STREAMFLOW LOSSES ALONG THE BALCONES FAULT ZONE, NUECES RIVER BASIN, TEXAS

By L.F. Land, C.W. Boning, Lynn Harmsen, and R.D. Reeves

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METRIC CONVERSIONS

For those readers interested in using the metric system, the inch-pound units of measurements used in this report may be converted to metric units by using the following conversion factors:

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot	0.3048	meter
micromho (μmho)	1.000	microsiemen
mile	1.609	kilometer
square mile	2.590	square kilometer

Temperature data in this report are in degrees Celsius (°C) and may be converted to degrees Fahrenheit (°F) by the following formula:

$$°F = 1.8(°C) + 32.$$
$$°C = (°F - 32)/1.8$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

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ABSTRACT

An investigation was conducted to quantify and to determine distribution of streamflow losses and gains that occur during sustained flow conditions in the Balcones Fault Zone of the Nueces River basin. The streams studied include the West Nueces, Nueces, Dry Frio, Frio, and Sabinal Rivers, and Seco, Hondo, and Verde Creeks. Streamflow measurements made during the recession of storm flows identified direct recharge to outcrops of the Edwards aquifer and related limestones that ranged from as high as 393 cubic feet per second for the Dry Frio River to as low as 42 cubic feet per second for the Sabinal River. Recharge to outcrops of the Buda Limestone, Eagle Ford Shale, and Austin Group also eventually reaches the Edwards aquifer, and measurements identified losses to these formations ranging from as high as 174 cubic feet per second for the Frio River to near zero for Verde Creek.

Statistical evaluations of historical daily flow records for the streams that have gaging stations upstream and downstream from the recharge zone provided mathematical relationships that expressed downstream flow in terms of other significant parameters. For each stream, flow entering the recharge zone is most significant in defining downstream flow; for some streams, antecedent flows at the upstream site and ground-water levels are also significantly related to downstream flow. The analyses also determined the discharges required upstream from the recharge zone to sustain flow downstream from that zone. These discharges ranged from 355 cubic feet per second for the combined Frio and Dry Frio Rivers to 33 cubic feet per second for the Nueces River. The entire flows of lesser magnitude are generally lost to recharge to the aquifer.

INTRODUCTION

Runoff from the Edwards Plateau in the Nueces River basin is a major source of water for south-central Texas. Part of the runoff infiltrates the streambed and recharges the Edwards aquifer, which is the principal source of water for the Uvalde-San Antonio-San Marcos area (fig. 1). Water that flows past the recharge zone for the Edwards aquifer becomes part of the surface-water supply for the Corpus Christi area. Demands on both the Edwards aquifer reservoir and the surface-water reservoirs in the basin are increasing and may lead to a water shortage during droughts.

Considerable hydrologic information is needed by agencies such as the U.S. Bureau of Reclamation and Edwards Underground Water District to plan for the most effective and efficient management of the interrelated surface- and ground-

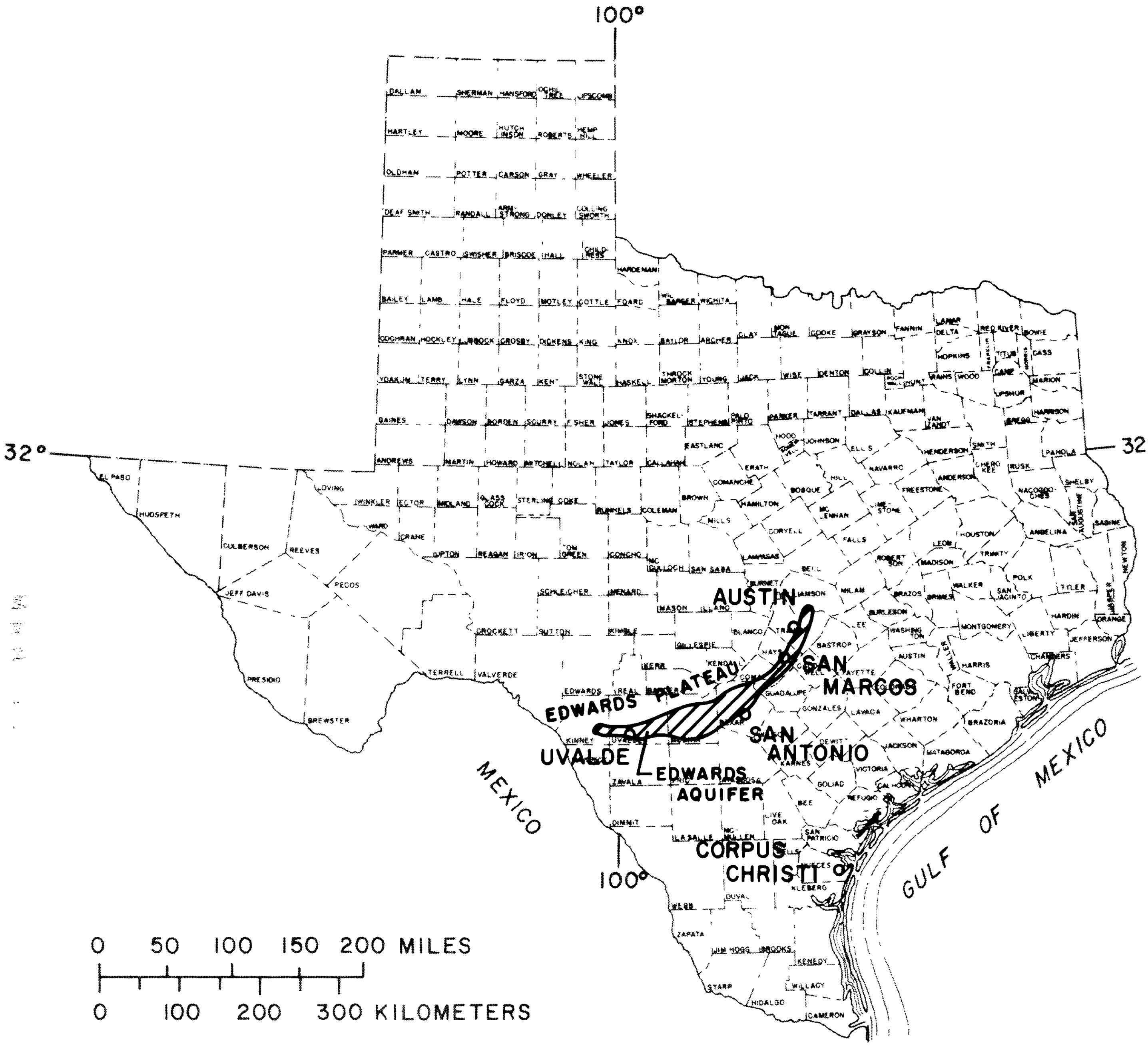

Figure 1.-Location of study area.

water resources. Some of the needed information includes distribution of recharge along the Balcones Fault Zone, relationship of recharge to streamflow entering the infiltration area, relationship of streamflows immediately upstream and downstream from the infiltration area, and relationship of recharge to antecedent conditions and ground-water levels.

In cooperation with the Bureau of Reclamation, Southwest Region, the U.S. Geological Survey conducted an investigation of losses to the Edwards aquifer from major streams in the Nueces River basin. The investigation began during October 1979 and ended during September 1981. This report presents data collected and analyses made during that study.

Purpose and Scope

The overall purpose of the investigation was to provide information useful for designing recharge reservoirs above the Balcones Fault Zone and for managing these reservoirs for efficient and effective use of the ground- and surface-water resources. Major objectives were to define the distribution of streamflow losses along the streams, to quantify the natural losses, and to determine the influence of various hydrologic conditions such as antecedent conditions, ground-water levels, and flow regimes on recharge.

The study was conducted in areas of the Balcones Fault Zone in the Nueces River basin (fig. 2). The investigation was limited to streams that have gaging stations upstream and downstream from the infiltration area or to streams where reasonably accurate gain-loss measurements could be made. Included in the study plans were the development of relationships of flows upstream from the recharge zone to recharge to the Edwards aquifer and to flows downstream from the recharge area.

Previous Investigations

Low-flow investigations for the Nueces River basin for 1918-58 are tabulated and summarized in Texas Board of Water Engineers Bulletin 5807-D (1960). Pettit and George (1956) discussed the results of the low-flow investigations made prior to 1956. Reeves and Rettman (1969) completed a study on the quantity and quality of low flow in the Hondo Creek basin for March 27-28, 1968.

HYDROLOGIC SETTING

The Nueces River basin (fig. 2) begins on the Edwards Plateau in Edwards, Real, and Bandera Counties where many small streams have cut deep valleys and canyons below the upland surface, forming areas of pronounced relief. These streams, many of which are springfed, flow generally southeast and cross the Edwards aquifer infiltration area in the Balcones Fault Zone. This zone ranges from about 3 to 20 miles in width, and extends from the Uvalde area, eastward to near San Antonio and northeastward to the vicinity of Austin. The major streams in the Nueces River basin that cross the Edwards aquifer infiltration area are the West Nueces, Nueces, Dry Frio, Frio, and Sabinal Rivers and Seco, Hondo, and Verde Creeks. These streams lose a substantial amount of their flow while crossing the fault zone and are dry or flow intermittently immediately downstream from this zone.

page 5 follows

Streamflow losses that occur in the outcrops of the Edwards and associated limestones go immediately into the Edwards aquifer and are called "direct recharge." Streamflow losses that occur in the outcrops of the Buda Limestone, Eagle Ford Shale, and the Austin Group eventually go into the Edwards aquifer and are called "indirect recharge." Exposed areas of formations that underlie the Edwards and associated limestones and outcrop upstream from the direct recharge area are treated only as contributing drainage areas and are considered neither direct or indirect recharge areas. Exposures of the Anacacho Limestone, Escondido Formation, and alluvium that often occur in the extreme downstream portions of the study reaches also are considered neither direct or indirect recharge areas.

The potential rate of recharge to the Edwards aquifer is related to the faults and the subsequent development of large solution openings. The amount of recharge depends on the sustained streamflows above the infiltration area and the infiltration characteristics of the streambed. Gravel deposits in the infiltration area also are recharged by storm runoff. These deposits can absorb large quantities of water, which either percolate into the underlying permeable formations such as the Edwards aquifer, seep back into the stream after the flood wave passes, or are lost to evapotranspiration.

METHODS OF INVESTIGATION

The study of recharge from streams crossing the Balcones Fault Zone in the Nueces River basin included the measurement of discharge at strategic points along the recharge zone of each stream and analyses of historic discharge records for the gaged streams. These gain-loss surveys provide data and understanding relative to the distribution and magnitude of losses from the streams. The analyses of historic records provide a relationship for flow in each stream downstream from the recharge zone as functions of upstream flow and other significant variables and indicate the upstream discharge necessary to sustain flow throughout each study reach.

Gain-Loss Survey

A reconnaissance was made of certain streams in the area to select sites for making streamflow measurements that would identify reaches where most of the recharge to the aquifer occurs. Geologic features, channel conditions, and accessibility were considered in the selection of the measuring sites. Where possible, sites on impermeable material were selected to prevent underflow from bypassing the measuring sections. Up to six measuring sites were selected along each stream, and each of these sites was measured during one to three levels of flow. Because much of the reach in the infiltration area is dry during normal conditions, measurements were made immediately after runoff which produced flow throughout the reach being studied and after most tributary inflow had ceased or was at a minimum.

