EDWARDS UNDERGROUND WATER DISTRICT
2603 TOWER LIFE BUILDING
SAN ANTONIO, TEXAS 78205

Statistical Analysis of Water-Level, Springflow, and Streamflow Data for the Edwards Aquifer in South-Central Texas

U.S. GEOLOGICAL SURVEY REPORT

JULY 1976

EDWARDS UNDERGROUND WATER DISTRICT

2603 Tower Life Building
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STATISTICAL ANALYSIS OF WATER-LEVEL, SPRINGFLOW, AND STREAMFLOW DATA FOR THE EDWARDS AQUIFER IN SOUTH-CENTRAL TEXAS

By

Celso Puente
U.S. Geological Survey

Prepared by the U.S. Geological Survey in cooperation
with the Edwards Underground Water District,
the Texas Water Development Board,
and the city of San Antonio

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STATISTICAL ANALYSIS OF WATER-LEVEL, SPRINGFLOW, AND STREAMFLOW DATA FOR THE EDWARDS AQUIFER IN SOUTH-CENTRAL TEXAS

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ABSTRACT

Water-level, springflow, and streamflow data were used to develop simple and multiple linear-regression equations for use in estimating water levels in wells and the flow of three major springs in the Edwards aquifer in the eastern San Antonio area. The equations provide daily, monthly, and annual estimates that compare very favorably with observed data.

Analyses of geologic and hydrologic data indicate that the water discharged by the major springs is supplied primarily by regional underflow from the west and southwest and by local recharge in the infiltration area in northern Bexar, Comal, and Hays Counties.

INTRODUCTION

The purpose of this report is to examine the interrelationships between water levels, springflow, and streamflow in the eastern San Antonio area by using statistical regression analysis. The primary objective is to determine the sources of water supplying the major springs and to develop equations that may be used to estimate water levels in wells and springflow at San Marcos, Comal, and Hueco Springs.

The Edwards aquifer underlies all or parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties, Texas. The study area in this report is referred to as the eastern San Antonio area and denotes the area within and adjacent to the Balcones Fault Zone in Bexar, Comal, and Hays Counties in south-central Texas (fig. 1). The Edwards aquifer provides potable water in the area between the Balcones Fault Zone and the interface between fresh water and saline water, the "bad-water line," which forms the southern boundary of the study area. Downgradient from this boundary, the water in the aquifer contains more than 1,000 mg/l (milligrams per litre) dissolved solids and contains hydrogen sulfide gas.

The collection of data used in this report is part of the program of hydrologic investigations by the U.S. Geological Survey in cooperation with the Edwards Underground Water District, the Texas Water Development Board, and the city of San Antonio.

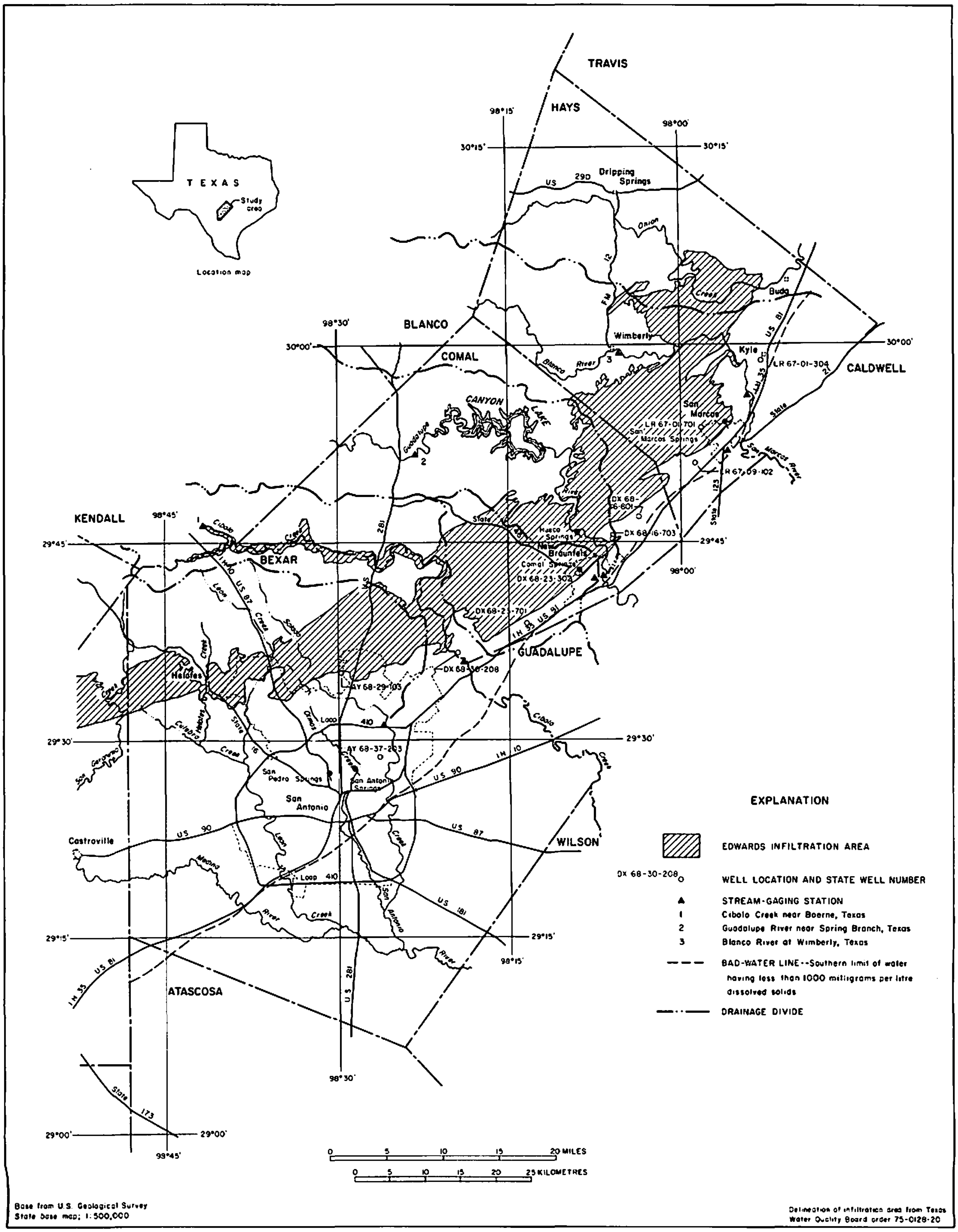


FIGURE 1.-Drainage basins and data-collection sites in the eastern San Antonio area

For those readers interested in using the metric system, the metric equivalents of English units of measurements are given in parentheses. The English units used in this report may be converted to metric units by the following factors:

From		Multiply by	To obtain	
Unit	Abbreviation		Unit	Abbreviation
acre-feet	--	0.001233	cubic hectometres	hm^3
cubic feet per second	ft^3/s	.02832	cubic metres per second	m^3/s
feet	--	.3048	metres	m
miles	--	1.609	kilometres	km
square miles	--	2.590	square kilometres	km^2

GEOLOGY AND HYDROLOGY OF THE AREA

The geology and hydrology of the Edwards aquifer in the eastern San Antonio area has been studied by numerous investigators, including George and others (1952), Petitt and George (1956), DeCook (1963), and Garza (1962, 1966). The aquifer consists of 400 to 500 feet (122 to 152 m) of fine-grained carbonate rocks between the base of the Del Rio Clay and the top of the Glen Rose Formation. In the eastern part of the San Antonio area, the aquifer consists of the Georgetown Formation, and the Person and Kainer Formations of Rose (1972). The Balcones Fault Zone is the dominant structural feature in the area (fig. 2), and the major faults occur as a series of closely spaced step faults that trend generally northeastward across the study area. The exceptionally high capacity of the aquifer to transmit water results from fractures and secondary porosity that are well developed in some stratigraphic units.

The baseflows of the streams that drain the Edwards Plateau in the study area are derived from the many springs that discharge water from the Edwards aquifer. The baseflows, and parts of the flood flows, are lost by infiltration in the Balcones Fault Zone. Recharge to the Edwards aquifer is calculated as the difference between total inflow above and total outflow below the infiltration area plus direct infiltration from precipitation in the infiltration area. Inflow and outflow are measured by stream-gaging stations near the upper and lower boundaries of the infiltration area (fig. 1).

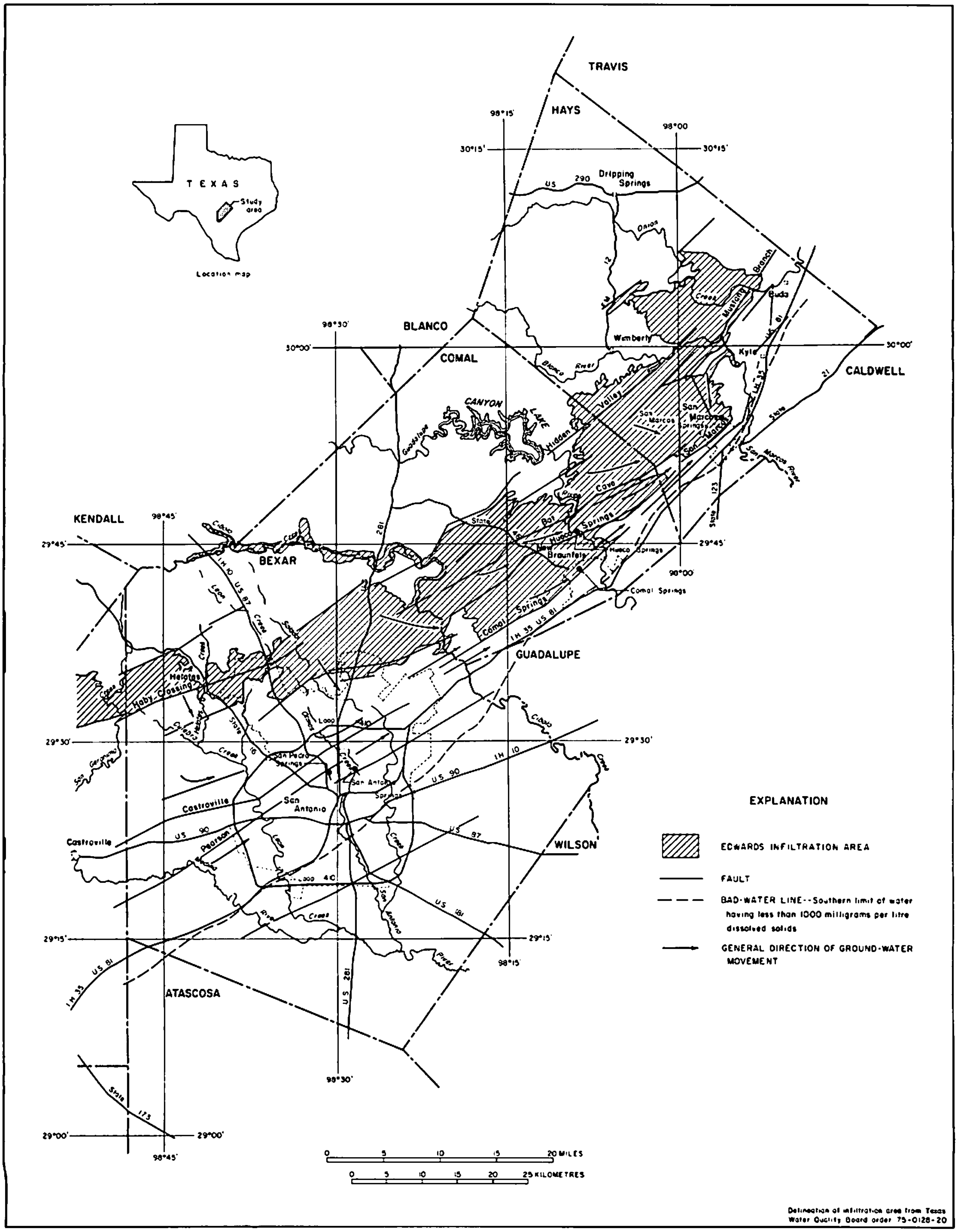


FIGURE 2.-Geologic and hydrologic features in the eastern San Antonio area

Natural discharge from the Edwards aquifer is by six large springs in the Balcones Fault Zone, five of which are in the study area. The combined average annual discharge of these five springs for 1945 through 1973 was about 325,000 acre-feet (400.7 hm^3), or about 60 percent of the average annual recharge to the Edwards aquifer. The average annual discharge from wells in the study area is about 206,200 acre-feet (254.2 hm^3), of which 197,200 acre-feet (243.1 hm^3) is from wells in Bexar County. Approximately 35 percent of the total recharge and about 90 percent of the total discharge from the Edwards aquifer occurs in the study area.

The approximate altitude of the potentiometric surface in the Edwards aquifer in the study area during July 1973 is shown on figure 3. The movement of the ground water is in the direction of the hydraulic gradient, which is perpendicular to the contour lines representing equal aquifer heads. The distribution of available wells for obtaining water-level measurements is not adequate for determination of local directions of ground-water movement within the aquifer. In the infiltration area, the water moves generally southward or southeastward toward the artesian part of the aquifer. In the artesian area, the water moves toward the east and northeast.

