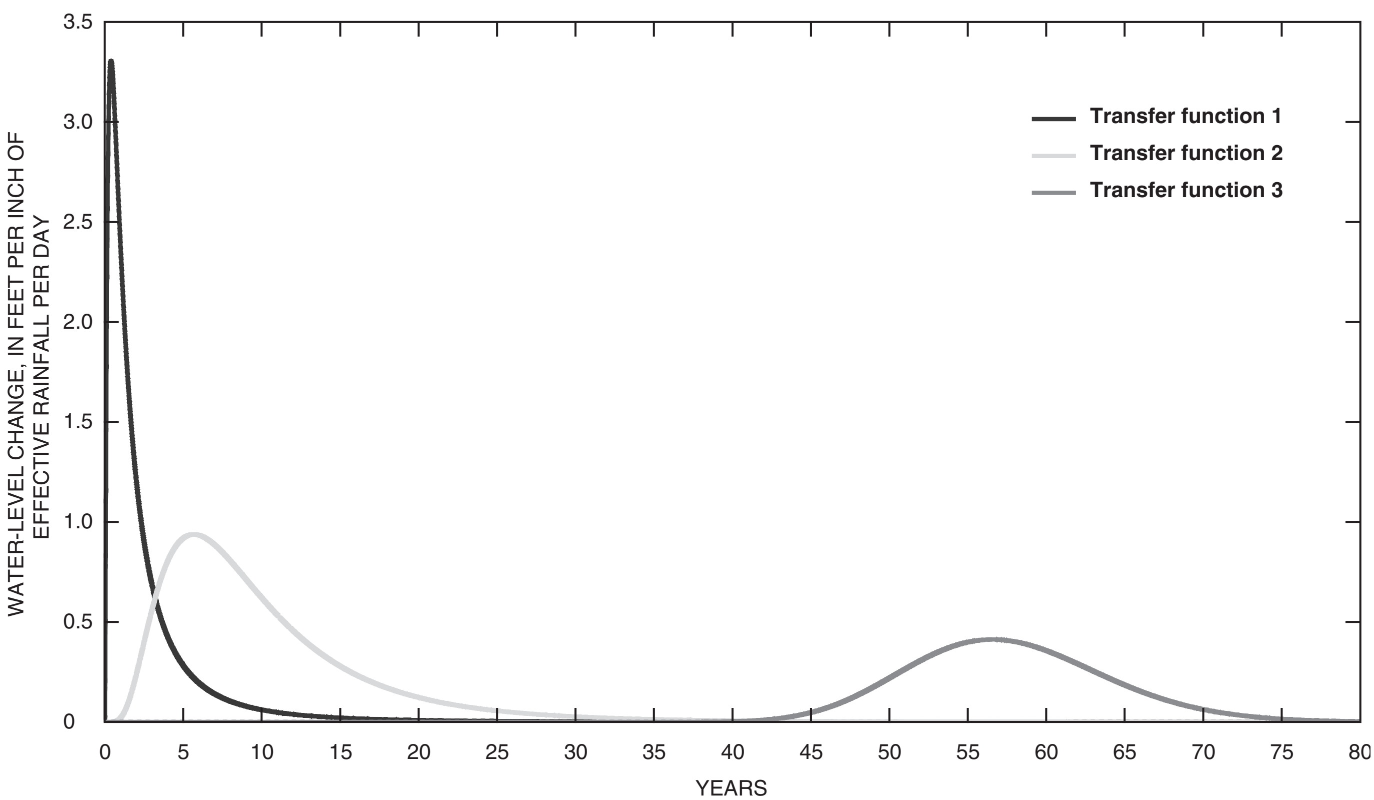


Figure 11. Calibrated transfer-function models for Medina County FM 1796 well (TD–69–38–601), Edwards aquifer, San Antonio region, Texas.