Measurements of specific conductance at the sites were made at the time of the streamflow measurements to give an indication of whether there was inflow from surface-water runoff, from the Edwards aquifer, or from inflow from the alluvial aquifer along the stream. Spring flow from the Edwards aquifer in the Edwards plateau is saturated with calcium and magnesium bicarbonate dissolved from the aquifer. Changes due to temperature, aeration, and loss of carbon dioxide cause the calcium carbonate to precipitate slowly as the spring water flows downstream. Thus, an increase in the specific conductance at the downstream site would indicate an inflow from a ground-water source, and a decrease would indicate inflow from surface runoff or from an alluvial deposit.

Historical Data Analyses

Daily streamflow records are available at the streamflow-gaging stations shown in figure 2. Their primary purpose has been to provide the hydrologic data needed to compute recharge to the Edwards aquifer. The stations in the area are paired on major basins with the intent of gaging the flows before the streams reach the recharge zone (upstream station) and immediately after leaving the recharge zone (downstream station). The Nueces and Frio Rivers have major tributaries that enter the main stem in the recharge area; these also are gaged. Complete records are available at all the stations, from October 1, 1961, or earlier, to the present (1983). These records include daily, monthly, and annual mean discharges. Records on some streams are available during the drought of the 1950's, providing valuable information to assess the impact of that hydrologic extreme.

The method of estimating recharge to the Edwards aquifer is based on a water balance equation, in which recharge within a stream basin is the difference between measured streamflow upstream and downstream from the recharge area of the aquifer plus the estimated runoff in the intervening area (Puente, 1978). For purposes of this report, net recharge is defined to be the difference in streamflow upstream and downstream from the recharge zone:

$$\text{Recharge} = \text{Discharge}_{\text{upstream}} - \text{Discharge}_{\text{downstream}}$$

The definition of net recharge for this report is considered valid because the analysis considers only those periods when runoff from the intervening area is negligible and evapotranspiration and change in storage are believed to be small. Thus, only one dependent variable--downstream discharge--in the statistical analysis is warranted because the other variable (recharge) can subsequently be computed directly.

Historical records for the gaging stations on several streams in the study area strongly indicate that downstream flows are dependent not only on upstream flow but also on antecedent hydrologic conditions. Records on the Nueces River show that during dry seasons, steady flows downstream of the fault zone continue for significant periods of time, indicating that ground-water levels and antecedent flows influence streamflow losses. During 1977, when water in wells were at record high levels and when substantial upstream flow had occurred for several months, records for the downstream gage showed that flows were abnormally high and for an extended time exceeded the combined flow at the upstream gages. As flow declined from 1977 to 1979 and ground-water levels dropped, lesser percentages of upstream flow passed the downstream gage site. As the relatively minor drought of 1980 developed, the recharge increased presumably in response to depletion of ground-water storage. Although significant variations in upstream flow occurred during the 1980 drought period, downstream flows were relatively steady, reflecting the characteristic of ground-water inflow.

During and following the extended and severe drought of the 1950's, even greater variations in flow between upstream and downstream stations were observed. Flows at the downstream gages remained very low during the drought recovery period of 1958 owing to the severely depressed ground-water condition even though upstream flows were substantially above average for a sustained period of time.

Two indices were used to determine the influence of antecedent conditions on the streamflow losses. One is the record of water levels (depth to water) in an index well in each basin. This record was used to indicate antecedent hydrologic conditions and to show the influence of ground-water levels in the Edwards on streamflow losses. The other index is the past streamflow record at the upper gaging site. This was represented by the time, in days, required to accumulate specific flow volumes at the upstream gage site prior to each observation or by the flow volume for a specified period of time preceding each observation.

Flow periods used in the development of statistical relationships for downstream flow were selected from historical records primarily considering periods when flow was steady or slowly receding. Periods of rapidly changing flow were avoided to minimize error introduced by variable travel time through the study reaches. Periods of high flow were excluded because runoff from intervening drainage areas was likely. Finding desirable periods was difficult for the smaller basins, because sustained flow never occurred at the downstream stations. Even at the upstream stations, steady flow seldom occurred on many of the streams, forcing the utilization of data that did not entirely satisfy selection criteria.

Multiple-regression techniques, including statistical correlation, were used to develop and test the statistical relationships of flow at the downstream gaging sites to independent variables. The independent variables were flow upstream from the recharge zone, concurrent ground-water levels in a representative Edwards aquifer well in the study basin, and either a length of time prior to each observation to satisfy accumulated antecedent flow volumes at the upstream gage site or an accumulated flow volume for a specific time period at the upstream gage site. The correlation coefficients describe the strength of a linear relationship between two variables. Based on these coefficients, the independent variables that have strong relationships with the dependent variable (downstream discharge) were identified. The regression analyses produced mathematical expressions of downstream discharge in terms of the significant independent variables.

The statistical analyses were first conducted using natural values for all variables. Examination of scatter diagrams and the comparison of downstream flow and the time for antecedent flow volumes indicated nonlinearity of relations using the time variable. Consequently, values of the times for antecedent flow volumes were converted to their base 10 logarithmic equivalents for use in the statistical analyses. Examination of the depth to ground-water levels showed considerable variability between the basins particularly for the minimum (highest water levels) values. To normalize this variable, a constant was subtracted from the records for some basins to produce comparable minimum and maximum values for each basin.

The multiple linear-regression analyses provided mathematical relationships of the form:

$$Q_{dn} = a + b\ Q_{up} + c\ Gwl + d\ \log_{10} t_{zzz} + e\ V_m \qquad (1)$$

where Q_{dn} is the dependent variable of downstream flow, in cubic feet per second;

a is a regression constant;

b, c, d, and e are regression coefficients; and

Q_{up}, Gwl, t_{zzz}, and V_m are the respective independent variables of flow at the upstream site, in cubic feet per second; depth to water, in feet, in the well used in the analysis; time, in days, required to satisfy specific antecedent flow volumes at the upstream gage site; and flow volumes accumulated in a specific time at the upstream gage site. Criteria for defining t_{zzz} and and V_m are given later.

The selected multiple-regression approach considers, in stepwise fashion, all independent variables. The procedure provides statistics on the level of significance of each independent variable in defining the developed relation. The selected expressions for this study utilized only those independent variables that have a 95-percent probability of effectiveness in defining the dependent variable. The overall reliability of each developed relation is indicated by its standard error of estimate and by its R-square value, the square of the multiple correlation coefficient, a term that identifies how much of the variation in the dependent variable is accounted for by the model.

DISCUSSION OF RESULTS

Gain-Loss Survey

The recession flows from several storms in the Nueces River basin were studied during the investigation. Some of the storms covered the entire basin, while others covered only several of the eight streams. During each gain-loss survey, tributary inflow had ceased or was measured as part of the survey. The days when measurements were made for each stream are given in table 1.

The reliable determination of recharge rates required that data be collected during constant flow conditions. Unfortunately these ideal conditions did not exist during the study period. All measurements were made on falling stages, and personnel limitations precluded the collecting of data that would allow tracking of equivalent points on the recession hydrograph as the flow crossed the infiltration zone. However, adjustment of measurements to account for time lag in the basin with the longest traveltime indicates that the measurements adequately represent the gain-loss distribution through the study reaches.

Table 1.--Dates of gain-loss surveys

Date	West Nueces River	Nueces River	Dry Frio River	Frio River	Sabinal River	Seco Creek	Hondo Creek	Verde Creek
Sept. 8, 1980	--	--	--	--	--	--	--	X
Sept. 11, 1980	--	--	--	X	--	--	--	--
Apr. 2, 1981	--	--	--	X	X	--	--	--
Apr. 24, 1981	--	--	--	--	--	--	--	X
May 6, 1981	--	--	--	X	--	--	--	--
May 27, 1981	--	--	--	--	--	--	X	--
June 17, 1981	--	--	--	--	--	--	--	X
June 18, 1981	--	--	X	--	--	X	--	--
June 19, 1981	--	--	--	--	--	X	--	--
June 20, 1981	X	--	--	--	--	--	--	--
June 22, 1981	--	--	--	--	--	X	--	--
Aug. 6, 1981	--	--	--	--	X	--	--	--
Aug. 10, 1981	--	X	--	--	--	--	--	--

Information presented for each tributary basin includes a description of the data collected in each study reach and summary discussions of the gains and losses provided by the field data and gaging-station records. Supporting illustrations such as location maps, discharge hydrographs, and tables that give the gains, losses, and their distribution during the times of data collection in each study reach also are presented. Distribution of recharge is referenced in the tables by river mile, defined in this report as the distance downstream from the upstream gaging station rather than by the conventional mileage upstream from the stream mouth.

The data show that for several of the streams and especially the Nueces River, some of the losses are recovered by the stream in the portion of the reach immediately upstream from the downstream gage. It is not known whether this return flow originates from the Edwards aquifer proper, or if the return flow is derived from the Buda Limestone, Eagle Ford Shale, Austin Group, or alluvium that overlies the Edwards aquifer. Some of the base flow in this segment could be coming from ground-water seepage in the local area.

West Nueces River

On June 20, 1981, discharge measurements were made (fig. 3) at the streamflow-gaging station 08190500 West Nueces River near Brackettville (1A), and at Shaw Ranch Crossing (3A), 1.7 miles upstream from the Nueces River (table 2). Site 3A is immediately downstream from the contact between the direct and indirect recharge areas. A major tributary, Live Oak Creek was also measured (site 2A).

Streamflow was rapidly declining on June 20, 1981, as indicated on the hydrograph (fig. 4) following the large flows on June 11 and June 16. The only known tributary inflow (Live Oak Creek) was measured immediately upstream from its mouth. The slight decline in specific conductance indicates no appreciable inflow from springs or additional streamflow from tributaries. Losses probably exceed the 286 ft^3/s indicated on the table, because the flow was measured during falling stages at the upper sites. No adjustment was made for time of travel as the recession of the flood wave moved downstream.

Flows occur in the Balcones Fault Zone of the West Nueces River for only a few days following heavy rains in the area. Because of high infiltration rates reasonably steady flow conditions throughout the reach probably never exist. The low flow from Live Oak Creek at site 2A is sustained by springs from the isolated outcrops of the Edwards and associated limestones in the stream valley. Inflow to the infiltration area of the Edwards aquifer is the combined flow of sites 1A and 2A, except during or closely following storms when inflow from intervening areas occurs.