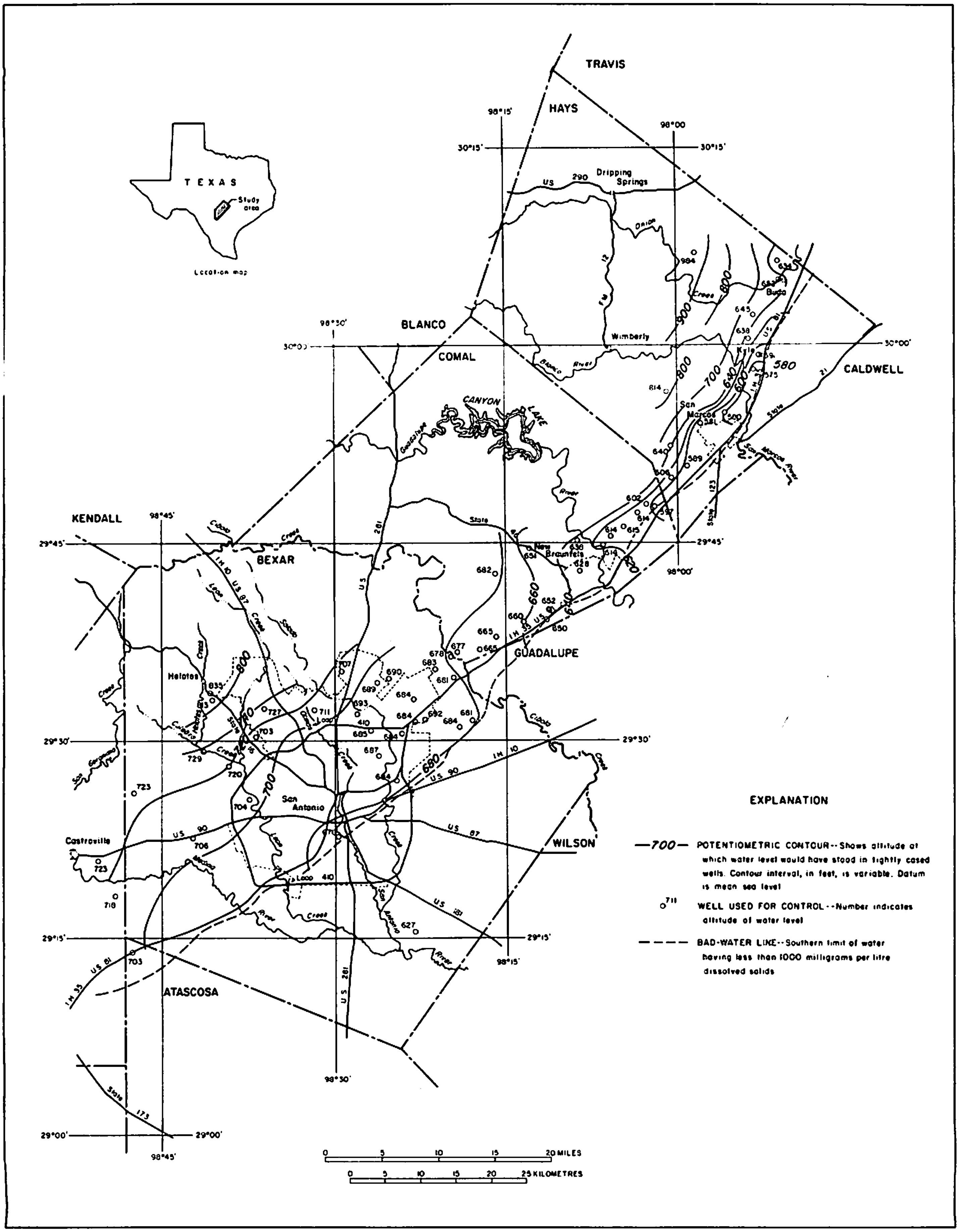
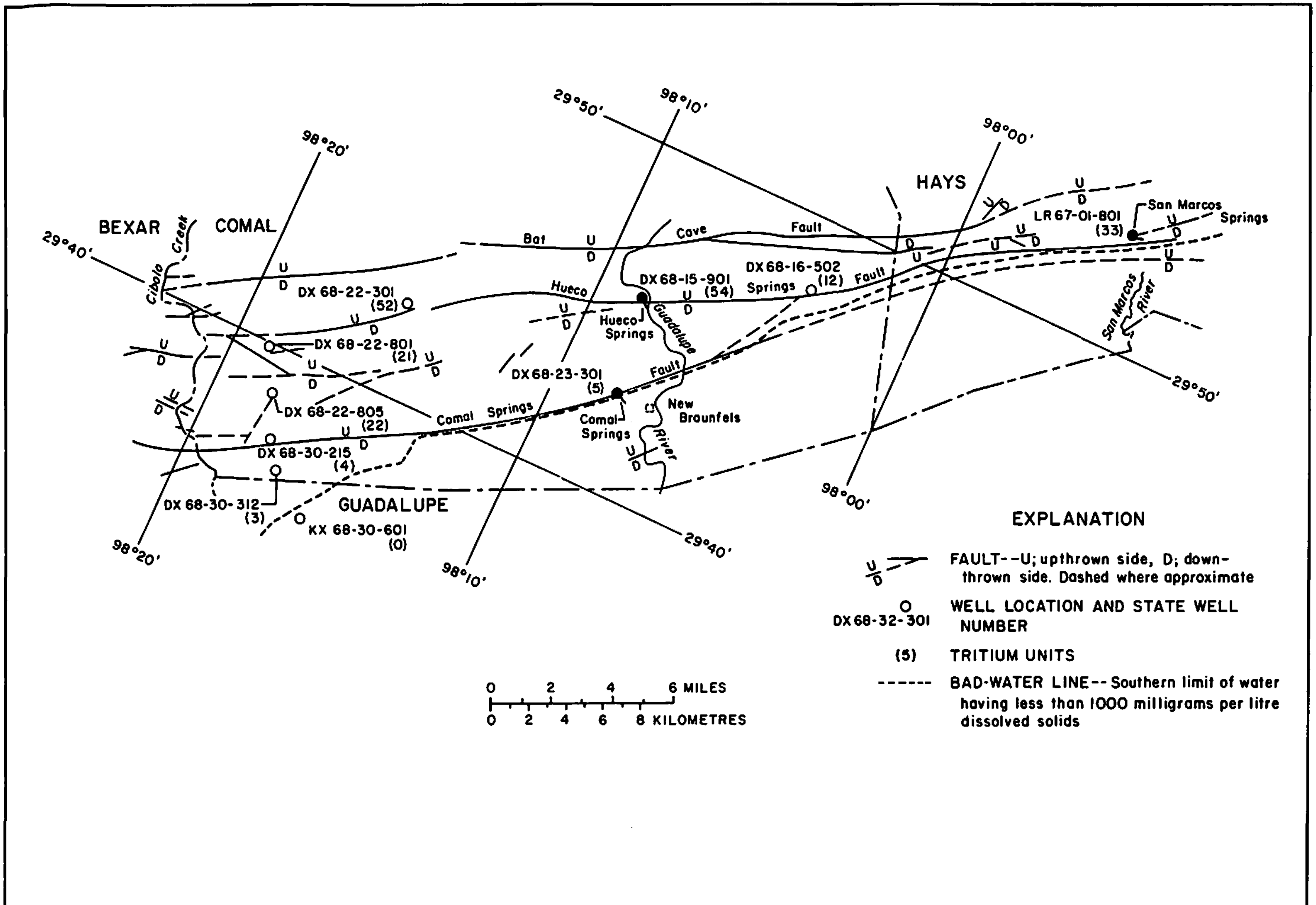


FIGURE 3.-Approximate altitude of the potentiometric surface in the Edwards aquifer, July 1973

Studies of the tritium content of water from the Edwards aquifer by Pearson, Rettman, and Wyerman (1975) give additional information about ground-water movement in the study area. Tritium studies provide a method for determining the relative age of ground water in different geographic areas. Higher tritium concentrations indicate that the water is younger (shorter residence time in the aquifer) than water with lower concentrations.

Because San Marcos Springs is at a lower altitude than Comal Springs, and because a water-budget analysis of the study area (Pearson, Rettman, and Wyerman, 1975, p. 22) indicates that recharge in the immediate vicinity of San Marcos Springs is insufficient to account for more than about 35 percent of its discharge, it would appear that much of the discharge of San Marcos Springs has moved through the artesian part of the Edwards aquifer southwest of San Marcos Springs. The tritium studies indicate, however, that the tritium concentration in water from San Marcos Springs is much higher than the tritium concentration in water from Comal Springs (fig. 4).

The relatively low tritium concentration in water from Comal Springs, which is representative of the concentrations in water in the deeper artesian zone in Bexar County, indicates that the water has had a longer residence time than the water from San Marcos Springs. The tritium studies also show that the tritium concentrations are much greater in water from wells located on and near the Edwards outcrop, north and northeast of Comal Springs. The water from Hueco Springs, which is in the infiltration area in northern Comal County, also has a high concentration of tritium.



(From Pearson, Rettman, Wyerman, 1975)

FIGURE 4.-Locations of faults and concentrations of tritium in water in the Edwards aquifer in the vicinity of Comal and San Marcos Springs

These data indicate that much of the water discharged from Hueco and San Marcos Springs entered the aquifer in northern Comal and Hays Counties. This information suggests that the tritium-bearing ground water in the recharge areas of northern Bexar, Comal, and Hays Counties has not entered the artesian zone (Pearson, Rettman, Wyerman, 1975, p. 22). The water that moves through the artesian zone adjacent to Comal Springs Fault, as it enters Comal County from the southwest, is discharged mostly at Comal Springs. The water that is recharged to the aquifer in northern Bexar and Comal Counties does not mix with water from the deeper artesian part of the Edwards aquifer, but flows to the east in a separate subsystem and is discharged at Hueco Springs and San Marcos Springs.

HYDROLOGIC DATA

Water Levels

The fluctuations of water levels in representative wells in the Edwards aquifer in the study area are shown on figure 5. The locations of the wells are shown on figure 1, and historical water-level data for selected wells are given in table 1.

Water-level fluctuations in wells west of Comal Springs exhibit a pattern similar to that of well DX-68-23-701 (fig. 5). The water levels in these wells show a seasonal response to changes in ground-water pumping and show annual fluctuations that reflect the shifting imbalance between recharge to and discharge from the aquifer.

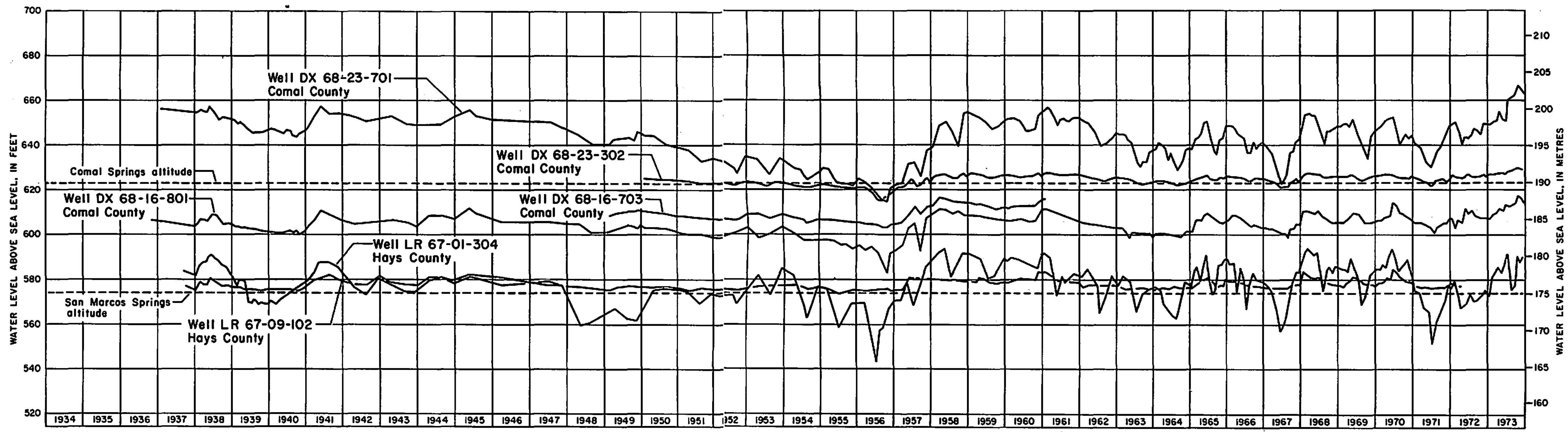


FIGURE 5.-Hydrographs of selected wells in the Edwards aquifer

Table 1.--Water-level records for selected wells in the Edwards aquifer
(Elevations in feet above mean sea level)

Well no.	County	Elevation	Lowest recorded water level	Date	Highest recorded water level	Date	Period of record
AY-68-37-203	Bexar	730.80	612.5	8/17/56	696.5	10/22/73	1934-74
DX-68-23-701	Comal	684.45	614.4	10/ 2/56	666.6	10/29/73	1937-74
DX-68-23-302	Comal	642.70	613.3	9/21/56	629.8	10/26/73	1950-74
DX-68-16-801	Comal	752.71	583.2	10/ 1/56	620.0	12/30/74	1936-74
LR-67-09-102	Hays	696.8	573.9	7/13/55	583.7	10/31/60	1937-74
LR-67-01-304	Hays	718.0	542.2	7/12/56	593.8	3/29/68	1937-74

Well DX-68-23-302 is a water-table well at Landa Park in New Braunfels. The pattern of water-level fluctuations in this well is similar to the patterns in wells west of Comal Springs. The main difference is in the magnitude of the fluctuations because of the proximity of well DX-68-23-302 to Comal Springs. Wells DX-68-16-703, DX-68-16-801, and LR-67-09-102 (fig. 5) are all located between Comal Springs and San Marcos Springs.