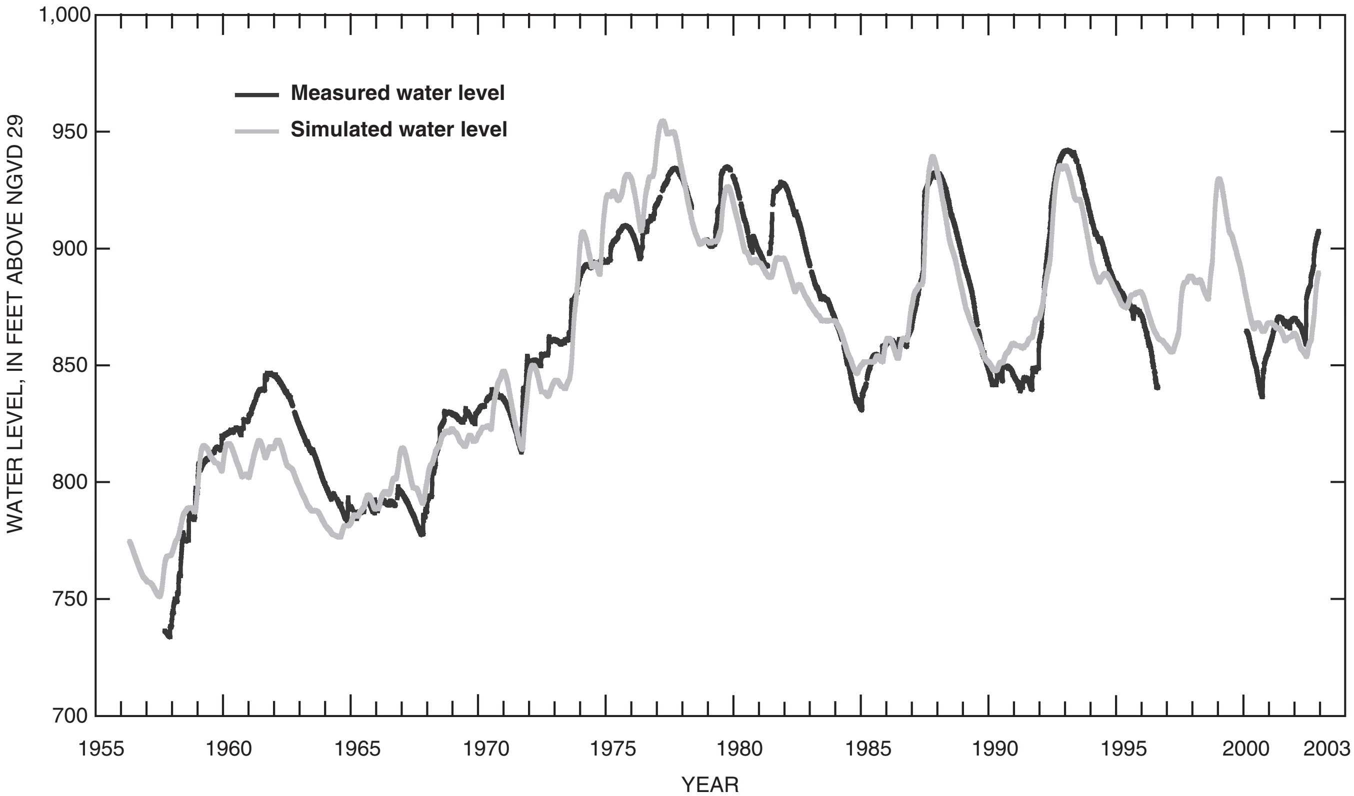


Figure 12. Measured and simulated water level for Medina County FM 1796 well (TD–69–38–601), Edwards aquifer, San Antonio region, Texas.

Discussion of Transfer-Function Model Results

The transfer-function models showed that (1) the Edwards aquifer in the San Antonio region responds differently to effective rainfall at different wells, and (2) multiple flow components are present in the aquifer, likely of the type reported by Long and Putnam (2004), as described in the "Convolution" section; that is, conduit flow, diffuse flow, and delayed flow (table 3).

Each of the three wells for which water levels were simulated had different transfer-function models. All three wells (one confined zone and two recharge zone) had short-term transfer functions that peaked from 2 to 6 months, which might indicate a flow component with conduit response; and intermediate-term functions that peaked from 6 to 16 years, which might indicate a flow component with diffuse response. The Bexar County index well and Medina County FM 1796 well had long-term functions that peaked at about 27 and 57 years, respectively, which might indicate a flow component with delayed response. A long-term transfer function was not used to simulate water levels at the Hill Country Village well. The long-term effect at the Hill Country Village well probably was accounted for by decreasing effective rainfall at a constant rate starting on January 1, 1940, and continuing to January 1, 2003.