Nueces River

Six discharge measurements were made August 10, 1981, at sites 1-6 (table 3) beginning at the streamflow station 08190000 Nueces River at Laguna and ending at the streamflow station 08192000 Nueces River below Uvalde (site 6; fig. 3). Although the contact between the direct and indirect recharge areas is between measuring sites 2 and 3, the direct recharge zone is treated as

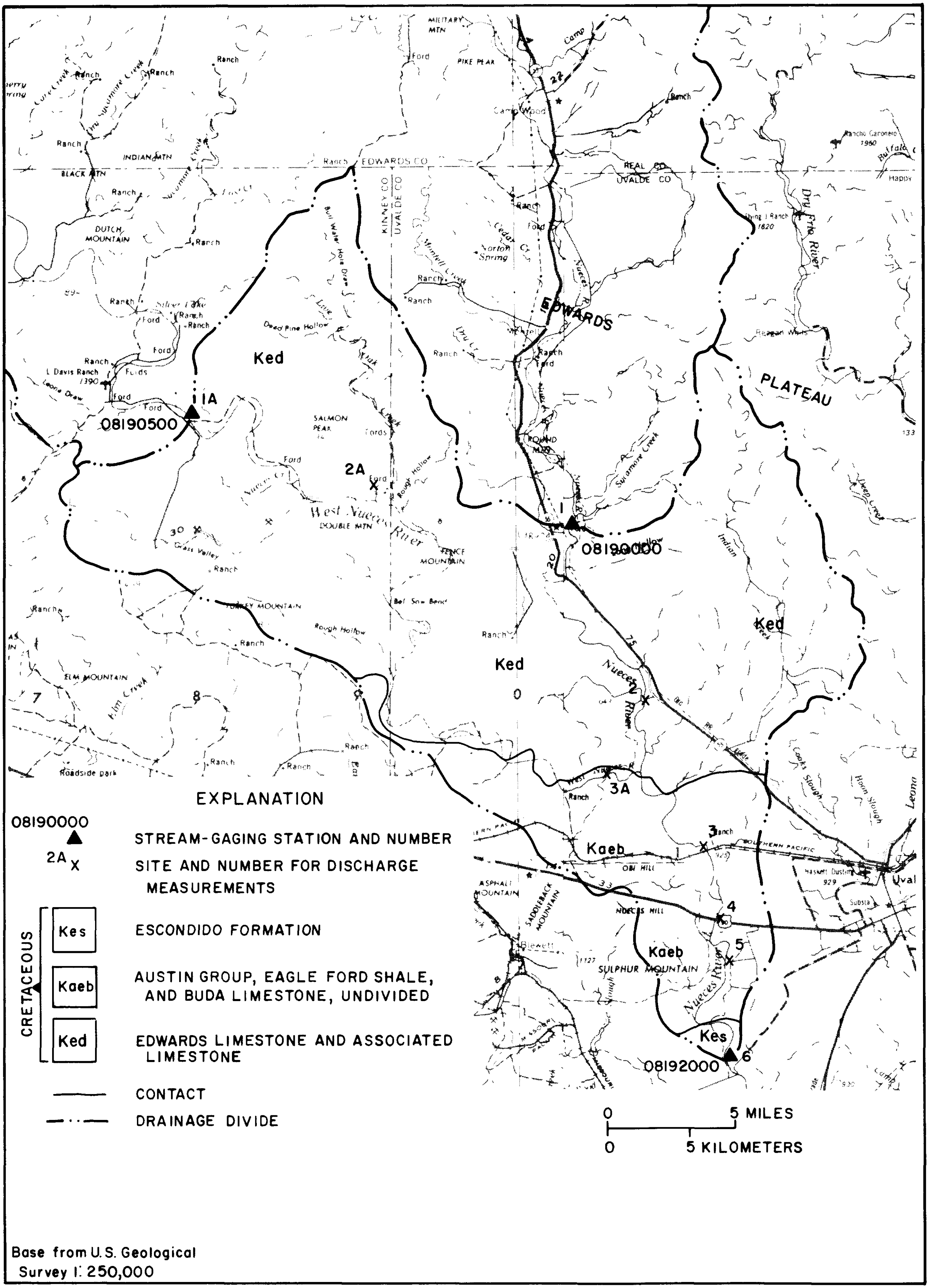

Figure 3.-Locations of discharge measurement sites in the Nueces River basin.

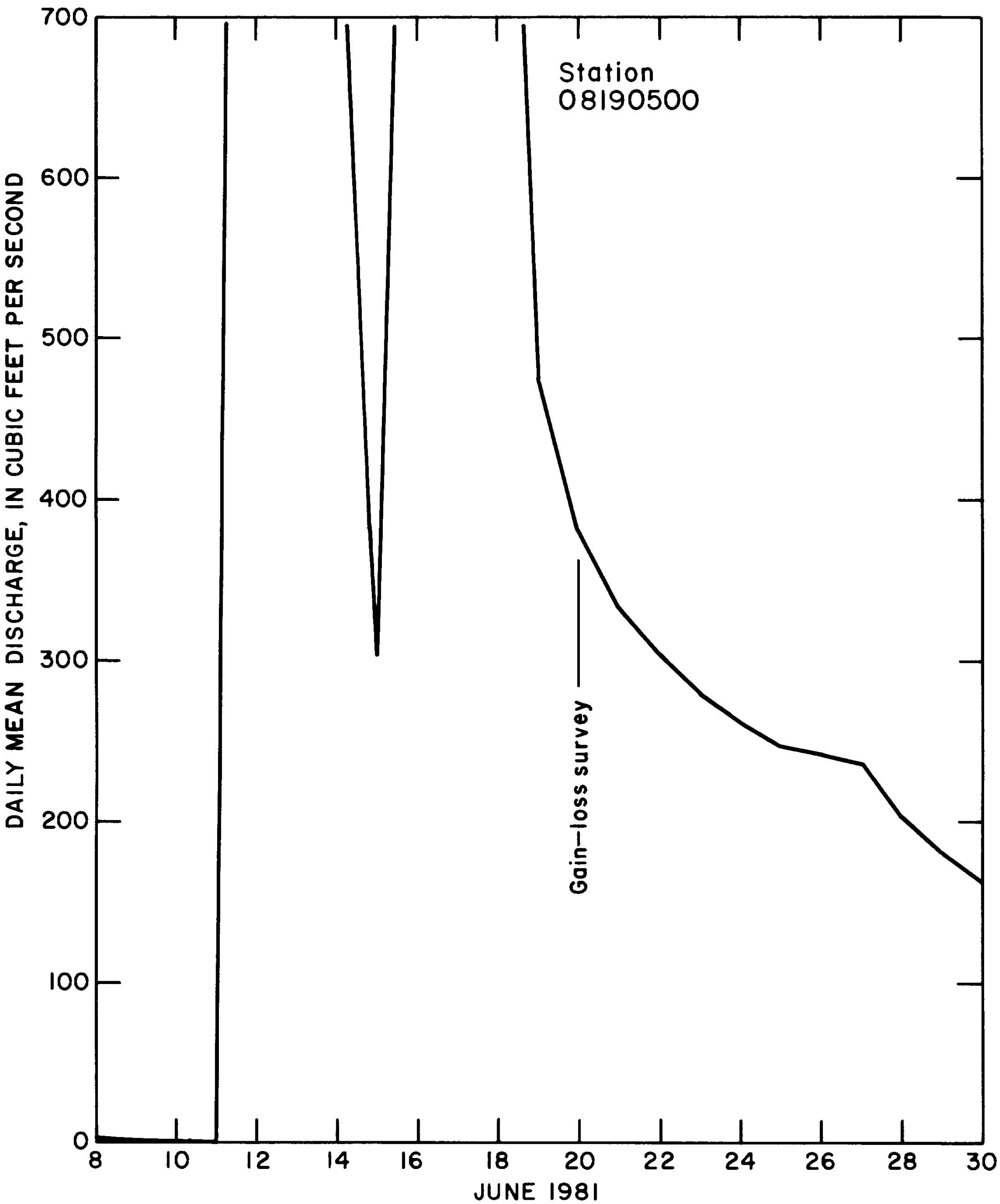

Figure 4.-Discharge hydrograph for West Nueces River, June 1981.

Table 2.--West Nueces River survey data

Site no.	Stream	Location	River mile	June 20, 1981 Dis-charge (ft^3/s)	Specific conduct-ance (µmho)	Water temper-ature (°C)	Flow losses (-) or gains (+) (ft^3/s)	Streambed material
1A	West Nueces River.	Lat 29°28'21", long 100°13'10" at gaging station 08190500.	0	378	329	24.0	--	Gravel and bedrock.
2A	Live Oak Creek. 1/	Lat 29°26'39", long 100°07'18" at FM 334 Road, 20.0 miles northeast of Brackettville.	12.4	64.0	358	27.5	--	Asphalt road on bedrock.
3A	West Nueces River.	Lat 29°17'07", long 99°58'21" at Shaw Ranch crossing, 1.7 miles upstream from Nueces River.	38.5	156	292	28.0	-286	Gravel and bedrock.

1/ Tributary to West Nueces River.

Table 3.--Nueces River survey data

Site no.	Stream	Location	River mile	August 10, 1981 Dis-charge (ft^3/s)	Specific conduct-ance (µmho)	Water temper-ature (°C)	Flow losses (-) or gains (+) (ft^3/s)	Streambed material
1	Nueces River.	Lat 29°25'42", long 99°50'49" at gaging station 08190000.	0	236	431	28.0	--	Bedrock.
2	do.	Lat 29°19'42", long 99°56'51" at Haby Crossing, 13.5 miles northwest of Uvalde.	7.8	189	417	29.5	-47	Bedrock.
3	do.	Lat 29°14'38", long 99°54'25" at Southern Pacific Railroad bridge, 8 miles northwest of Uvalde.	17.2	185	389	29.0	-4	Gravel and bedrock.
4	do.	Lat 29°12'19", long 99°54'07" at U.S. Highway 90 bridge, 7.5 miles west of Uvalde (discontinued station 08191000).	20.5	137	391	27.5	-48	Low-water crossing on bedrock.
5	do.	Lat 29°10'52", long 99°53'40" at low-water crossing, 7.5 miles southwest of Uvalde.	23.2	148	425	29.0	+11	Gravel and bedrock.
6	do.	Lat 29°07'25", long 99°53'40" at gaging station 08192000.	29.4	212	423	30.0	+64	Bedrock.

ending at site 2. Flow conditions on the West Nueces River were not determined because of inaccessibility to the mouth. However, because of the minimal flow (about 8 ft^3/s) on the West Nueces River near Bracketville (site 1A) and the was no inflow to the Nueces River from the West Nueces River for this period. large losses shown for June 20, 1981 (see table 2), it was assumed that there was no inflow to the Nueces River from the West Nueces River for this period.

Streamflow at the upper station was declining on August 10, 1981, following a peak discharge of 334 ft^3/s on August 8, as indicated in figure 5. The measured discharge at the lower station (site 6) was 212 ft^3/s on August 10; this measurement was made during the peak flow at this site. The hydrographs indicate that there is significant traveltime between the upper and lower stations, and total streamflow losses are therefore greater than indicated by direct comparison of measured discharge.

Because the flow was declining during the measurement period and the traveltime is reasonably long (about 30 hours) the direct comparison of measurements produces values of gain or loss with less than desired reliability unless the measurements are adjusted for time of travel of the flow through the reach. By time adjusting all measurements, based on the 30-hour travel time through the entire reach and on the proportional distance of each measuring site from the upper gage, a segment of the recession hydrograph at each measuring site was constructed (fig. 6). These hydrograph segments more appropriately depict the gains or losses in the subreaches during comparable times of the flow recession. Approximate losses and gains from this analysis at the beginning of August 10 during the steadily declining recession period are given below along with measured discharges.