All of the wells in the study area respond to regional climatic conditions, but the wells between Comal Springs and San Marcos Springs show water-level fluctuations that differ significantly from the water-level fluctuations in wells west of Comal Springs and east of San Marcos Springs. The water-level fluctuations in the wells between the two springs show dampening effects because of their location relative to Comal and San Marcos Springs and because of local recharge in northern Comal and Hays Counties.

The water-level fluctuations in well LR-67-01-304, east of San Marcos Springs, are similar to the water-level fluctuations in the wells west of Comal Springs. Well LR-67-01-304 responds to seasonal withdrawals and periods of high recharge as well as to the regional climatic conditions of the San Antonio area. Figure 5 shows that the water levels in well LR-67-01-304 are at times at a lower altitude than the altitude of San Marcos Springs. Well LR-67-01-304 is located in an area of low transmissivity in the aquifer. The decline of the water level below the altitude of San Marcos Springs may result from heavy pumping in the Kyle area, a few miles northeast of San Marcos Springs. Periods of higher water levels may result from local recharge.

Springflow

The large springs in the San Antonio area occur along faults that provide natural outlets for the discharge of water from the Edwards aquifer. The principal springs are the Leona River Springs near Uvalde, San Antonio and San Pedro Springs at San Antonio, Comal and Hueco Springs at and near New Braunfels, and San Marcos Springs at San Marcos. In this report, only Comal, Hueco, and San Marcos Springs are examined closely.

Stream-gaging stations were established by the U.S. Geological Survey on the Comal River at New Braunfels in 1927 and on the San Marcos River at San Marcos in 1956. The streamflow at these gaging stations is derived entirely from springflow except during periods of local surface runoff, for which the discharge derived from springflow is estimated by hydrograph-separation techniques. Monthly measurements of the discharge of Hueco Springs are available since 1944. Estimates of the monthly average discharge of Hueco Springs were made on the basis of interpolation between periodic measurements, by use of data from nearby gaging stations, and by use of local precipitation data. Estimates of the monthly average discharge of San Marcos Springs from 1934 to April 1956 were made by interpolating between periodic measurements. Figure 6 shows the hydrographs of Comal, Hueco, and San Marcos Springs from 1934 through 1973.

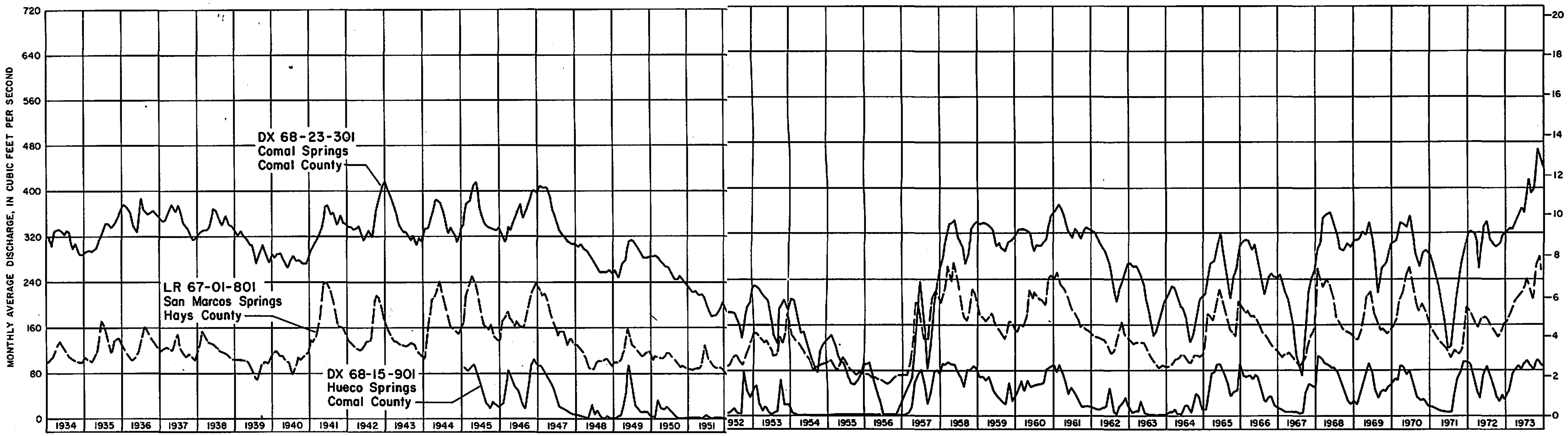


FIGURE 6.-Hydrographs of major springs in the Edwards aquifer

The hydrographs of Comal Springs at New Braunfels and well AY-68-37-203 are shown on figure 7. Well AY-68-37-203, an artesian well near the center of pumping in Bexar County, is representative of wells producing water from the Edwards aquifer west of Comal Springs. The hydrographs of well DX-68-23-701 (fig. 5) and well AY-68-37-203 (fig. 7) show that there is a close correlation between the flow of Comal Springs and the water-level fluctuations in wells west of Comal Springs. Fluctuations in the discharge of Comal Springs appear to reflect changes in pumping rates in the area of heavy pumping in Bexar County. This information is consistent with the observation stated earlier, that most of the discharge of Comal Springs is derived from underflow from the artesian area west of Comal Springs.

The only period of zero flow at Comal Springs occurred from June 13, 1956, to November 4, 1956, during a severe drought and at a time when increased pumping in Bexar County lowered the water levels to the spring's outlet altitude of approximately 623 feet (189.9 m) above mean sea level.

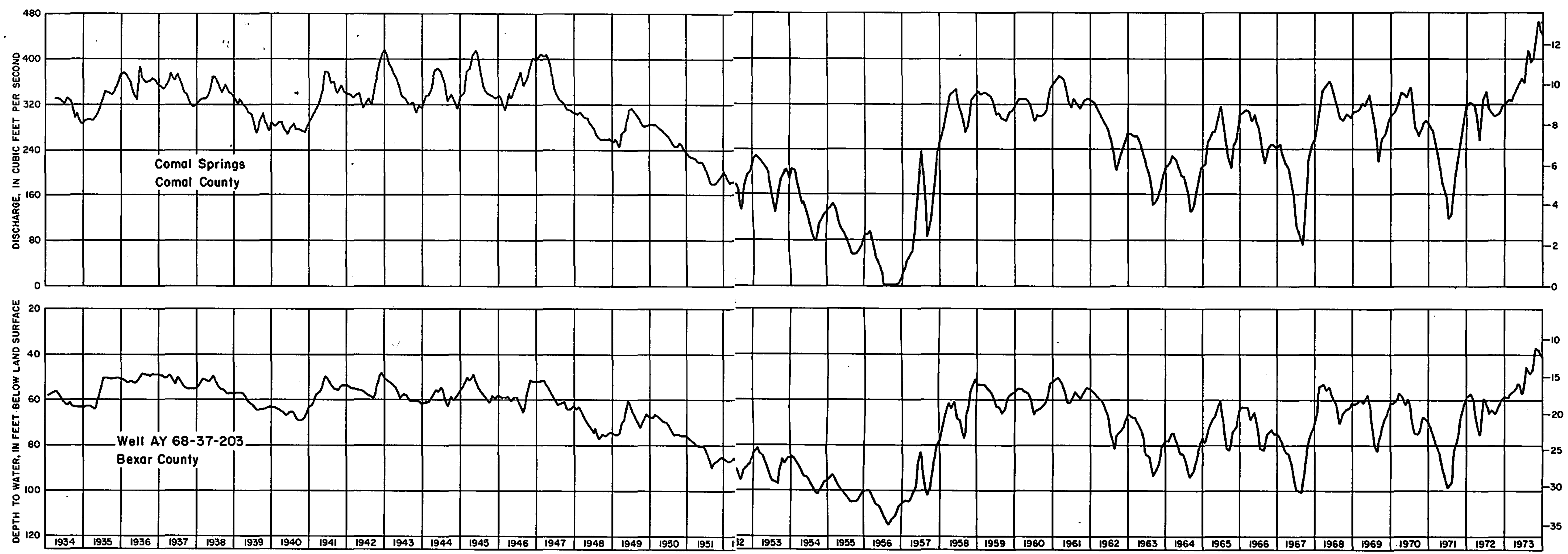


FIGURE 7.-Hydrographs of the monthly average discharge of Comal Springs and the monthly average water level in well AY-68-37-203

Hueco Springs are located approximately 3 miles (4.8 km) north of New Braunfels near the Guadalupe River. The springs issue from two outlets in a faulted zone along the Hueco Springs Fault. The lowest spring outlet is at an altitude of approximately 652 feet (198.7 m) above mean sea level, which is about 29 feet (8.8 m) higher than the outlet of Comal Springs. The hydrographs of Hueco Springs and San Marcos Springs generally show the same trend observed at Comal Springs (fig. 6), but at some times the discharge trends are significantly different.

Previous studies of Hueco Springs (George and others, 1952; Petitt and George, 1956; and Guyton and Associates, 1958) have determined that the recharge area of the springs consists of the drainage basins of Dry Comal Creek and other tributaries to the Guadalupe River north of the Hueco Springs Fault and west of the Guadalupe River. Water-level data (Guyton and Associates, 1958) indicate that recharge supplying Hueco Springs does not occur in the areas east of the Guadalupe River and south of the Hueco Springs Fault because the water-level altitudes in these areas are below the altitude of the springs. Water levels in the area northwest of Hueco Springs show a hydraulic gradient that is sufficient to provide water to the springs.

The water-level fluctuations in wells just north of the Hueco Springs Fault correlate best with the fluctuations in the discharge of Hueco Springs, and several characteristics of the springs indicate that the recharge area is relatively small. The springs exhibit rapidly rising flows for short periods after heavy rains in the vicinity, and the temperature of the water is not constant as it is at Comal Springs, but has been observed to vary by as much as several degrees. The tritium concentration in the water from Hueco Springs is very high, which indicates that the water was recently recharged to the aquifer. Figure 6 shows that Hueco Springs frequently go dry for periods of several months during cycles of low precipitation in the area.

San Marcos Springs discharges at an altitude of about 574 feet (175.0 m) above mean sea level or about 49 feet (14.9 m) lower than the altitude of Comal Springs at New Braunfels. The springs occur in the vicinity of the San Marcos Springs Fault where it converges with the Comal Springs Fault.

The similarity in the fluctuations of the discharge of San Marcos Springs and Hueco Springs indicates that a significant part of the spring-flow is derived from water that enters the aquifer in Comal and Hays Counties north of the Hueco Springs Fault. The hydrographs of water levels in wells east of Comal Springs, except for well LR-67-01-304, and the discharge of San Marcos Springs show similar patterns of fluctuations, which indicate that the wells and the springs are in hydraulic continuity and reflect the occurrence of recharge in the area between Comal Springs and San Marcos Springs.

From October 1955 to February 1957, the pattern of water-level fluctuations in well DX-68-23-302 at Landa Park in New Braunfels and the variation in springflow at San Marcos Springs were very similar (figs. 5 and 6). This was a period of severe drought when Hueco and Comal Springs recorded little or no flow and the streams in the study area provided little or no recharge to the Edwards aquifer. During this period, the monthly average springflow at San Marcos Springs was sustained at about 60 ft^3/s (1.7 m^3/s) by underflow from the artesian part of the aquifer to the west.

These data indicate that the water discharged at San Marcos Springs is derived from two sources: (1) Regional underflow from the Comal Springs area and (2) local recharge from northern Comal and Hays Counties. During periods of normal and above-normal recharge in the area, the discharge of San Marcos Springs is composed of both underflow and local recharge, and the fluctuations in the discharge will differ significantly from the fluctuations in the discharge of Comal Springs because of the effects of local recharge.

Table 2 contains information regarding the geologic setting and discharge characteristics of San Marcos, Hueco, and Comal Springs.