Two possible explanations are hypothesized for the long-term transfer functions for two of the wells (Bexar County index and Medina County FM 1796) and for the long-term effect accounted for by slowly decreasing effective rainfall for the Hill Country Village well: (1) The long-term function represents a third and long-term (delayed response) flow component, and (2) the long-term function does not represent a true flow component but instead represents a change in the hydrologic budget (nonlinearity in the system). Nonlinearities might be related to land- or water-use changes within the well catchment area. Differences in aquifer properties at different depths in the aquifer also might explain nonlinear responses. As water levels in the recharge area change as a result of long-term climatic changes, different parts of the aquifer or different thicknesses of the aquifer can become saturated. If, for example, rising water levels cause a previously unsaturated part of the aquifer to become saturated, and if the newly saturated part has different properties than the originally saturated part, then the response characteristics might change as a result. Hence the simulated long-term system response might be reflecting actual long-term nonlinear effects. If the long-term system response does indeed result from nonlinearity in the hydrologic system, then water levels would be more difficult to simulate accurately. Short-term simulations probably are feasible; however, the extent to which accurate simulations can be made over time might be subject to the degree of understanding of nonlinear effects.

Other errors or differences between measured and simulated water levels might occur for several reasons. Some might be caused by errors in the estimation of effective rainfall. Errors in the estimation of effective rainfall might occur because (1) rainfall measured at a single site might not represent rainfall over the entire well catchment area, (2) recharge beyond the catchment area of a well might affect water levels, (3) there are rainfall measurement errors, and (4) the method used to estimate effective rainfall simplifies the numerous complexities that influence the amount of water reaching the aquifer. In addition, errors could be incurred because the lognormal transfer functions are approximations of the true transfer functions. Ongoing urbanization also might affect recharge to the aquifer in varying degrees over time and might not be reflected adequately in a given transfer-function model. Urbanization also probably affects the amount of water being withdrawn from the aquifer.

Some of the differences between measured and simulated water levels might occur because aquifer pumpage and recharge from streamflow losses to the aquifer were not used to develop the transfer-function models. These stresses were not included because (1) long-term daily pumpage data were not available, (2) adequate spatially distributed daily streamflow loss data were not available, and (3) it was assumed that most recharge to the aquifer occurred during storm events when rainfall and streamflow would be closely correlated. Thus rainfall was assumed to be a surrogate for streamflow loss. Despite these sources of error, the authors believe the models do an adequate job, in many cases, of simulating aquifer water-level response from rainfall data.

Summary

In 2003 the U.S. Geological Survey, in cooperation with the San Antonio Water System, did a study using historical data to statistically analyze hydrologic system components in the San Antonio region of Texas and to develop models to simulate water levels at selected sites (wells) in the Edwards aquifer on the basis of rainfall. This report briefly describes (1) statistical analyses used to investigate the relations among Edwards aquifer water levels, springflows, rainfall, and streamflow in the San Antonio region, and (2) lumped-parameter transfer-function models developed to simulate water-level response at three wells in the Edwards aquifer on the basis of rainfall. Two of the wells, one in the recharge zone (outcrop) of the Edwards aquifer and one in the confined zone, are in Bexar County; and one well is in the recharge zone in Medina County.

Statistical techniques used consist of determination of correlation coefficients between water levels at wells, and between water levels at wells and springflows; hydrographic analyses (including storm and recession analyses); and linear regression. Spearman's rho correlation coefficients were computed using long-term concurrent daily maximum water levels at selected wells in the Edwards aquifer and daily mean springflow at Comal Springs. Water levels for two wells in the confined zone in Medina County (Medina County index and City of Castroville) and one well in the confined zone in Bexar County (Bexar County index) were highly correlated and showed little or no lag time between water-level responses. Water levels in these wells also were highly correlated with springflow at Comal Springs.

Water-level hydrographs for 35 storms showed that an individual well can respond differently to similar amounts of rainfall. Fourteen water-level-recession hydrographs for the Medina County index well showed that recession rates were variable. Average recession rates ranged from about 0.11 to 1.22 feet per day.

Linear regression equations were developed to estimate water levels at selected wells using water levels from nearby wells, springflow, rainfall, streamflow, and the monthly Palmer drought severity index. Because the regression equations might not adequately take into account both short-term (hours or days) and long-term (days, weeks, or months) variation in water levels, transfer-function models were developed to simulate water-level response to rainfall.

Transfer-function models were developed to simulate water levels at one confined-zone well and two recharge-zone wells in response to rainfall. For the confined-zone well (Bexar County index), three transfer-function models were used to simulate water levels, with peaks occurring at about 2 months, 9 years, and 27 years, respectively. Fifty percent of the simulated water levels are within 10 feet of the measured water levels, and 80 percent of the simulated water levels are within 15 feet of the measured water levels. For one recharge-zone well (Hill Country Village), two transfer-function models were used to simulate water levels, with peaks occurring at about 6 months and 16 years. To obtain a better match between measured and simulated water levels (the need for which possibly was caused by a change in the hydrologic budget [nonlinearity in the system]), effective rainfall was decreased at a constant rate during the simulation period. Fifty percent of the simulated water levels are within 5 feet of the measured water levels, and 90 percent of the simulated water levels are within 14 feet of the measured water levels. For the other recharge-zone well (Medina County FM 1796), three transfer-function models were used to simulate water levels, with peaks occurring at about 5 months, 6 years, and 57 years. Fifty percent of the simulated water levels are within 14 feet of the measured water levels, and 90 percent of the simulated water levels are within 27 feet of the measured water levels.