Site no.	River mile	Measured discharge (ft^3/s)	Loss (-) or gain (+) (ft^3/s)	Time adjusted discharge (ft^3/s)	Loss (-) or gain (+) (ft^3/s)
1	0	236	--	245	--
2	7.8	189	-47	195	-50
3	17.2	185	-4	175	-20
4	20.5	137	-48	120	-55
5	23.2	148	+11	130	+10
6	29.4	212	+64	190	+60

This analysis shows that about 125 ft^3/s of flow probably was lost to the aquifer between sites 1 and 4 when the flow at the upstream site was about 245 ft^3/s. About 70 ft^3/s of flow was gained between sites 4 and 6 at this same time. The net loss of 55 ft^3/s from the upper site to the lower site during this portion of the recession closely agrees with time adjusted flow differences at these sites prior to and subsequent to the storm runoff of

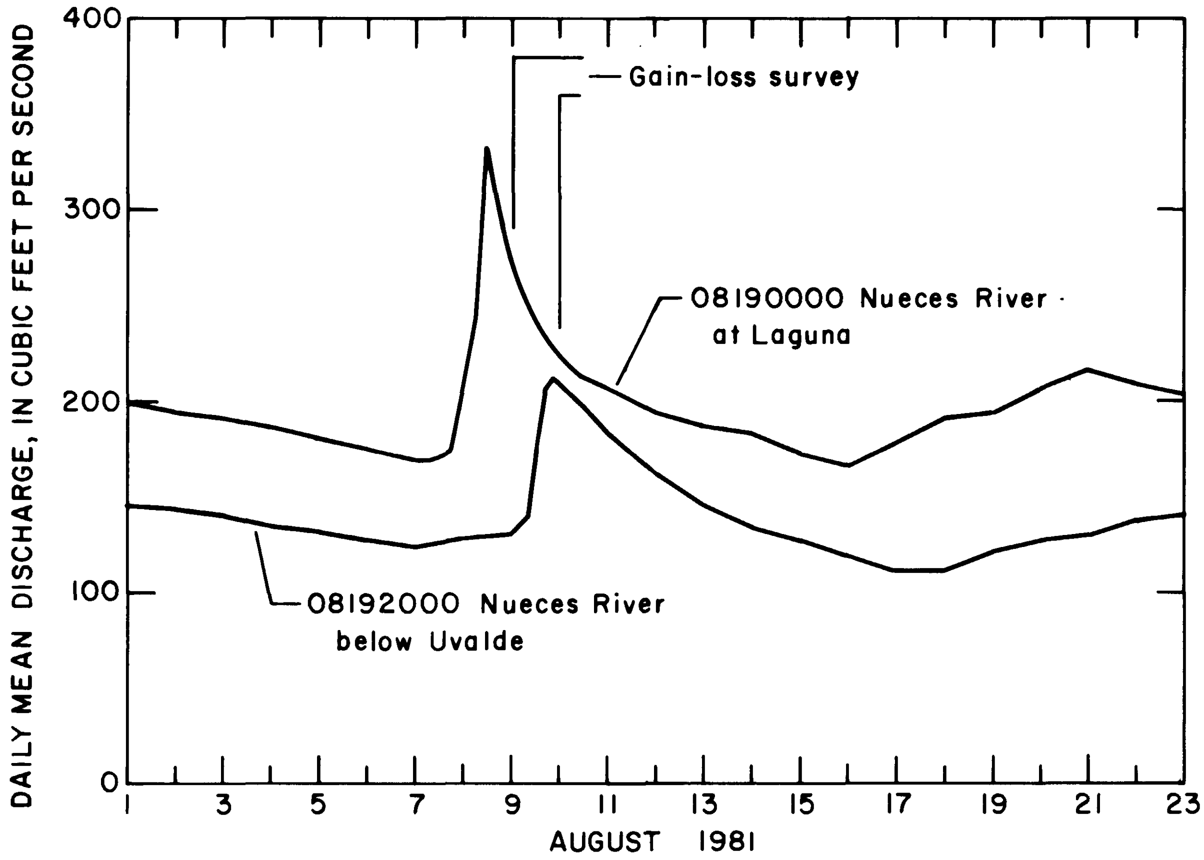

Figure 5.-Discharge hydrographs for Nueces River, August 1981.

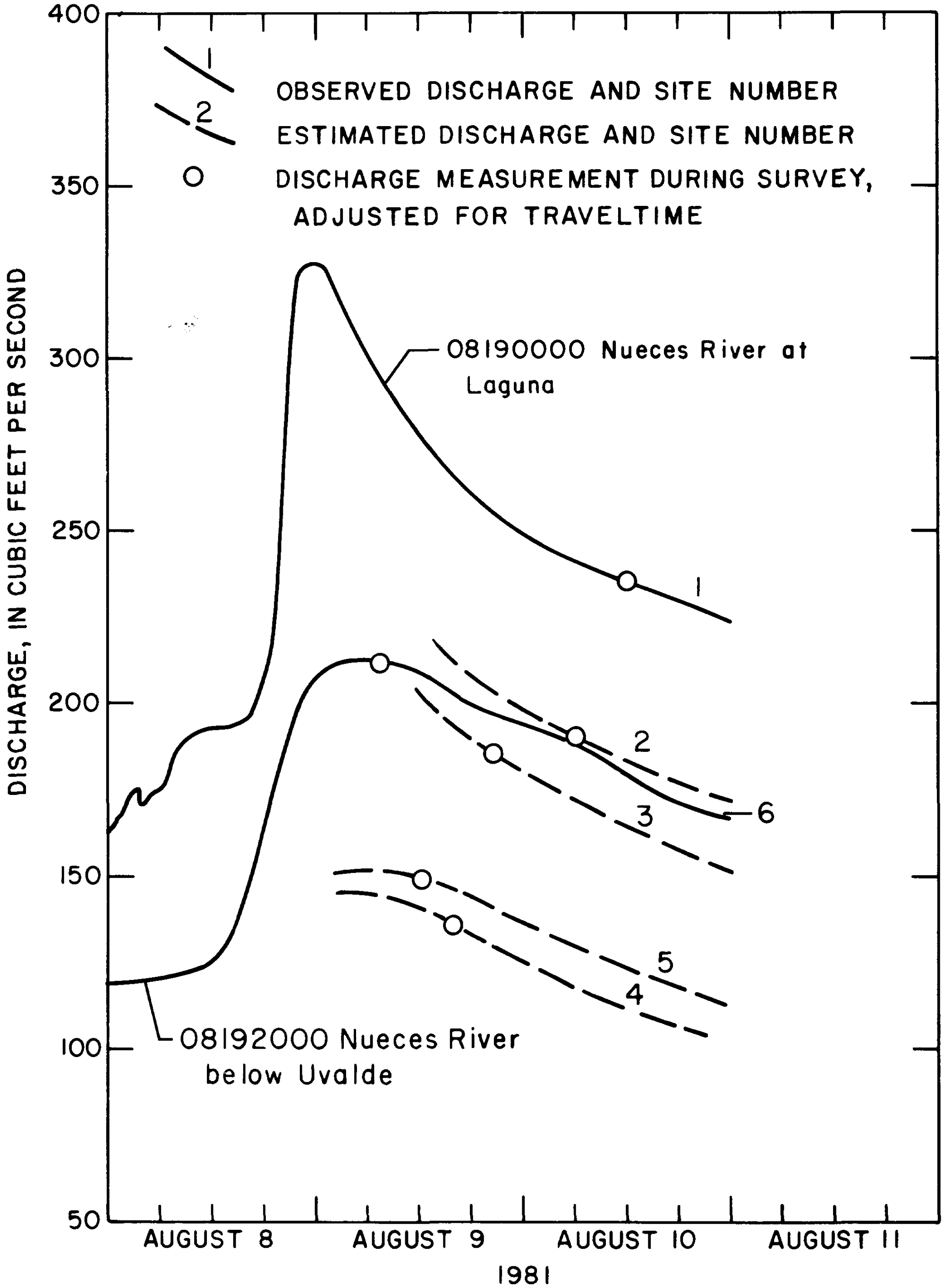

Figure 6.-Time adjusted discharge hydrographs at each measurement site on the Nueces River, August 6-15, 1981.

August 8-10, 1981, as shown in figure 5. The increase in flow between sites 4 and 6 is largely attributed to inflow from a ground-water source as indicated by the increase in specific conductance from 391 μmho at site 4 to 423 μmho at site 6.

The analysis shows that direct comparison of discharge measurements made during recession periods may indicate losses of lesser magnitude than actually occur. The variation is not large, however, and the measurements are considered to be reasonably accurate in defining the magnitude and distribution of losses in the study reaches. Therefore, traveltime adjustments are not made for each survey.

Dry Frio River

A series of six discharge measurements (fig. 7 and table 4) were made on June 18, 1981, beginning at the streamflow station 08196000 Dry Frio River at Reagan Wells (site 1) and ending 1.5 miles upstream from the confluence with the Frio River (site 6). Site 4 is near the contact between the direct and indirect recharge area.

The recession flow followed a large rise on June 18, 1981, as indicated on the discharge hydrograph (fig. 8). Tributary draws had ceased to flow at the time of the investigation.

Measurements indicate a net loss of 426 ft^3/s in the reach with 393 ft^3/s being lost to the direct recharge area (sites 1-4), and a net 33 ft^3/s loss to the indirect recharge area (sites 4-6). There was a general decrease in specific conductance from 431 to 368 μmho between sites 1 and 6, indicating no significant inflow in the reach.

Frio River

Three series of discharge measurements were made at seven sites on September 11, 1980, April 2, 1981, and May 6, 1981 (fig. 7 and table 5), beginning at the streamflow station 08195000 Frio Creek at Concan (site 11) and ending at the streamflow station 08197500 Frio River below Dry Frio River near Uvalde (site 17). Site 14 was near the contact between the direct and indirect recharge area.

Streamflow was declining during each survey following the storm periods shown on the discharge hydrographs for the two stations (figs. 9, 10, and 11). Tributary flow had ceased at the time of each investigation. At several sites, more than one discharge measurement was made; the losses given in table 5 are based on the highest discharge measurement at each site. Measurements made on September 11 indicate a net loss of 200 ft^3/s in the entire reach. Of this amount, 128 ft^3/s were lost in the portion of the reach crossing the direct recharge area (sites 11-14).

Measurements of April 2, 1981, indicate a net loss of 259 ft^3/s in the reach with 153 ft^3/s being to the direct recharge area (sites 11-14) and a net 106 ft^3/s loss to the indirect recharge area (sites 14-17).