Table 2.--Characteristics of springs in the Edwards aquifer

Name of spring	Geologic setting	Period of record	Discharge Maximum (ft^3/s)	Discharge Minimum (ft^3/s)	Discharge Mean (ft^3/s)
Comal Springs (Altitude of springs about 623 feet.)	Issues from a large number of solution cavities in a distance of 1,500 feet along the Comal Springs Fault. Springs form the headwaters of the Comal River.	1882 to 1974. 1882 to Nov. 1927, discharge measurement only.	534 (Oct. 16, 1973)	0 (June 13 to Nov. 4, 1956)	281 (1928-74)
San Marcos Springs (Altitude of springs about 574 feet.)	Issues from five large fissures and numerous small solution openings along the San Marcos Springs Fault. Springs form large pools that are the headwaters of the San Marcos River.	May 1956 to 1974. Periodic measurements of springflow since Nov. 14, 1894 to May 1956.	310 (Oct. 17-20, 1973)	46 (Aug. 15, 16, 1956)	161 (1956-74)
Hueco Springs (Altitude of springs about 652 feet.)	Issues from two major outlets of different altitudes in stream gravels overlying the Hueco Springs Fault. Springs discharge into the Guadalupe River.	Measured 8-31-24, 10-8-37; monthly periodic discharge measurements from Aug. 4, 1944, to 1974.	131 (Jan. 21, 1968)	0 (No flow measurements in 1948-57, 1963, 1964, 1967.)	36.6 (1944-74)

Streamflow

The major streams draining the Edwards Plateau in the study area are Cibolo Creek, Dry Comal Creek, the Guadalupe River, and the Blanco River (table 3). Except for Dry Comal Creek, these streams are monitored by continuous stream-gaging stations established by the U.S. Geological Survey (fig. 1). These streams and their tributaries, except the Guadalupe River, provide recharge to the Edwards aquifer in the study area.

Figure 8 shows a hydrograph of the monthly average discharge of the Blanco River at Wimberley, Texas, from 1934 to 1973. This stream is representative of the streams draining the Edwards Plateau in the study area because it has a large drainage basin and its perennial flow is relatively free of manmade diversions and obstructions before it flows across the infiltration area of the Edwards aquifer.

Figures 6 and 8 show that there is a high degree of correlation among the discharge fluctuations of Hueco Springs, San Marcos Springs, and the Blanco River. The occurrence of flow peaks and discharge recessions correspond closely. This suggests that discharge records for the Blanco River at Wimberley may serve as an index to the recharge occurring in northern Hays and Comal Counties.

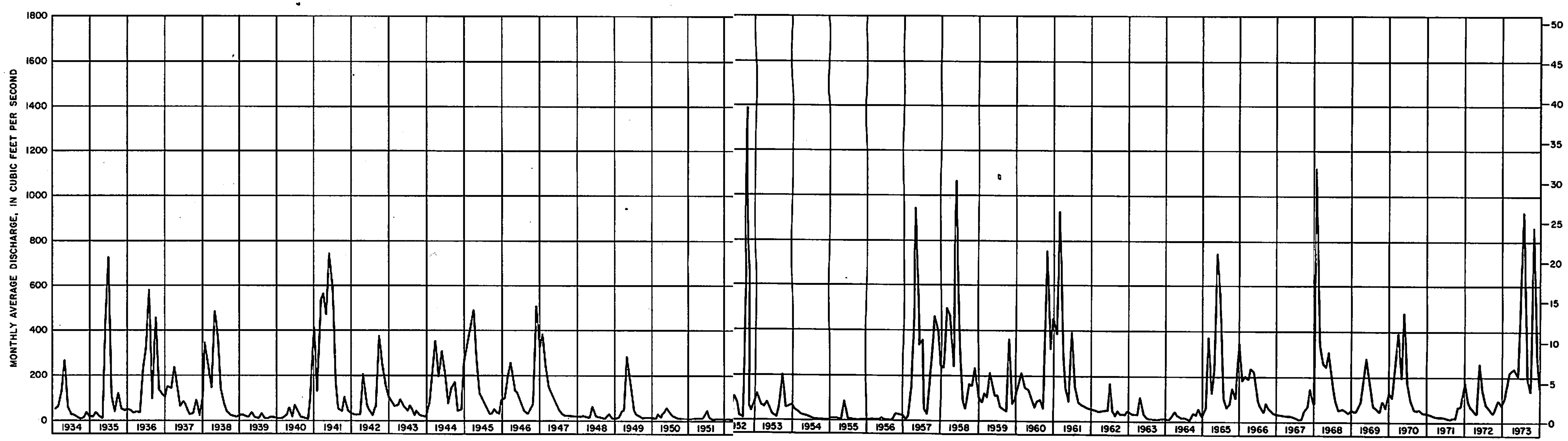


FIGURE 8.-Hydrograph of monthly average discharge of the Blanco River at Wimberley, Texas

Table 3.--Characteristics of major streams in the area of the Edwards aquifer

Streamflow station	Geologic setting	Period of record	Discharge		
			Maximum (ft^3/s)	Minimum (ft^3/s)	Mean (ft^3/s)
Cibolo Creek near Boerne, Tex.	Drainage area is 68.4 square miles in the Edwards Plateau catchment area. Approximately 25.0 miles of the creek's course is over the infiltration area of the Edwards aquifer. Major faults intersected in the infiltration area include the Bat Cave Fault and Hueco Springs Fault. The Cibolo Creek basin contributed about 1.339 x 10^6 acre-feet of recharge to the Edwards aquifer from 1954 to 1973.	Mar. 1962 to 1974	36,400 (Sept. 27, 1974)	0 (1962-64, 1966-67, 1971)	26.1
Guadalupe River near Spring Branch, Texas	Drainage area is 1,315 square miles in the Edwards Plateau catchment area. Approximately 6.0 miles of the river's course is over the infiltration area of the Edwards aquifer. Major faults intersected in the infiltration area include the Bat Cave Fault, Hueco Springs Fault, and Comal Springs Fault. No significant amount of recharge to the Edwards aquifer is contributed by the Guadalupe River.	June 1922 to 1974	121,000 (July 3, 1932)	0 (1951-52, 1954-56, 1963-64)	276
Blanco River at Wimberley, Tex.	Drainage area is 364 square miles in the Edwards Plateau catchment area. Approximately 4.0 miles of the river's course is over the infiltration area of the Edwards aquifer. Major faults intersected in the infiltration area include the Hidden Valley Fault and the Mustang Fault. The Blanco River basin contributed about 3.833 x 10^5 acre-feet of recharge to the Edwards aquifer from 1954 to 1973.	Aug. 1924 to Sept. 1926. June 1928 to 1974.	113,000 (May 28, 1929)	.6 (Aug. 16, 1956)	116

REGRESSION ANALYSES OF HYDROLOGIC DATA

Simple Linear Regression

Quantitative expressions of the relationships between the hydrologic variables were determined by simple linear-regression analyses. Regression analysis defines the relation between a set of independent and dependent variables. The end product of the analysis is a regression equation that may be used to estimate values of a dependent variable when values of the independent variable are known (Riggs, 1968, p. 6).

The simple linear equation used in this regression analysis is

$$Y = A + BX$$

where Y is the dependent variable,

X is the independent variable,

A is a regression constant representing the value of Y when X is equal to zero, and

B is the regression coefficient representing the increase of Y per unit change of X.

Regression equations expressing the relationships between water levels in selected wells and the relationship between water levels and springflow are given in table 4. The correlation coefficient (R), the standard error of estimate (S.E.), the range of the data base, and the number of data observations for each regression (n) are given for each equation.

The correlation coefficient (R) is a measure of the degree of association between the dependent variable Y and the independent variable X. A perfect relationship between two variables would have a correlation coefficient value of 1.0. Equations expressing hydrologic relationships that have a correlation coefficient greater than or equal to 0.80 are considered to be very significant.

Table 4.--Simple linear regression equations, correlation coefficients, and standard errors of estimate of water-level and springflow relationships for the Edwards aquifer

Water level vs. water level (datum is feet below land surface)

Equation no.	Equation	R	S.E. 1/ (feet)	Time period	Range of "X" (feet	Range of "Y" (feet)	Y variable	X variable	N
1	Y = 8.46 + 0.13X	0.9902	0.22	Monthly mean	(36.9 - 104.8)	(13.0 - 22.6)	Y = Water level at DX-68-23-302	X = Water level at AY-68-37-203	81
2	Y = -3.50 + 0.15X	.9943	.14	Monthly mean	(130.6 - 170.5)	(15.8 - 22.1)	Y = Water level at DX-68-23-302	X = Water level at DX-68-30-208	48
3	Y = -7.39 + 0.18X	.9810	.41	Annual mean	(126.4 - 175.5)	(13.9 - 24.1)	Y = Water level at DX-68-23-302	X = Water level at DX-68-30-208	18
4	Y = 86.32 + 0.83X	.9988	.57	Annual mean	(48.9 - 107.7)	(126.4 - 175.5)	Y = Water level at DX-68-30-208	X = Water level at AY-68-37-203	18
5	Y = 222.7 + 0.67X	.9658	1.81	Annual mean	(48.9 - 85.7)	(252.8 - 279.7)	Y = Water level at AY-68-29-103	X = Water level at AY-68-37-203	16
6	Y = -64.35 + 0.73X	.9920	.97	Daily	(130.6 - 171.3)	(30.4 - 62.5)	Y = Water level at DX-68-23-701	X = Water level at DX-68-30-208	27
7	Y = -48.20 + 4.97X	.9910	1.01	Daily	(15.9 - 22.3)	(30.4 - 62.5)	Y = Water level at DX-68-23-701	X = Water level at DX-68-23-302	28
8	Y = 41.04 + 5.35X	.9530	2.52	Daily	(15.9 - 22.3)	(125.4 - 161.4)	Y = Water level at LR-67-01-304	X = Water level at DX-68-23-302	35
9	Y = 39.76 + 0.54X	.9606	.47	Daily	(142.3 - 153.8)	(114.6 - 121.0)	Y = Water level at LR-67-09-102	X = Water level at DX-68-16-801	30
10	Y = 54.19 + 0.87X	.9814	.27	Daily	(113.5 - 121.0)	(152.5 - 159.1)	Y = Water level at LR-67-01-701	X = Water level at LR-67-09-102	30

Springflow (ft^3/s) vs. water level (feet below land surface)

Equation no.	Equation	R	S.E. 1/ (ft^3/s)	S.E. 2/ (percent)	Time period	Range of "X" (feet)	Range of "Y" (feet)	Y variable	X variable	N
11	Y = 1,065.0 - 44.4X	0.9943	7.1	3	Daily	(15.9 - 22.3)	(30.9 - 385)	Y = Comal Springflow (DX-68-23-301)	X = Water level at DX-68-23-302	33
12	Y = 1,038.3 - 43.5X	.9963	10.0	4	Monthly mean	(13.7 - 22.6)	(87 - 272)	Y = Comal Springflow (DX-68-23-301)	X = Water level at DX-68-23-302	83
13	Y = 677.0 - 5.8X	.9923	14.8	6	Monthly mean	(36.9 - 104.5)	(87 - 247	Y = Comal Springflow (DX-68-23-301)	X = Water level at AY-68-37-203	81
14	Y = 655.4 - 5.5X	.9909	11.3	5	Annual mean	(48.9 - 107.7)	(87 - 272)	Y = Comal Springflow (DX-68-23-301)	X = Water level at AY-68-37-203	24
15	Y = 3,234.5 - 26.0X	.9878	7.7	5	Daily	(113.5 - 121.0)	(64 - 350)	Y = San Marcos Springflow (LR-67-01-801)	X = Water level at LR-67-09-102	30
16	Y = 2,266.7 - 14.4X	.9503	13.6	9	Daily	(142.3 - 153.8)	(54.9 - 429)	Y = San Marcos Springflow (LR-67-01-801)	X = Water level at DX-68-16-801	31
17	Y = 4,631.5 - 28.5X	.9591	11.8	8	Daily	(152.5 - 159.1)	(54.9 - 467)	Y = San Marcos Springflow (LR-67-01-801)	X = Water level at LR-67-01-701	30

1/ Standard error expressed in terms of dependent variable units.
2/ Standard error expressed in terms of percent of mean of dependent variable.

The standard error of estimate, which is a measure of the reliability of an equation, can also be used to determine the reliability of the estimates of the dependent variable made from the regression equation (Riggs, 1968, p. 15). It is a measure of the variation or scatter of points about the line of regression and may be expressed in the same units as the dependent variable, Y, or as a percentage of the mean of the dependent variable. About 68 percent of the data points will plot within ± 1 standard error of estimate if they are normally distributed about the line of regression. The validity of the equations applies to the range of the data base. If the equations are extended beyond this range, the estimates are subject to large errors. Equations 1-3, 7, and 8 (table 4) are not valid when water-level values at well DX-68-23-302 equal or exceed 24 feet (7.3 m) below land surface. At this depth, Comal Springs ceases to flow, thereby removing the spring's stabilizing effect on well DX-68-23-302. This results in greater water-level fluctuations that are not representative of those used in the development of the equations.