The transfer-function models showed that (1) the Edwards aquifer in the San Antonio region responds differently to recharge (effective rainfall) at different wells; and (2) multiple flow components are present in the aquifer. If the simulated long-term system response results from a change in the hydrologic budget, then water levels would be difficult to simulate accurately. Short-term simulations probably are feasible; however, the extent to which accurate simulations can be made over time might be subject to the degree of understanding of nonlinear effects.

References Cited

Ashworth, J.B., and Hopkins, Janie, 1995, Aquifers of Texas: Texas Water Development Board Report 345, 69 p.

Asquith, W.H., and Jennings, M.E., 1993, Generalized statistical model of the Edwards aquifer, *in* Texas Section Joint Spring Meeting, American Institute of Hydrology and American Water Resources Association, Austin, Texas, April 16, 1993, Proceedings: 6 p.

Barker, R.A., and Ardis, A.F., 1996, Hydrogeologic framework of the Edwards-Trinity aquifer system, west-central Texas: U.S. Geological Survey Professional Paper 1421–B, 61 p.

Doherty, John, 2002, PEST—Model-independent parameter estimation (4th ed.): Brisbane, Australia, Watermark Numerical Computing [variously paged].

Dooge, J.C.I., 1973, Linear theory of hydrologic systems: Washington, D.C., U.S. Department of Agriculture, Agriculture Research Service Technical Bulletin 1468, 327 p.

Helsel, D.R., and Hirsch, R.M., 1992, Studies in environmental science 49—Statistical methods in water resources: New York, Elsevier, 522 p.

Jakeman, A.J., and Hornberger, G.M., 1993, How much complexity is warranted in a rainfall-runoff model?: Water Resources Research, v. 29, p. 2,637–2,649.

Long, A.J., and Putnam, L.D., 2004, Linear model describing three components of flow in karst aquifers using ^{18}O data: Journal of Hydrology, v. 296, p. 254–270.

Maclay, R.W., 1995, Geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Water-Resources Investigations Report 95–4186, 64 p.

Maclay, R.W., and Land, L.F., 1988, Simulation of flow in the Edwards aquifer, San Antonio region, Texas, and refinement of storage and flow concepts: U.S. Geological Survey Water-Supply Paper 2336–A, 48 p.

National Climatic Data Center, 2006, Data & products: National Environmental Satellite, Data, and Information Service (NESDIS) at http://ncdc.noaa.gov/oa/ncdc.html

National Weather Service Climate Prediction Center, 2005, Explanation [Palmer drought severity index]: accessed August 25, 2005, at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/palmer_drought/wpdanote.shtml

Puente, Celso, 1976, Statistical analysis of water-level, springflow, and streamflow data for the Edwards aquifer in south-central Texas: U.S. Geological Survey Open-File Report 76–393, 58 p.

San Antonio Water System, 2006, Aquifer management plan: accessed April 3, 2006, at http://www.saws.org/conservation/aquifermgmt/.

Schultz, A.L., 1994, 1994 review and update of the position of the Edwards aquifer freshwater/saline-water interface from Uvalde to Kyle, Texas: San Antonio, Edwards Underground Water District Report 94–05, 31 p.

Singh, V.P., 1988, Hydrologic systems, rainfall-runoff modeling: Englewood Cliffs, N.J., Prentice Hall, 480 p.

Tomasko, David, Fisher, Ann-Marie, Williams, G.P., and Pentecost, E.D., 2001, A statistical study of the hydrological character of the Edwards aquifer: Chicago, Argonne National Laboratory, final report [variously paged].

U.S. Geological Survey, 2001, USGS water data for the Nation—Surface water: National Water Information System (NWISWeb) at http://waterdata.usgs.gov/nwis/.

White, W.B., and White, E.L., 2001, Conduit fragmentation, cave patterns, and localization of karst ground water basins—The Appalachians as a test case: Theoretical and Applied Karstology, v. 13–14, p. 9–23.

Prepared by the USGS Texas Water Science Center:
8027 Exchange Drive
Austin, TX 78754–4733

Information regarding water resources in Texas is available at
http: //tx.usgs.gov/