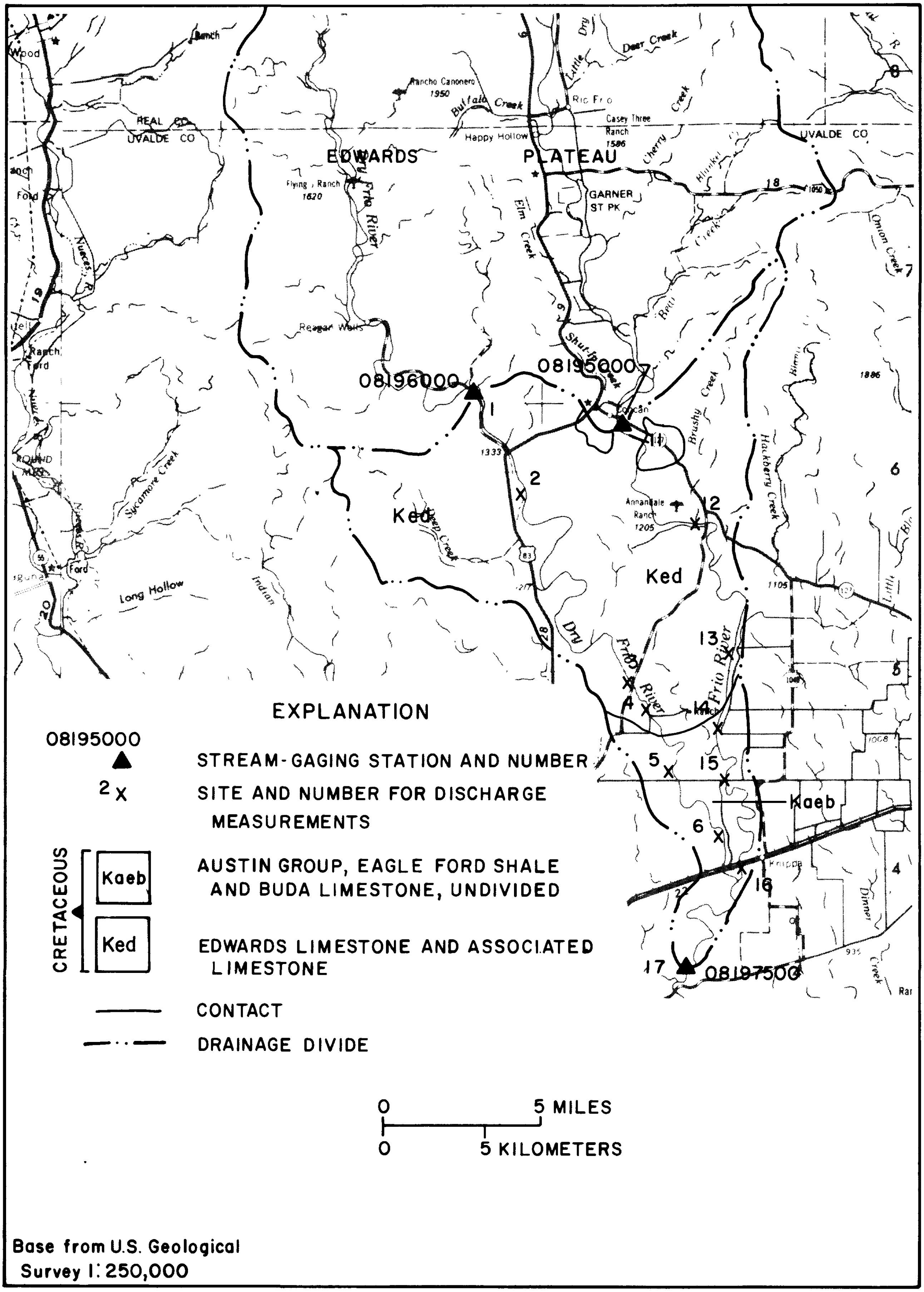

Figure 7.—Locations of discharge measurement sites in the Frio River Basin.

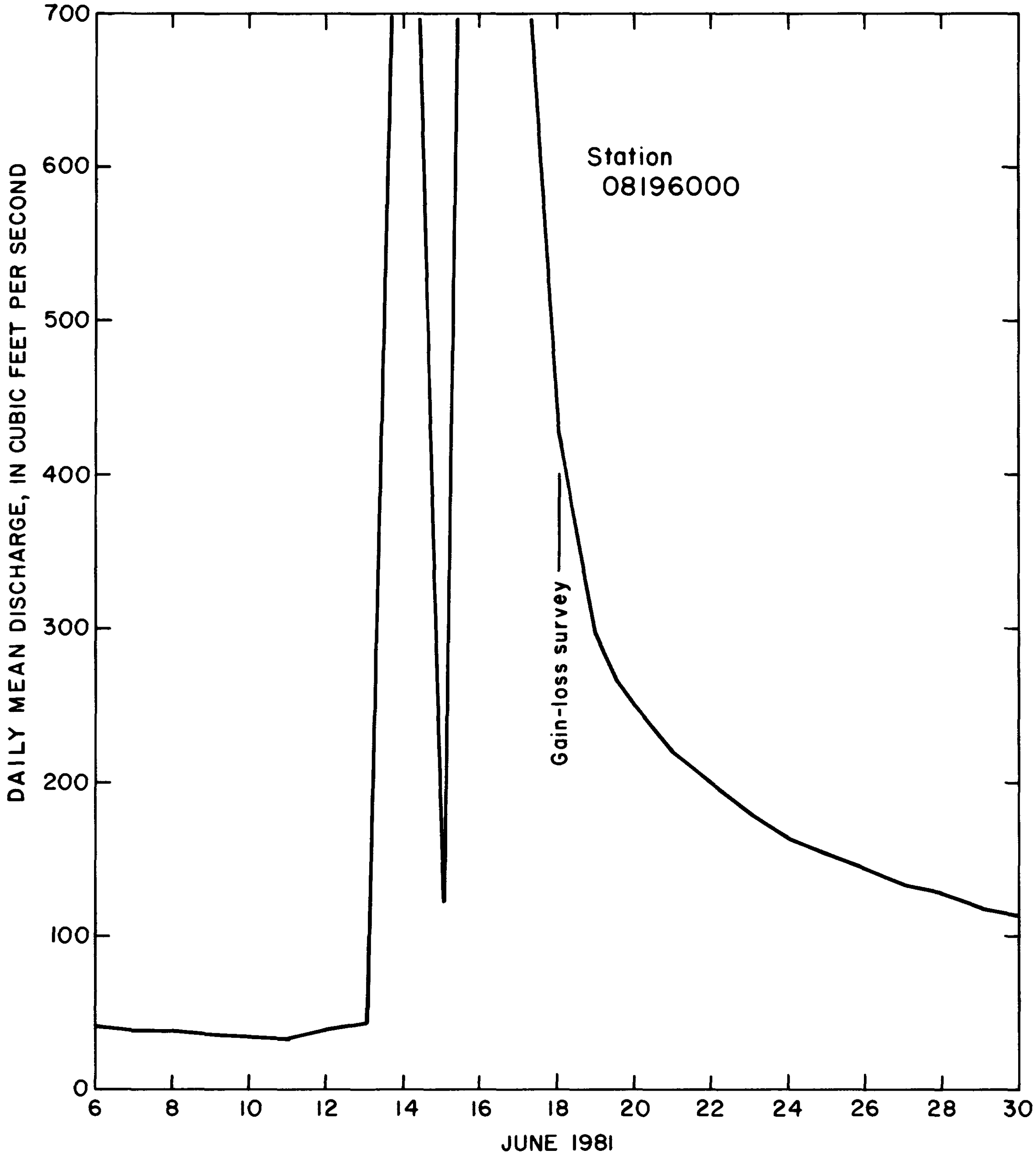

Figure 8.-Discharge hydrograph for Dry Frio River, June 1981.

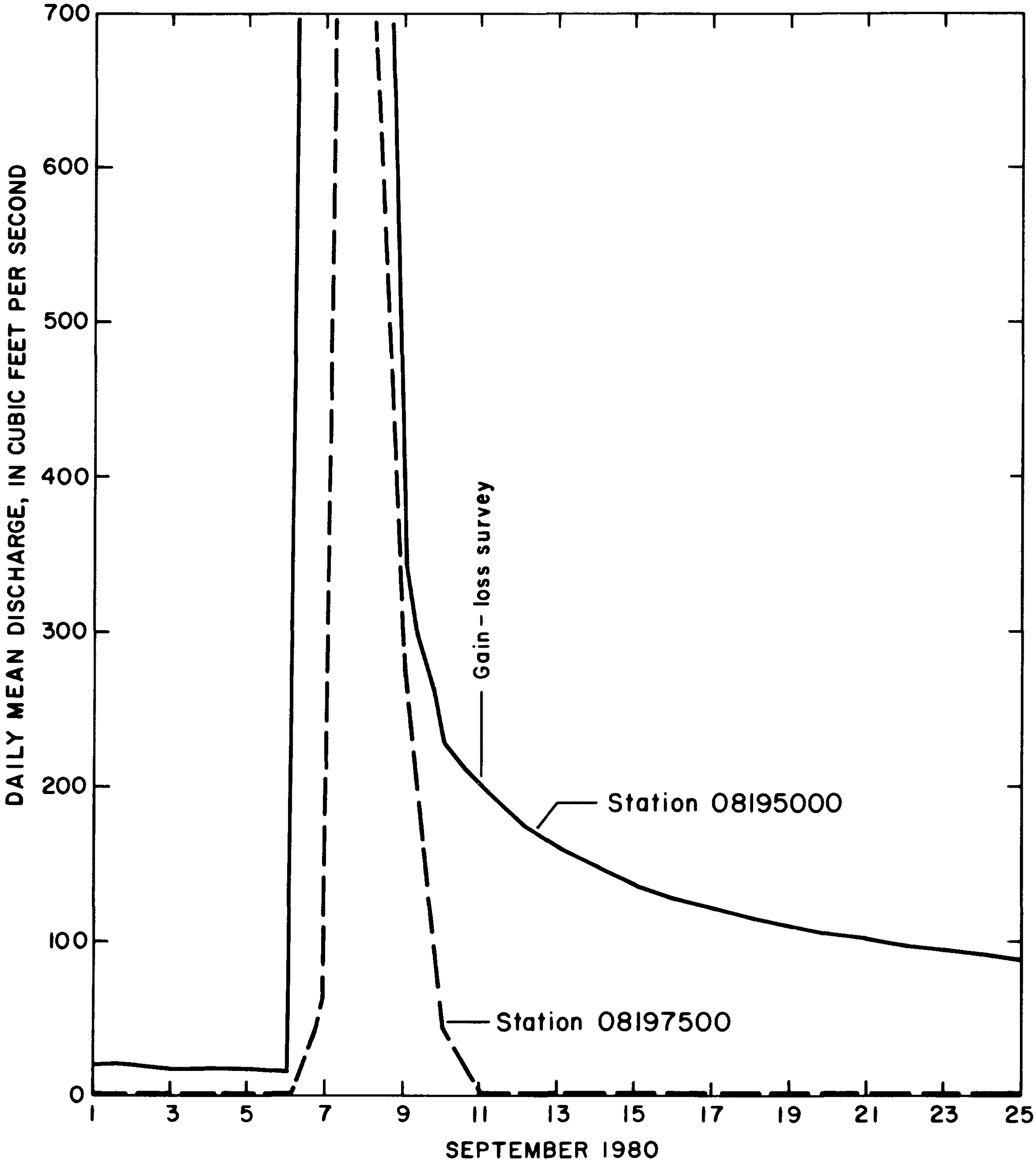

Figure 9.-Discharge hydrographs for Frio River, September 1980.