Figures 9-12 show the linear relationships between the variables in equations 1, 12, 13, and 15 (table 4). Because of the very high correlation coefficients and low standard errors of estimate as listed in table 4, it appears that the simple linear-regression technique provided regression equations with excellent accuracy for estimating water levels and springflow by using only water-level data.

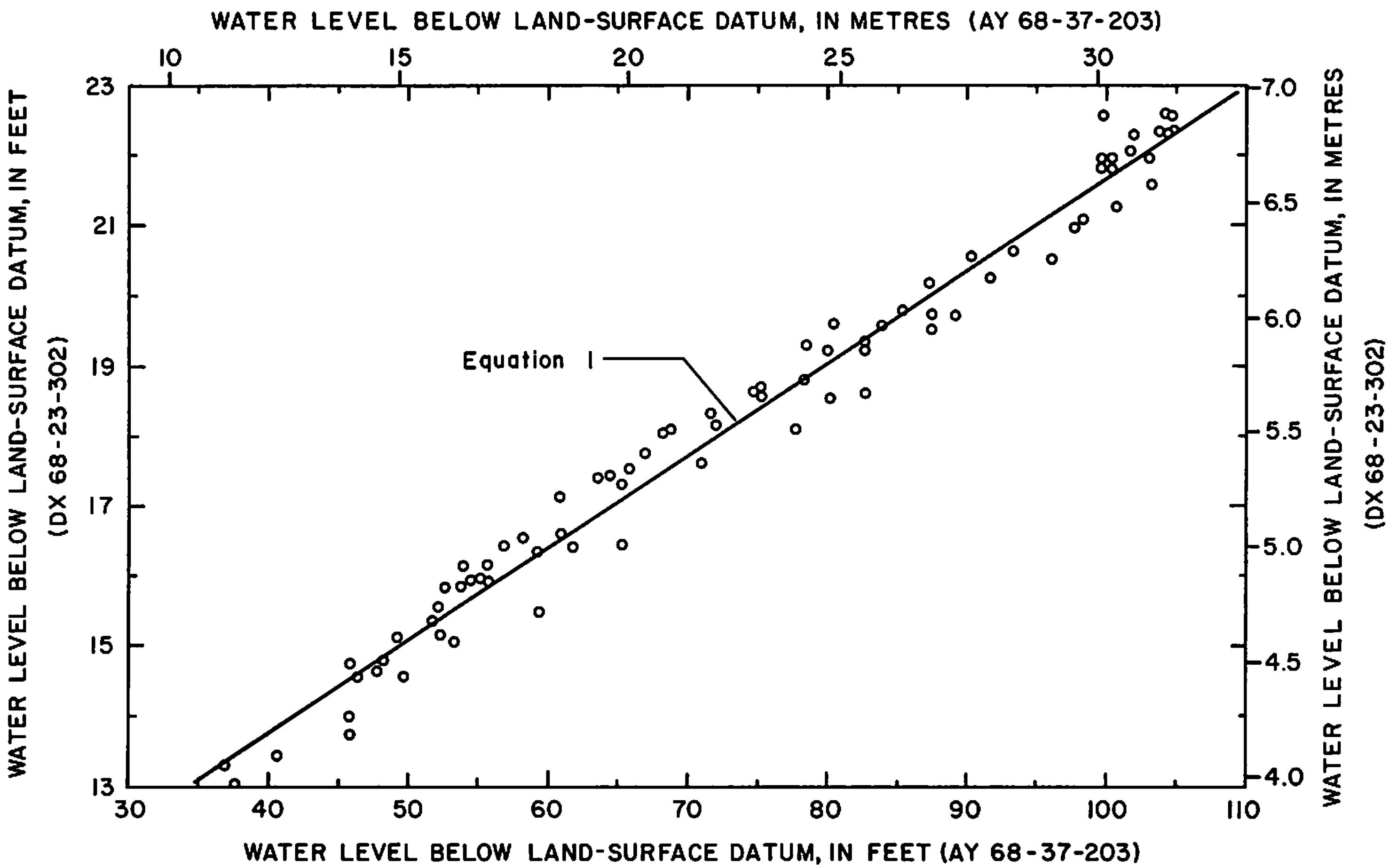


FIGURE 9.-Relationship between monthly average water levels in wells AY-68-37-203 and DX-68-23-302

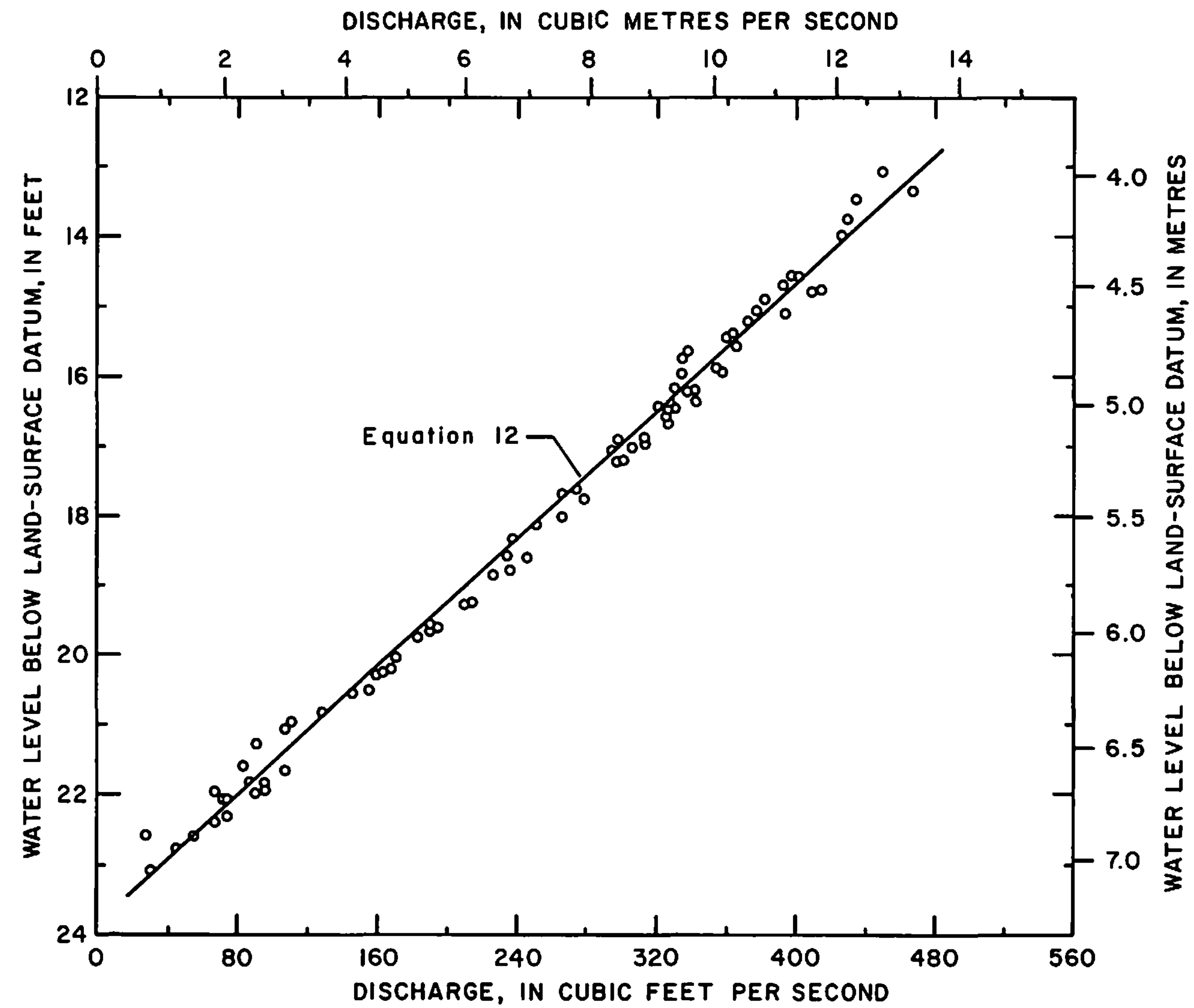


FIGURE 10.-Relationship between the monthly average flow of Comal Springs and the monthly average water level in well DX-68-23-302

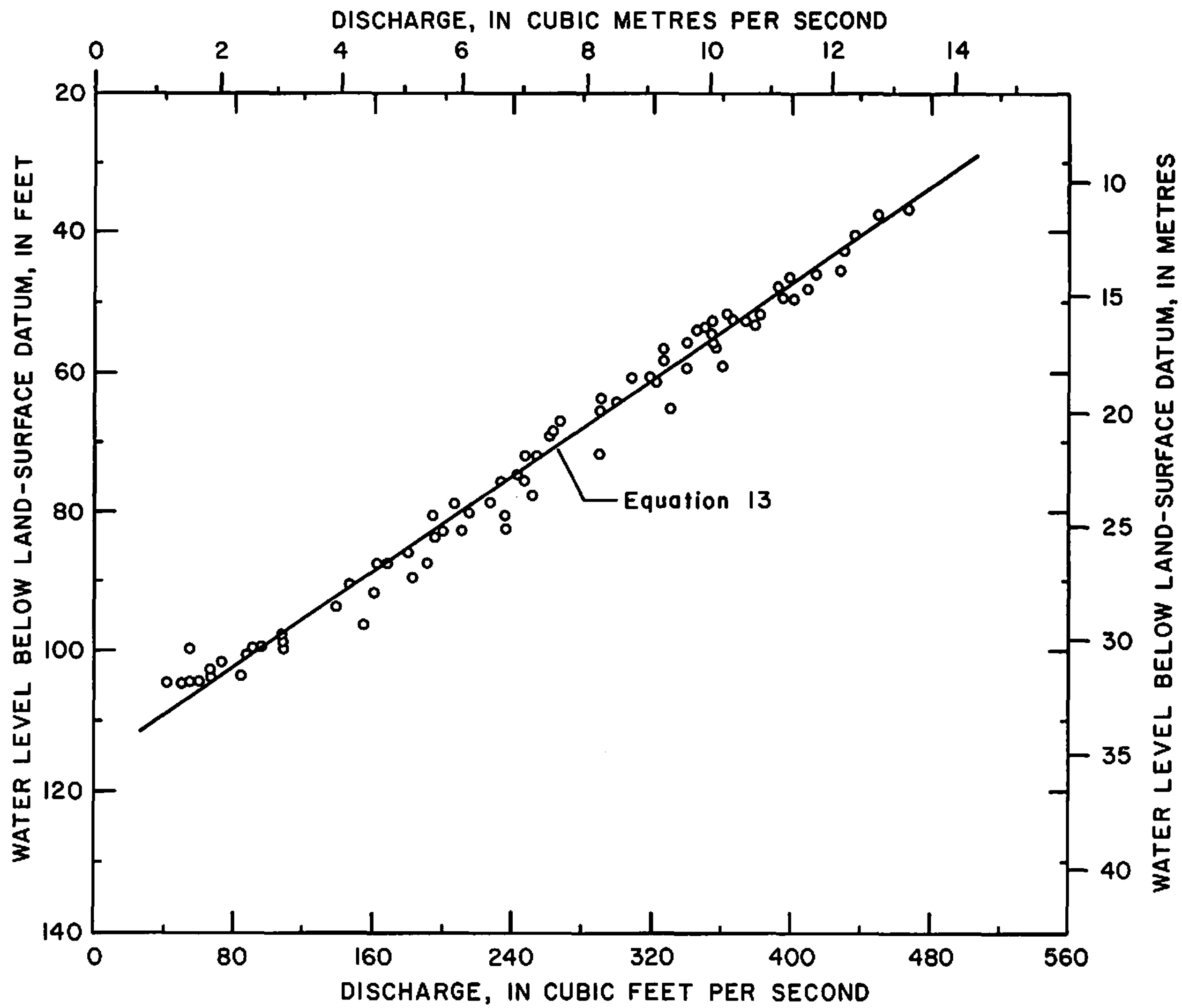


FIGURE 11.-Relationship between the monthly average flow of Comal Springs and the monthly average water level in well AY-68-37-203

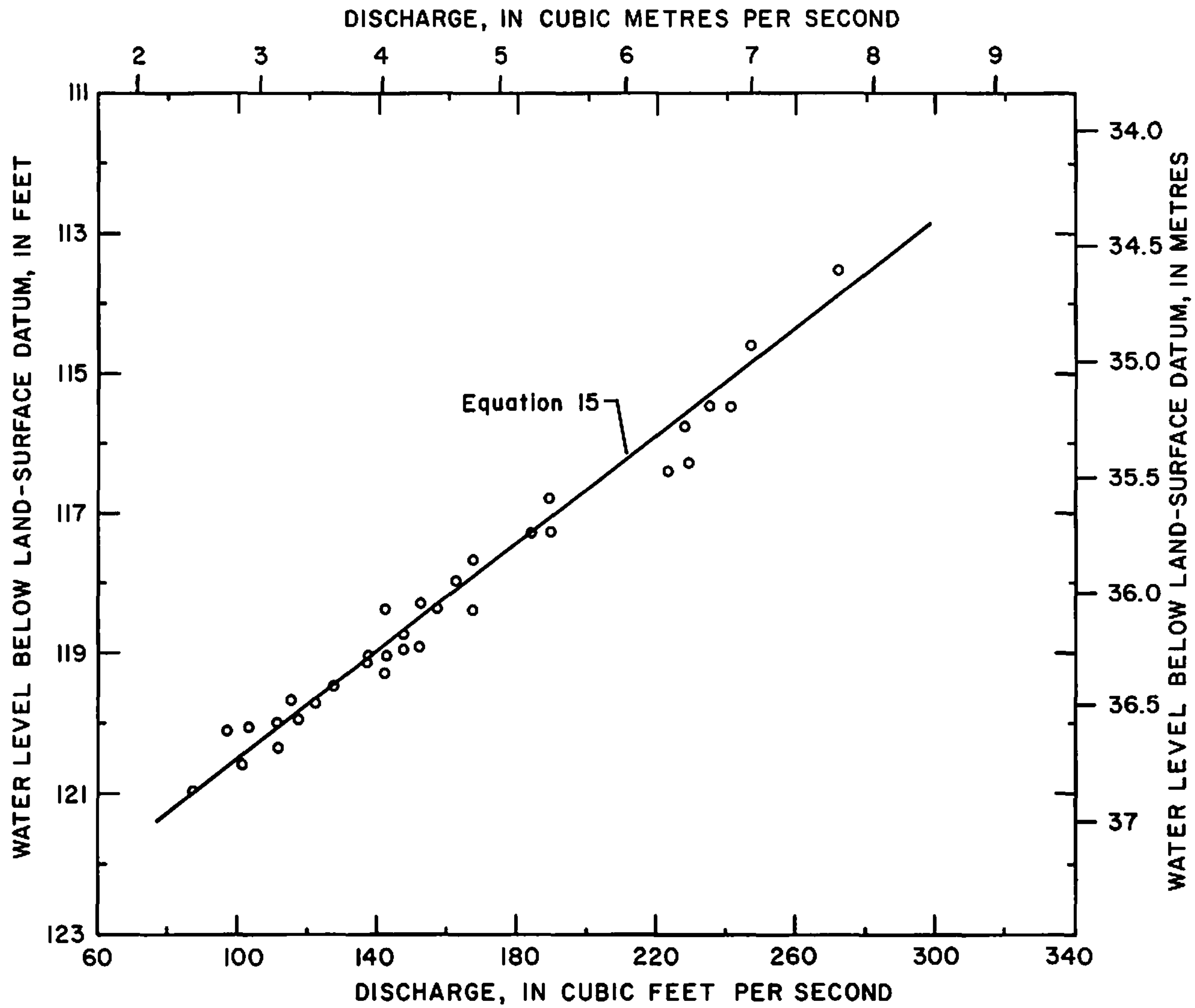


FIGURE 12.-Relationship between the daily average flow of San Marcos Springs and the daily average water level in well LR-67-09-102

Equations 11 through 14 (table 4) relate water-level data from wells in San Antonio and New Braunfels to the discharge of Comal Springs on a daily, monthly, and annual basis. The high degree of correlation shown by the graphs on figures 5 and 6 and the results of the regression analysis indicate a very good hydraulic continuity between Comal Springs and the artesian area of the Edwards aquifer southwest of Comal Springs. Although only a few wells were used to establish the relationship, the analysis indicates that other relationships between water levels in wells and the discharge of Comal Springs can be established by using simple linear-regression analysis. Comparisons between the observed and computed discharge of Comal Springs, on a monthly average and annual average basis are shown on figures 13 and 14. The computed springflow values were obtained from equations 13 and 14 (table 4).

Equations 15 through 17 (table 4) relate water-level data from wells east of Comal Springs and in the vicinity of the city of San Marcos to the discharge of San Marcos Springs. The high correlations observed between water-level fluctuations in wells east of Comal Springs (fig. 5) and the fluctuations in springflow at San Marcos Springs (fig. 6) also indicate that there is good hydraulic continuity between wells in this area and San Marcos Springs. Equations 15 through 17 can be used to estimate the daily discharge of San Marcos Springs with a high degree of accuracy.

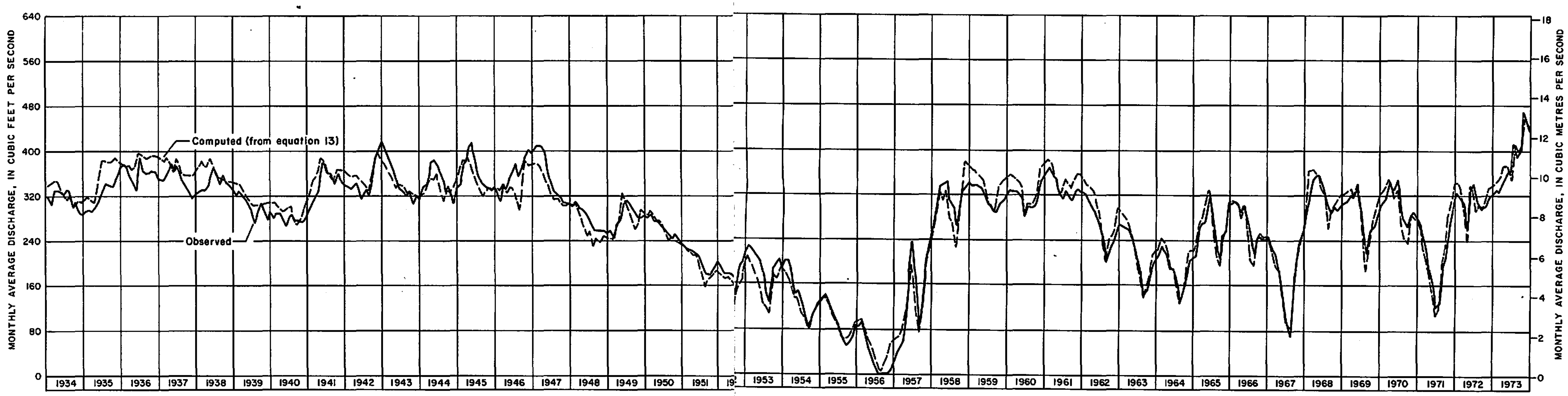


FIGURE 13.-Comparison of observed and computed monthly average discharge of Comal Springs

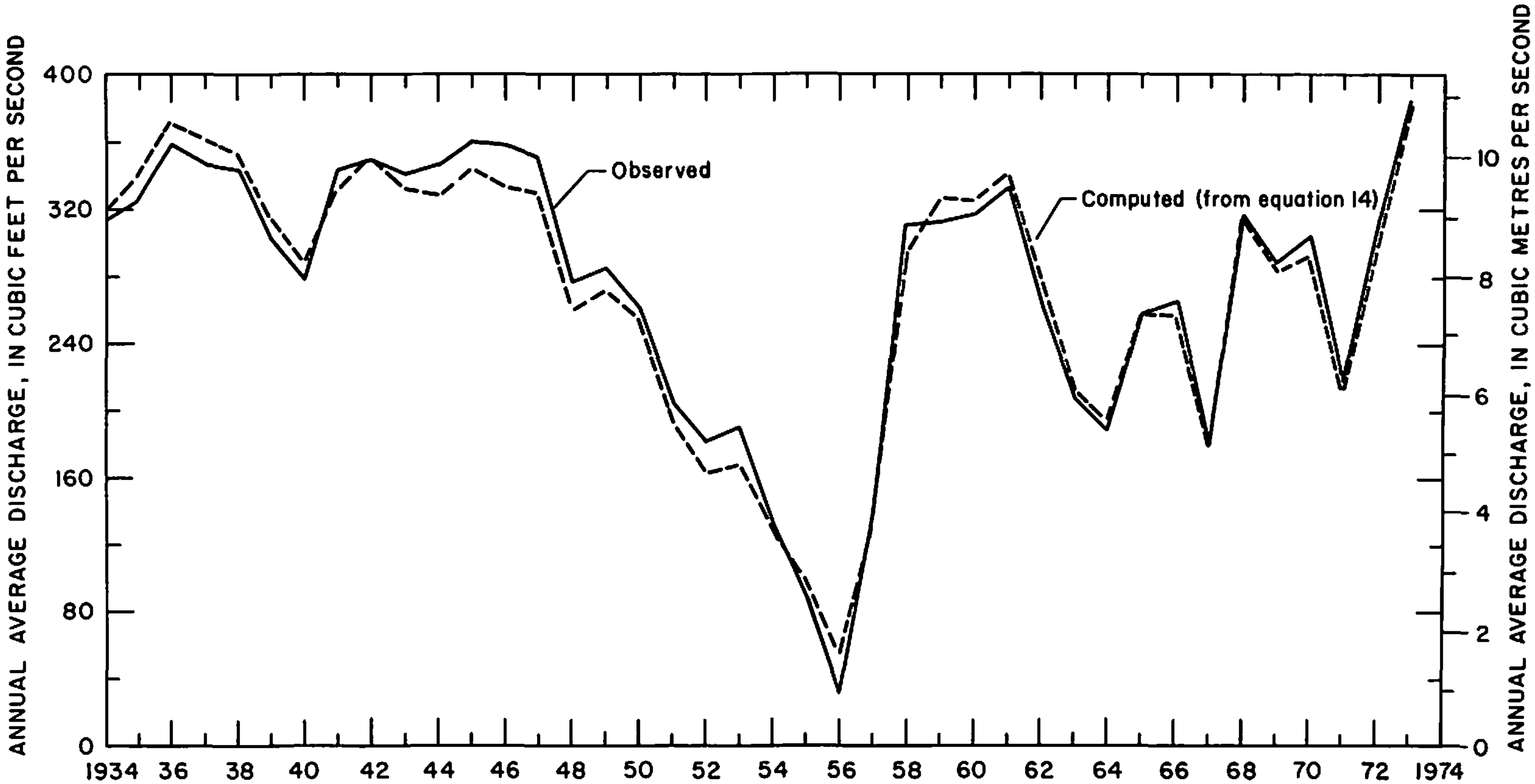


FIGURE 14.-Comparison of observed and computed annual average discharge of Comal Springs

Multiple Linear Regression

Simple linear regression was not attempted in the Hueco Springs analysis because sufficient data (independent-variable parameter) in the Hueco Springs recharge area were not available.

Multiple linear-regression analysis was used to develop equations for estimating springflow at Hueco Springs. In multiple linear-regression analysis, several independent variables and one dependent variable are used instead of one independent variable and one dependent variable, as in simple linear regression. In the analysis of Hueco Springs, the monthly average discharge of the Blanco River and water levels in a well at Landa Park in New Braunfels were used as the independent variables. The discharge of Hueco Springs was used as the dependent variable.

Because recharge occurs after moderate or heavy rainfall in the area, the precipitation records for the area should exhibit good correlation with the discharge records of Hueco Springs. Precipitation was considered as an independent variable to be used in the regression analysis; however, it was rejected because not enough data were available.

The monthly average discharge of the Blanco River at Wimberley, Texas, was selected an an independent variable because the discharge is representative of runoff from the Edwards Plateau and serves as an index to the recharge. Because the fluctuations in the discharge of Hueco Springs exhibit the same general trends as exhibited at Comal Springs, the water-level records of well DX-68-23-302 at Landa Park in New Braunfels were also used as an independent variable in the regression analysis.

The regression equation developed for estimating the monthly discharge of Hueco Springs is:

(18.) $HS(Q) = 41.54 - 4.60\ LP(W/L) + 46.77\ \text{Log}_{10}\ (BLAN(Q))$; if $HS(Q) \leq 0$ then set $HS(Q) = 0.0$

where HS(Q) is the monthly average discharge of Hueco Springs in ft^3/s (m^3/s);

LP(W/L) is the monthly average water level in well DX-68-23-302 in feet (m) below land surface; and

BLAN(Q) is the monthly average discharge of the Blanco River at Wimberley, in ft^3/s (m^3/s).

The correlation coefficient (R) is 0.8707 and the standard error of estimate is 14.93 ft^3/s (0.423 m^3/s), or 31 percent of the mean.

Figures 15 and 16 show comparisons of the observed and computed discharge of Hueco Springs on a monthly and annual basis. The annual discharges shown on figure 16 were obtained by averaging the monthly values.

Equations 15 through 17 (table 4) are useful for estimating the daily discharge of San Marcos Springs; however, they cannot be used for estimating the monthly average discharge of San Marcos Springs and are not useful for determination of the individual components (regional underflow and local recharge) that compose the total springflow.