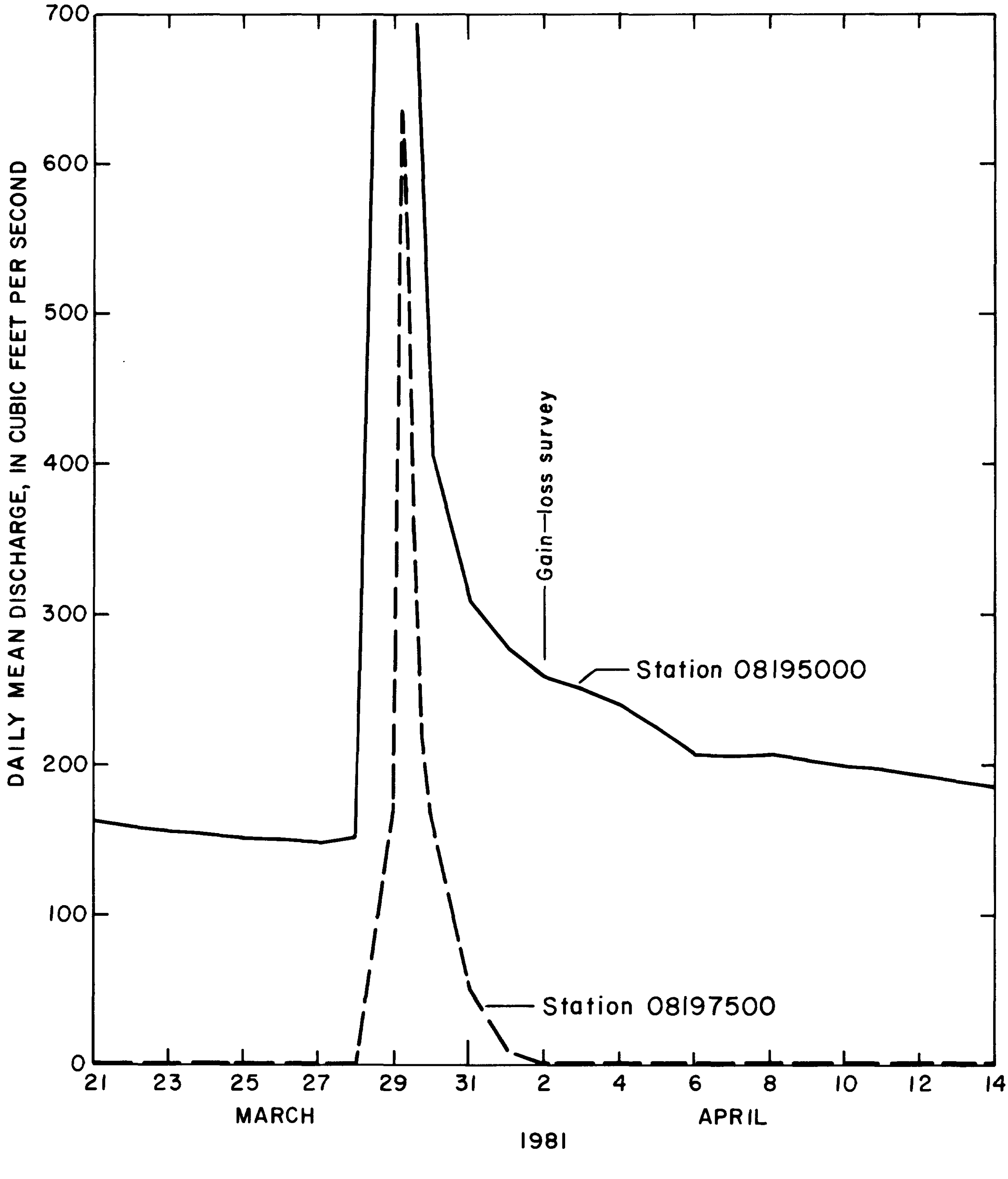

Figure 10.-Discharge hydrographs for Frio River, April 1981.

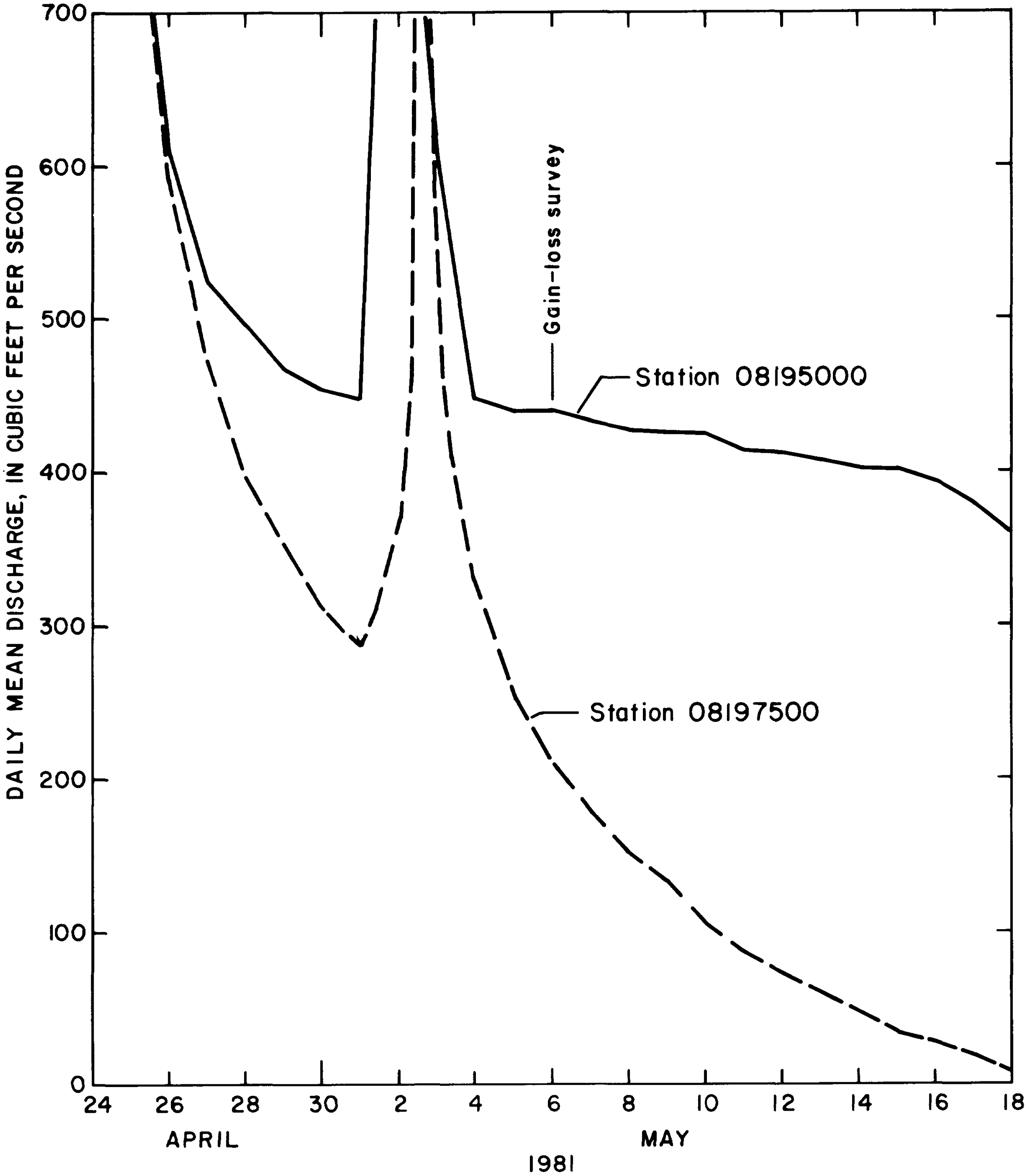

Figure 11.-Discharge hydrgraphs for Frio River, May 1981.

Table 4.--Dry Frio River survey data

Site no.	Stream	Location	River mile	June 18, 1981: Discharge (ft^3/s)	June 18, 1981: Specific conductance (µmho)	June 18, 1981: Water temperature (°C)	June 18, 1981: Flow losses (-) or gains (+) (ft^3/s)	Streambed material
1	Dry Frio River.	Lat 29°30'16", long 99°46'52" at gaging station 08196000.	0	430	431	25.0	--	Limestone.
2	do.	Lat 29°27'26", long 99°45'31" at low-water crossing on Briscoe Ranch 16.6 miles north of Uvalde.	4.0	376	424	26.0	-54	Gravel and bedrock.
3	do.	Lat 29°22'26", long 99°42'12", 30 feet upstream from FM 2690, 6.5 miles northwest of Knippa.	16.8	121	392	25.5	-255	Gravel and bedrock.
4	do.	Lat 29°21'30", long 94°41'39" at county low-water crossing, 5.7 miles northwest of Knippa.	18.2	37.2	387	26.0	-84	Gravel on limestone.
5	do.	Lat 29°19'48", long 99°40'44", 50 feet upstream from Helbig Road crossing, 3.7 miles northwest of Knippa.	21.3	19.8	376	28.5	-17.4	Gravel on limestone.
6	do.	Lat 29°18'10", long 99°39'17" at wire gate on county road, 0.9 mile north of U.S. Hwy. 90 and 1.5 miles northwest of Knippa.	24.6	1/ 4.39	368	29.0	-15.4	Gravel on limestone.

1/ Note: Water flows into pond created by dike near mouth of Dry Frio River. No flow from Dry Frio River into Frio River.

Table 5.--Frio River survey data

Site no.	Stream	Location	River mile	September 11, 1980				April 2, 1981				May 6, 1981				Streambed material
				Dis-charge (ft^3/s)	Specific conduct-ance (μmho)	Water temper-ature (°C)	Flow losses (+) or gains (-) (ft^3/s)	Dis-charge (ft^3/s)	Specific conduct-ance (μmho)	Water temper-ature (°C)	Flow losses (-) or gains (+) (ft^3/s)	Dis-charge (ft^3/s)	Specific conduct-ance (μmho)	Water temper-ature (°C)	Flow losses (-) or gains (+) (ft^3/s)	
11	Frio River.	Lat 29°29'18", long 99°42'16" at gaging station 08196000.	0	1/201	--	24.5	--	1/260	424	18.5	--	1/440	463	22.5	--	Limestone.
12	do.	Lat 29°26'47", long 99°39'55", 300 feet upstream from FM 2690, 10.8 miles north of Knippa.	5.6	160	--	26.5	-41	209	418	18.5	-51	463	457	22.5	+23	Limestone.
13	do.	Lat 29°23'23", long 98°38'57" at Sidel Ranch, 6.6 miles north of Knippa.	11.7	93.7	--	28.0	-66	148	407	--	-61	415	443	24.5	-48	Limestone.
14	do.	Lat 29°21'03", long 99°39'32", at county road extension, 4.2 miles north of Knippa.	14.6	72.7	--	30.0	-21.0	107	431	20.5	-41	385	441	25.0	-30	Gravel.
15	do.	Lat 29°16'46" long 99°39'13", 200 ft downstream from Helbig crossing, 2.7 miles north of Knippa.	16.8	42.8	--	29.5	-29.9	2/71.3 3/71.2 4/69.2	402 421 -	19.5 21.5 --	-36	326	420	--	-59	Gravel.
16	do.	Lat 29°17'30", long 99°38'43", 50 feet downstream from U.S. Hwy. 90, 0.8 mile west of Knippa (partial-record station 08195500).	22.2	2/10.6 6/ 3.58	-- --	26.0 29.0	-32.2	5/26.3 7/23.7	420 415	19.5 21.5	-45.0	251	427	--	-75	Gravel.
17	do.	Lat 29°14'44", long 99°40'17" at gaging station 08197500.	28.4	0.86	--	31.0	-9.7	0.82	355	21.5	-25.5	211	412	--	-40	Gravel and clay.

1/ Discharge from rating curve.
2/ 0920 hours.
3/ 1548 hours.
4/ 1615 hours.
5/ 1050 hours.
6/ 1625 hours.
7/ 1620 hours.

Measurements of the May 6, 1981, investigation define a net loss of 229 ft^3/s in the reach with 78 ft^3/s to the portion of the direct recharge area between sites 12 and 14 and a 174 ft^3/s loss to the indirect recharge area (sites 14-17). The measurements show an increase in discharge of 23 ft^3/s between sites 11 and 12; the cause of this increase is unknown.

The general decreases in specific conductance (424-355 μmho) between sites 11 and 17 for the April 2, 1981, investigation and (463-412 μmho) between the same sites on May 6, 1981, indicate there was no significant inflow in the reach. Specific conductance samples were not obtained during the September 11, 1980, study. The specific conductance measurements made on April 2 indicate there may have been some inflow of ground water between sites 13 and 14.

Sabinal River

Two series of discharge measurements at four sites (fig. 12 and table 6) were made on April 2 and August 6, 1981, beginning at the streamflow station 08198000 Sabinal River near Sabinal (site 1) and ending at streamflow station 08198500 Sabinal River at Sabinal (site 4). Site 2 was at or near the contact between the direct and indirect recharge areas. Site 3 was at or near the contact between the indirect recharge area and the Anacacho Limestone.

The recession flow of April 2 followed a large rise on March 29, 1981 (fig. 13). Streamflow on August 6, 1981, was declining slowly as shown on the discharge hydrograph for the two stations (fig. 14). Tributary draws had ceased to flow at the time of each investigation. Although approximately 1 day of traveltime is required for the flood wave to travel through the reach, the recession hydrographs indicate that flow was declining slowly enough during both series of measurements to reliably describe the recharge conditions.

The measurements of April 2 indicate a net loss of 82 ft^3/s with 52 ft^3/s being lost to the direct recharge area (sites 1-2) and a loss of 30 ft^3/s to the indirect recharge area (sites 2-3). There was no gain or loss to the Anacacho Limestone (sites 3-4).

The measurements of August 6 define a total reach loss of 91 ft^3/s with 40 ft^3/s being lost to the direct recharge area (sites 1-2) and a loss of 49 ft^3/s to the indirect recharge area (sites 2-3). The measurements indicate a loss of 2 ft^3/s to the area where the Anacacho Limestone is exposed (sites 3-4). This apparent loss could be to the Anacacho Limestone, to gravels, or attributed to measurement error.

There was a general decrease in specific conductance on April 2 (451 to 391 μmho) between sites 1 and 3 and an increase (467 μmho) at site 4 indicating the possibility of some inflow of water between sites 3 and 4. This same general decrease (465 to 379 μmho) and increase (442 μmho) in specific conductance was observed during the August 6 investigation.

Seco Creek

Three series of discharge measurements at eight sites (fig. 15 and table 7) were made on June 18, 19, and 22, 1981, beginning at the streamflow station

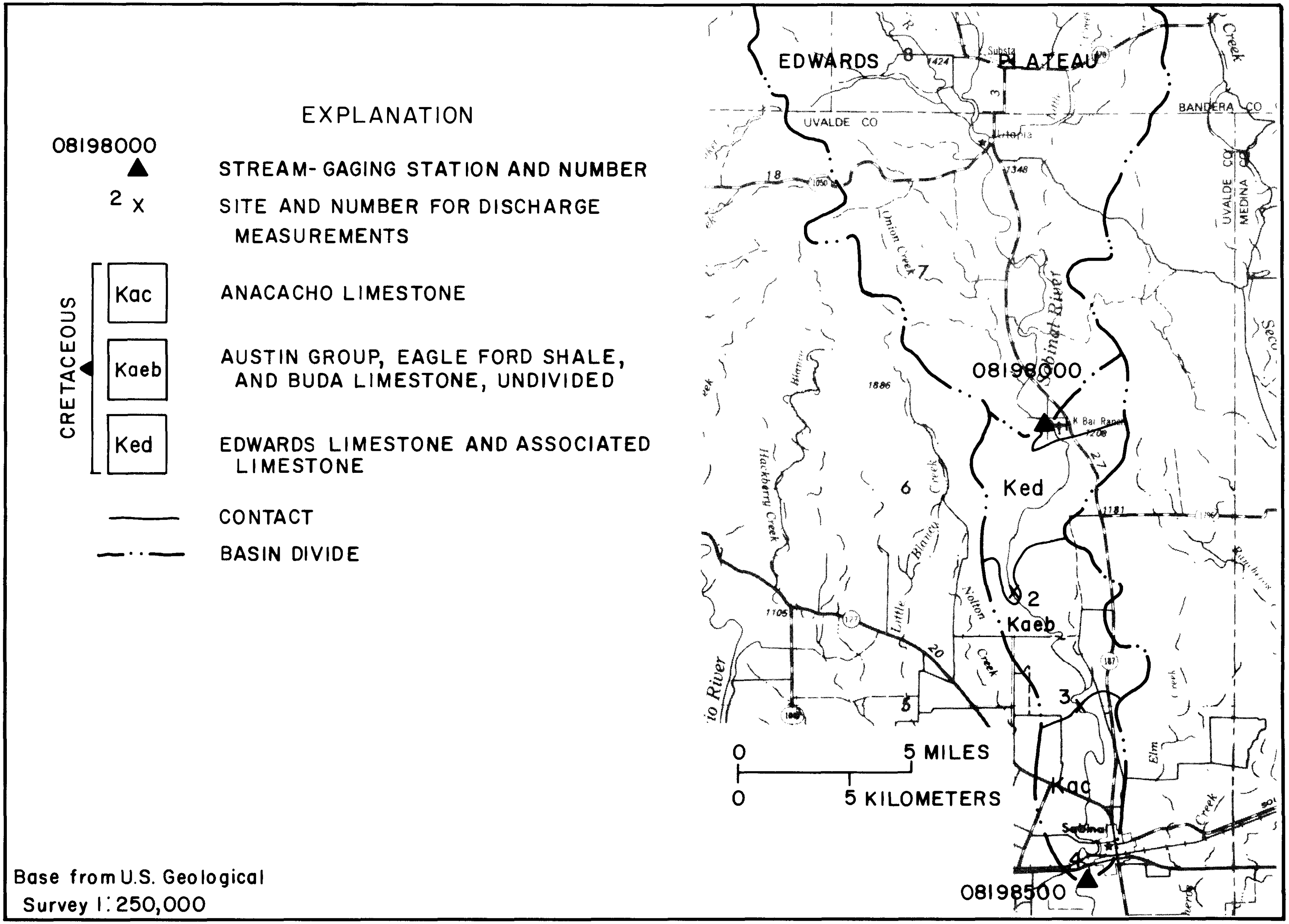

Figure 12.–Locations of discharge measurement sites in the Sabinal River basin.

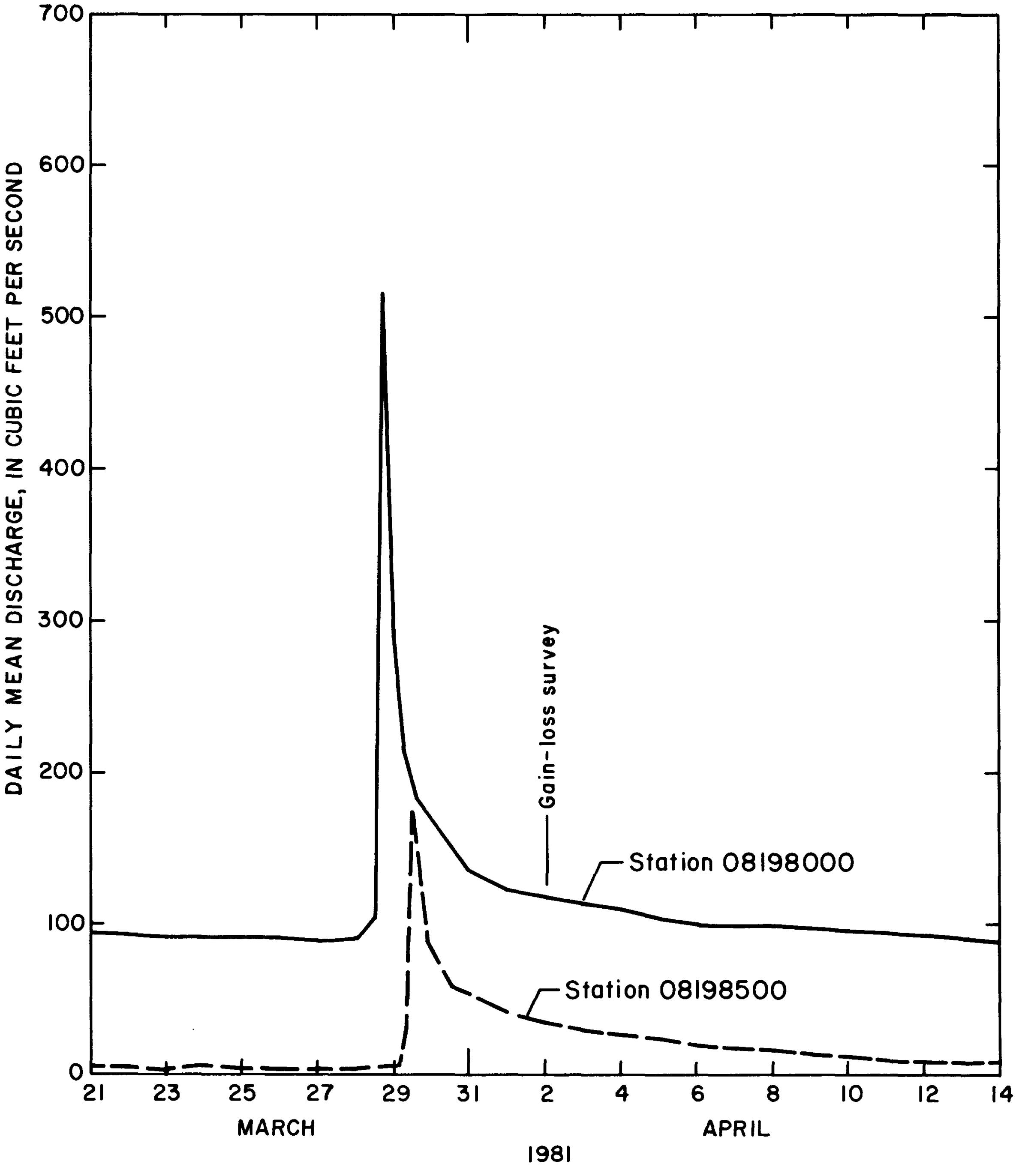

Figure 13.-Discharge hydrographs for Sabinal River, April 1981.