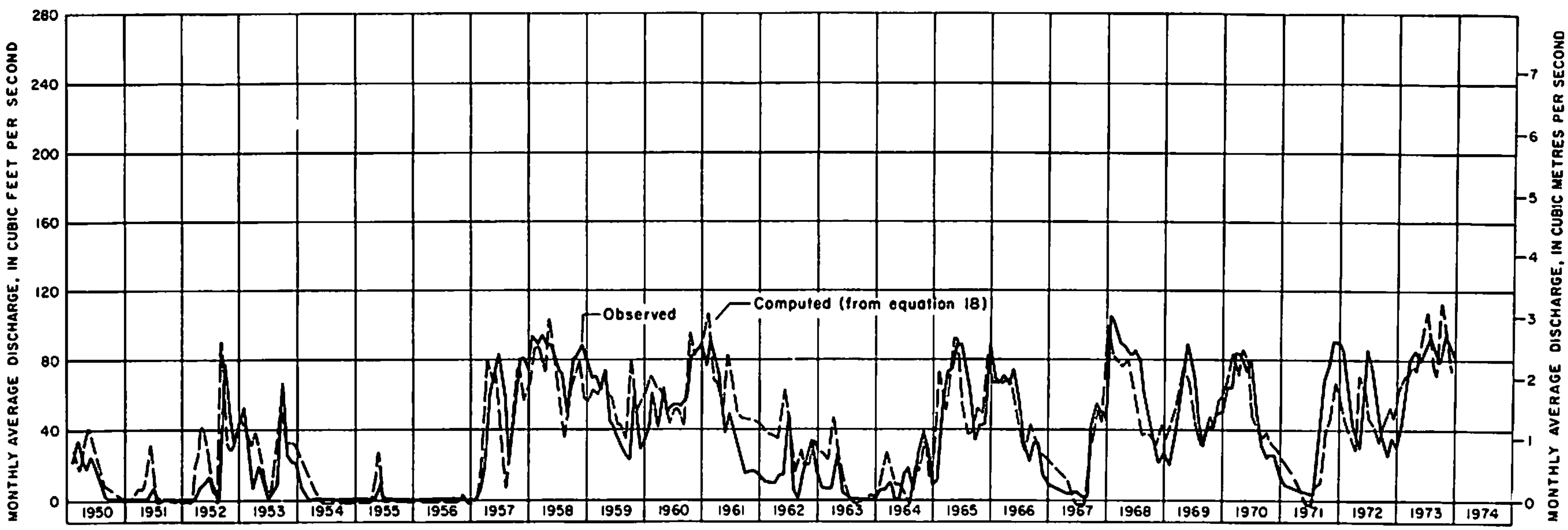


FIGURE 15.-Comparison of observed and computed monthly average discharge of Hueco Springs

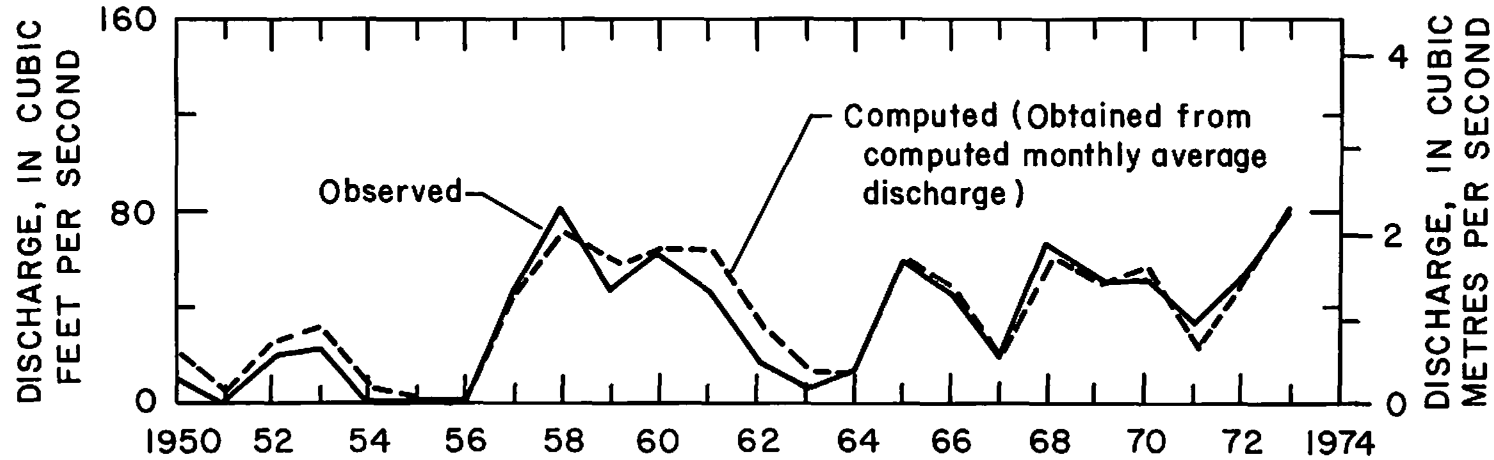


FIGURE 16.-Comparison of observed and computed annual average discharge of Hueco Springs

A method for estimating the monthly average discharge of San Marcos Springs was developed by writing regression equations for each component of the total springflow. Stated mathematically, the equation for the discharge of San Marcos Springs becomes:

$$SMQT = SMQ1 + SMQ2 \quad (19.)$$

where SMQT is the total monthly average springflow;

SMQ1 is the component of underflow from the Comal Springs area; and

SMQ2 is the component of local recharge in northern Comal and Hays Counties.

It was noted earlier that during the severe drought of October 1955 through February 1957, Hueco Springs and Comal Springs recorded little or no flow. The Blanco River and other rivers and creeks in the area also recorded little or no flow, and precipitation in the area was far below normal. The water levels in wells LR-67-01-701 and LR-67-01-304 were generally at or below the outlet altitude of San Marcos Springs while the water levels in wells southwest of the springs were well above the outlet altitude of the springs.

The low flow in the Blanco River and other gaged and ungaged streams in the area, the below normal rainfall, and the water-level data all indicate that the local-recharge component was very small (SMQ2 $\cong$ 0.0) and that the discharge of San Marcos Springs during this period was sustained mainly by underflow (SMQT $\cong$ SMQ1) from the artesian area southwest of San Marcos Springs. During this period, the water-level fluctuations in well DX-68-23-302 at Landa Park in New Braunfels and the fluctuations in the discharge of San Marcos Springs were very similar. The monthly water-level data for well DX-68-23-302 were plotted against the corresponding springflow data. Figure 17 shows this relationship at a time when nearly all of the water discharged at San Marcos Springs was derived from regional underflow.

Simple linear-regression analysis was applied to the plot to determine the relation between SMQ1 (dependent variable) and LP(W/L) (independent variable). The resultant regression equation is:

(20.) $$SMQ1 = 223.25e^{-0.05\ LP(W/L)}$$

where SMQ1 = the underflow component in ft^3/s (m^3/s),

LP(W/L) = the monthly average water level at well DX-68-23-302 in feet (m) below land surface, and

e = 2.71828.

The data range of LP(W/L) is from 18.5 to 28 feet (5.64 to 8.53 m). The correlation coefficient is 0.9436, and the standard error of estimate is 3.12 ft^3/s (0.09 m^3/s), or 4 percent of the mean.

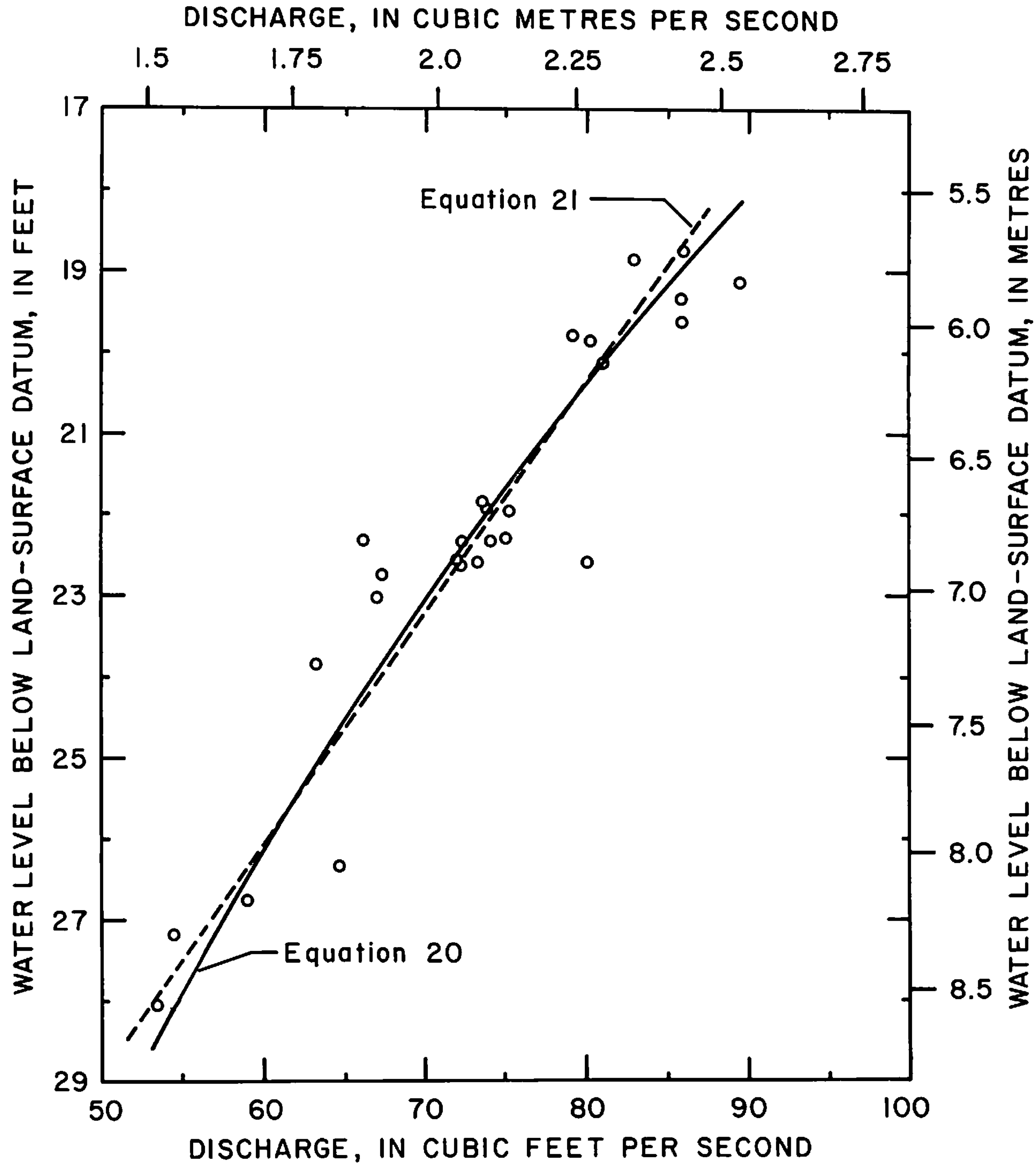


FIGURE 17.-Relationship between the monthly average water level in well DX-68-23-302 and the monthly average discharge of regional underflow at San Marcos Springs for the period October 1955-February 1957

A second regression equation (21.) of the linear form was also developed for the relationship between SMQ1 and LP(W/L):

(21.) $$SMQ1 = 152.10 - 3.53\ LP(W/L)$$

The data range of LP(W/L) in equation 21 is the same as in equation 20. The correlation coefficient is 0.9399, and the standard error of estimate is 3.16 ft^3/s (0.09 m^3/s) or 4 percent of the mean. Within the data range of LP(W/L), both equations 20 and 21 yield very good estimates of the underflow component of San Marcos Springs (SMQ1); however, equation 20 is accepted as the valid equation for defining the relationship between SMQ1 and LP(W/L) because it provides better springflow estimates and provides values approaching zero flow when water levels are extrapolated to the outlet altitude of the springs. The validity of these equations apply only to the range of the data base. If the equations are extended beyond this range, the estimates are subject to large errors.

Although the estimates of SMQ1 obtained by using values of LP(W/L) beyond the data base may not be valid, it is interesting to note the results after extrapolating SMQ1 values to zero flow. Equation 20 yields extrapolated values of SMQ1 that approach zero flow when values of LP(W/L) are extrapolated to the altitude of the outlet of San Marcos Springs. Equation 21 yields zero flow for SMQ1 when the values of LP(W/L) reach 43 feet (13.1 m). A depth of 43 feet (13.1 m) at well DX-68-23-302 corresponds to a depth of approximately 23 feet (7.0 m) below the outlet of Comal Springs and approximately 26 feet (7.9 m) above the outlet of San Marcos Springs. Equation 21 shows that SMQ1 is at zero when the water levels in the New Braunfels area show a head difference of 26 feet (7.9 m) with the altitude of the outlet of San Marcos Springs.

This information may be subject to geologic interpretation, but none is made in this report because the available geologic and hydrologic data are insufficient and because the extrapolated values of SMQ1 are outside the range of the data base.

Having established the relationship between well DX-68-23-302 (LP(W/L)) and the underflow component (SMQ1) of San Marcos Springs, the local-recharge component (SMQ2) of San Marcos Springs may be calculated by equation 22:

$$SMQ2 = SMQT - SMQ1 \quad (22.)$$

By using equations 20 and 22, the local-recharge component (SMQ2) of San Marcos Springs was estimated from January 1965 to December 1974. The independent variables of the regression analysis, BLAN(Q) and LP(W/L), of Hueco Springs were used in the regression analysis of San Marcos Springs because they proved to be significant variables in estimating the local recharge in the study area. SMQ2, obtained from equation 22, was used as the dependent variable.

An examination of the discharge record of the Blanco River (fig. 8) and the hydrograph of San Marcos Springs (fig. 6) indicates the occurrence of a time lag of about a month. However, the flow of San Marcos Springs closely parallels water-level changes in the well at Landa Park. The regression equation that relates these two hydrologic variables to the local recharge component of San Marcos Springs is:

(23.) $SMQ2 = 114.12 - 8.05\ LP(W/L) + 54.74\ Log_{10}\ (BLAN(Q))$, if $SMQ2 \leq 0$, then set $SMQ2 = 0.0$

where SMQ2 = the monthly average local-recharge component of the total monthly average discharge of San Marcos Springs in ft^3/s ($^3/s$);

LP(W/L) = the monthly average water level in well DX-68-23-302 in feet (m) below land surface; and

BLAN(Q) = the previous monthly average discharge of the Blanco River at Wimberley, Texas.

The correlation coefficient is 0.8604, and the standard error of estimate (S.E.) is 20.1 ft^3/s (0.57 m^3/s) or 27 percent of the mean.

By substituting equations 20 and 23 into equation 19, a new equation (24.) is obtained that may be used to estimate the monthly average discharge of San Marcos Springs as the sum of two components of the total springflow. Substituting 20 and 23 into 19 yields:

(24.) $$SMQT = [223.25e^{-0.05\ LP(W/L)}] + [114.12 - 8.05\ LP(W/L) + 54.74\ Log_{10}\ (BLAN(Q))]$$

The standard error of estimate for equation 24 is 20.3 ft^3/s (0.57 m^3/s) or 27 percent of the mean and was computed from the equation:

$$S.E._{eq.\ 24} = ((S.E._{eq.\ 20})^2 + (S.E._{eq.\ 23})^2)^{\frac{1}{2}}$$

Equation 24 is useful because it provides estimates of the monthly average discharge of San Marcos Springs and provides a means for isolating and quantifying the percentage attributed to each component composing the total springflow.

USE OF THE EQUATIONS

Equations 1 through 17 provide a simple and rapid method for estimating water levels and springflow by using only water-level data. The equations may be used to estimate missing records or to estimate historical water levels and springflow. It should be noted that in all of the regression equations developed for estimating springflow and in some of the equations for estimating water levels, negative values of the dependent variables may result for some values of the independent variables. Negative water levels indicate water levels above ground level. These values are considered unreasonable because they represent hydrologic conditions that are not likely to occur in the San Antonio area. Negative springflow values indicate conditions of no flow. When this occurs, the negative springflow values are set equal to zero.

Figures 13 and 14 show comparisons of the observed and computed discharge of Comal Springs on a monthly average and annual average basis. The computed values were obtained from equations 13 and 14 (table 4). These graphs show that the computed values are in close agreement with the observed values. Although there are differences between the observed and computed values at some times, the differences are generally small and may be attributed to other factors, such as local recharge and local pumping, that were not considered in the regression analysis.

Equation 18 estimates the flow of Hueco Springs with fairly good accuracy. Figures 15 and 16 show comparisons of the observed and computed monthly and annual average discharge of Hueco Springs. There are some large discrepancies between the observed and computed values for some years, but the general trend is in good agreement. The annual values obtained by averaging the monthly values (fig. 16) show better agreement than the monthly values.

Some large variations between observed and computed values of discharge for Hueco Springs may be attributed to other factors, such as local precipitation. A factor that may account for some of the variation is the independent variable, BLAN(Q). Although the discharge of the Blanco River at Wimberley served as the index of runoff providing recharge in the Hueco Springs area, there are times when this index may not be representative.

Equation 24 is used to estimate the total monthly average discharge of San Marcos Springs on the basis of its separate components as provided by equations 20 and 23. Figures 18 and 19 show a comparison of the observed and computed monthly and annual average discharge of San Marcos Springs as generated for the period from January 1950 to December 1974. The comparison shows that there is good agreement between the observed and computed values of springflow. The annual values obtained by averaging the monthly values (fig. 19) show better agreement than the monthly values. Large discrepancies between the observed and computed values occur during some periods, but may be attributed to effects of heavy rainfall in the vicinity of the springs or to runoff in the Blanco River basin that is not representative of runoff in the study area.

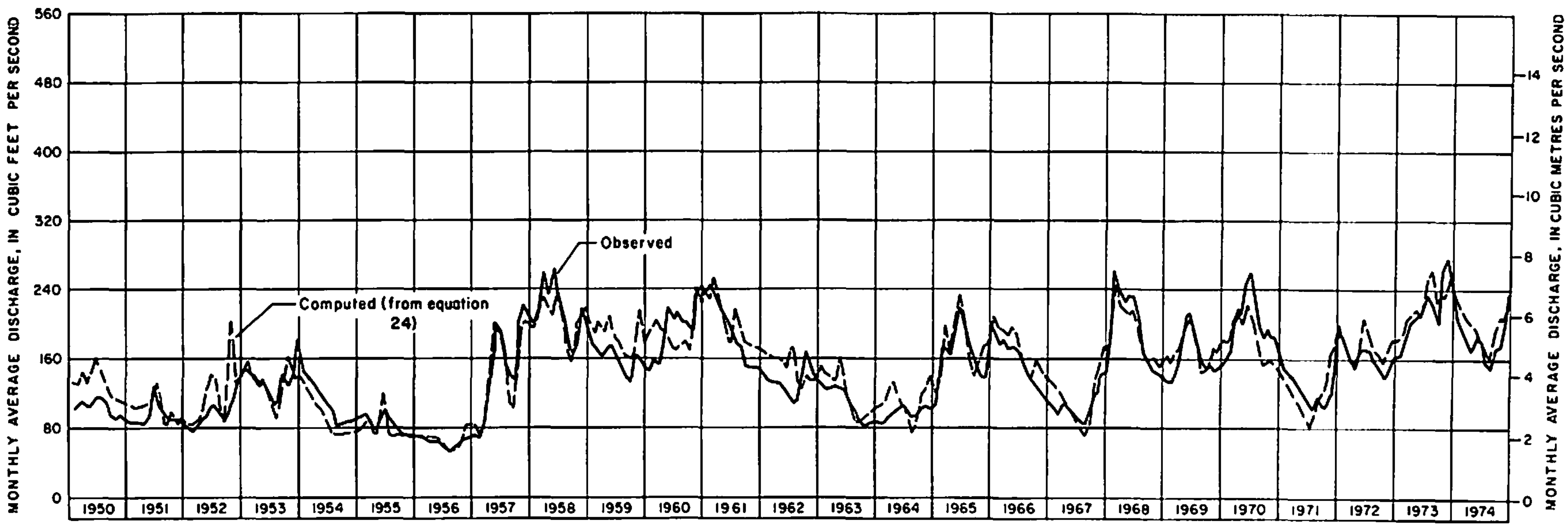


FIGURE 18.-Comparison of observed and computed monthly average discharge of San Marcos Springs

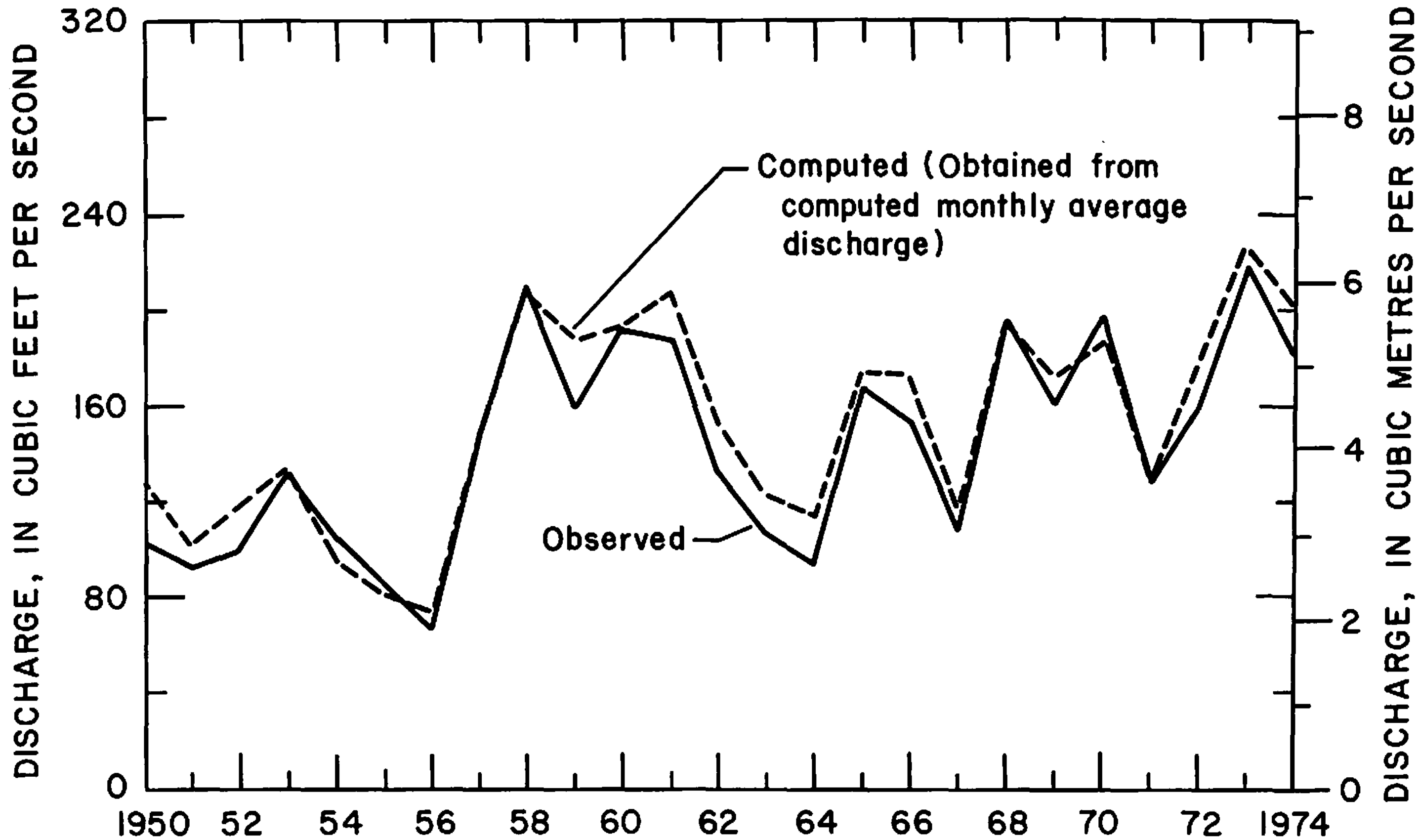


FIGURE 19.-Comparison of observed and computed annual average discharge of San Marcos Springs

The analysis indicates that on an annual basis, underflow from the artesian aquifer west of San Marcos Springs may account for 97 percent of the springflow during periods of extreme drought (1947 to 1956) and only 46 percent during wet periods (1973). On a monthly basis, the underflow component ranges from 40 to 100 percent of the total springflow. From January 1950 to December 1974, the underflow components accounted for about 60 percent of the total discharge of San Marcos Springs.

CONCLUSIONS

The primary conclusion in this study is that changes in water levels and springflow in the eastern part of the San Antonio area can be estimated accurately by a set of empirical equations. These equations were developed through regression analyses of water-level, springflow, and streamflow data. The equations were derived for making estimates on a daily, monthly, and annual basis.

Analyses of geologic and hydrologic data, including tritium analyses, indicate that the major springs are supplied by both underflow from the west and southwest of the study area and by local recharge in the infiltration area in northern Bexar, Comal, and Hays Counties.

The flow of Comal Springs is mostly regional underflow that has moved through the deeper part of the Edwards aquifer adjacent to the Comal Springs Fault as it enters Comal County from the southwest. Hueco Springs is supplied mainly from local recharge in the drainage area of Dry Comal Creek north of the Hueco Springs Fault and west of the Guadalupe River in Comal County. San Marcos Springs is supplied by regional underflow from the Comal Springs area and from local recharge in northern Comal and Hays Counties.

The relationships established by the regression equations are preliminary and may be refined by using additional information obtained through an expanded program of hydrologic-data collection in the study area.

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