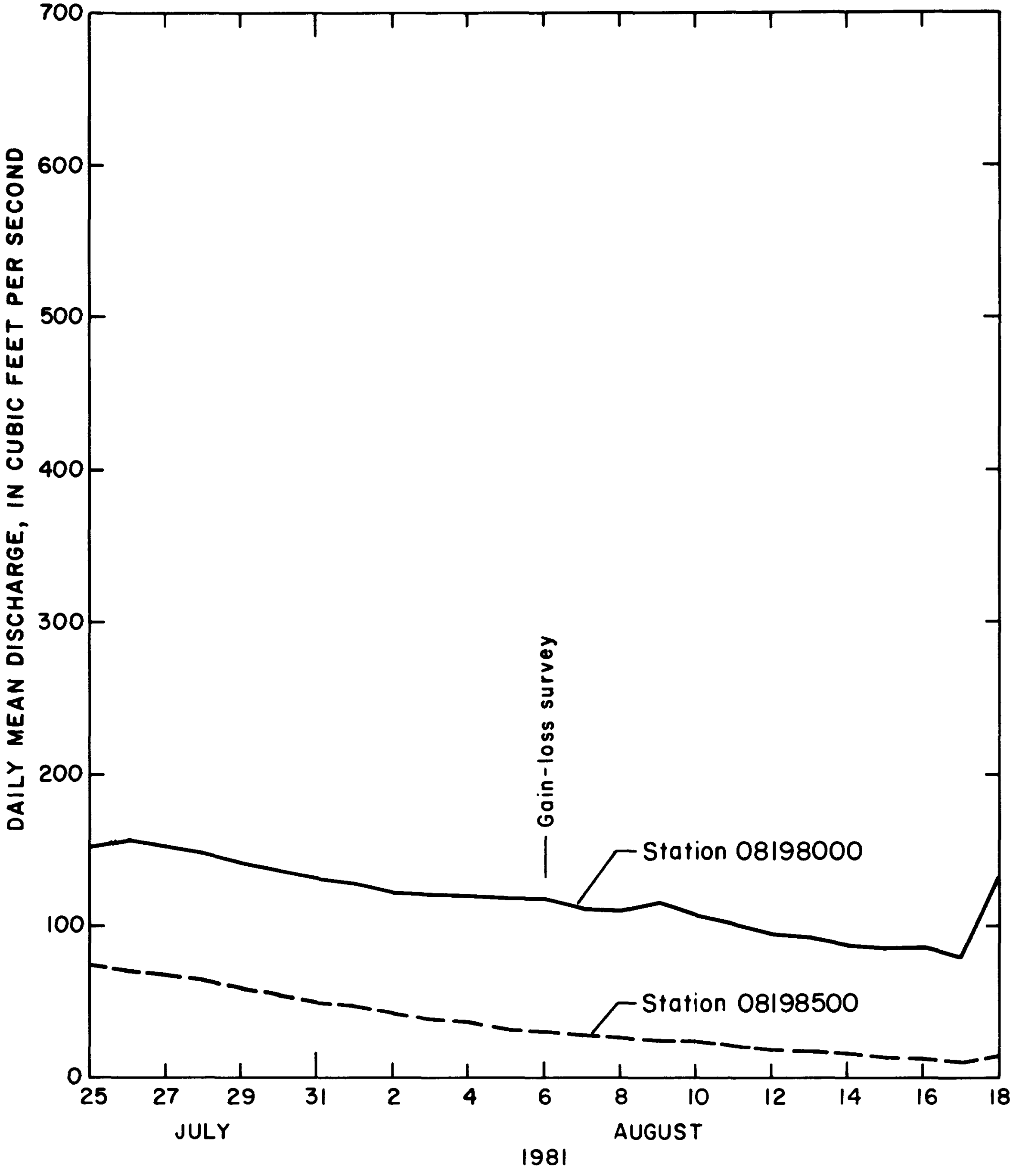

Figure 14.-Discharge hydrographs for Sabinal River, August 1981.

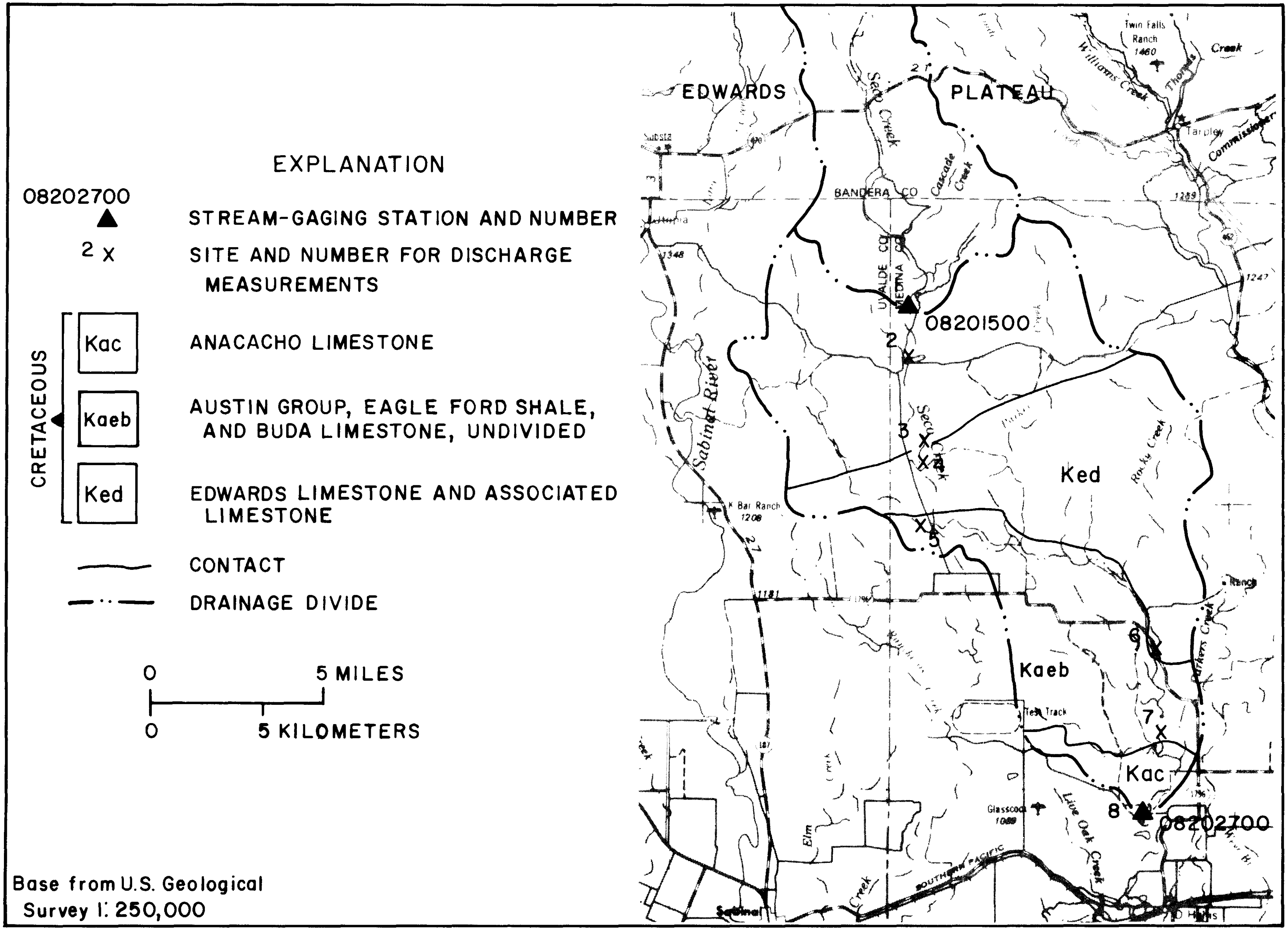

Figure 15.–Locations of discharge measurement sites in the Seco Creek basin.

Table 6.--Sabinal River survey data

Site no.	Stream	Location	River mile	April 2, 1981				August 6, 1981				Streambed material
				Dis-charge (ft^3/s)	Specific conduct-ance (μmho)	Water temper-ature (°C)	Flow losses (-) or gains (+) (ft^3/s)	Dis-charge (ft^3/s)	Specific conduct-ance (μmho)	Water temper-ature (°C)	Flow losses (-) or gains (+) (ft^3/s)	
1	Sabinal River.	Lat 29°29'35", long 99°29'49", at gaging station 08198000.	0	115	451	18.5	--	121	465	--	--	Limestone.
2	do.	Lat 29°25'57", long 99°31'02", 0.5 miles upstream from power-line crossing and 8.6 miles north of Sabinal.	5.3	63.1	420	19.5	-52	80.9	421	--	-40	Limestone.
3	do.	Lat 29°22'49", long 99°29'05", 500 feet downstream from house 4.2 miles north of Sabinal.	11.3	32.8	391	20.0	-30.3	31.5	379	--	-49.4	Gravel on lime-stone.
4	do.	Lat 29°18'47", long 99°28'46", at gaging station 08198500.	19.1	32.8	467	20.5	0.0	29.8	442	--	-1.7	Gravel on lime-stone.

Table 7.--Seco Creek survey data

Site no.	Stream	Location	River mile	June 18, 1981 Dis-charge (ft^3/s)	June 18, 1981 Specific conduct-ance (µmho)	June 18, 1981 Water temper-ature (°C)	June 18, 1981 Flow losses (-) or gains (+) (ft^3/s)	June 19, 1981 Dis-charge (ft^3/s)	June 19, 1981 Specific conduct-ance (µmho)	June 19, 1981 Water temper-ature (°C)	June 19, 1981 Flow losses (-) or gains (+) (ft^3/s)	June 22, 1981 Dis-charge (ft^3/s)	June 22, 1981 Specific conduct-ance (µmho)	June 22, 1981 Water temper-ature (°C)	June 22, 1981 Flow losses (-) or gains (+) (ft^3/s)	Streambed material
1	Seco Creek.	Lat 29°34'23", long 99°24'10", at gaging station 08201500.	0	1/345	--	--	--	1/278	--	--	--	1/179	493	24.5	--	Gravel and limestone.
2	do.	Lat 29°33'26", long 99°24'18", at county-road crossing, 17.0 miles north of D'Hanis.	1.3	326	478	25.5	-19	257	500	23.0	-21	170	494	24.5	-9	Concrete road on limestone.
3	do.	Lat 29°31'43", long 99°23'44", 300 feet downstream from north fence of Gose Ranch and 13.8 miles north of D'Hanis.	3.8	368	469	--	+42	291	--	27.0	+34	188	480	25.0	+18	Gravel and limestone.
4	do.	Lat 29°30'58", long 99°23'05", at Bat Cave, 200 feet downstream from recharge dam and 12.8 miles north of D'Hanis.	4.9	312	463	27.0	-56	309	490	24.0	+18	179	478	26.0	-9	Gravel and limestone.
5	Little Seco Creek. 2/	Lat 29°29'26", long 99°23''29", at Seco Valley road crossing, 12.5 miles north of D'Hanis.	--	0.35	--	--	--	0.20	--	--	--	0.005	--	--	--	Limestone.
6	Seco Creek.	Lat 29°26'22", long 99°17'05", at FM 1796 road crossing, 7.7 miles north of D'Hanis.	16.3	204	435	27.5	-108	175	417	27.5	-134	39.8	392	29.5	-139	Concrete base of bridge on limestone.
7	do.	Lat 29°24'04", long 99°16'57", 0.6 mile upstream from unnamed tributary and 5.4 miles north of D'Hanis.	19.5	181	423	--	-23	141	416	29.0	-34	15.8	361	30.0	-24.0	Gravel.
8	do.	Lat 29°21'43", long 99°17'05", at gaging station 08202700.	22.9	178	415	27.5	-3	119	417	28.5	-22	8.8	332	32.0	-7.0	Gravel.

1/ Disharge from rating curve.
2/ Tributary to Seco Creek.

08201500 Seco Creek at Miller Ranch near Utopia (site 1) and ending at the streamflow station 08202700 Seco Creek at Rowe Ranch near D'Hanis (site 8). Site 3 was at or near the contact of the upstream contributing drainage area and the direct recharge area. The stream reach between sites 5 and 6 generally follows the contact between the direct and indirect recharge area, but is treated as a direct recharge area. Site 7 was at or near the contact of the indirect recharge area and the Anacacho Limestone.

The measurements were made during the streamflow recession of the storm period of June 12-16, 1981, as shown on the discharge hydrographs for the two stations (fig. 16). Tributaries had ceased to flow at the time of these investigations. Traveltime through the reach, as indicated by fig. 16, ranges from about 12 hours for the flood wave to about 1 day during low flow. Each series of measurements indicate a loss in flow between sites 1 and 2, and an increase in flow between sites 2 and 3. These reaches are upstream from the direct recharge area.

The measurements on June 18 indicate losses of 164 ft^3/s to the direct recharge area (sites 3-6), and 23 ft^3/s to the indirect recharge area (sites 6-7). There was a loss of 3 ft^3/s to the Anacacho Limestone and alluvium (sites 7-8).

The measurements on June 19 define losses of 134 ft^3/s to the direct recharge area (sites 4-6), and 34 ft^3/s to the indirect recharge area (sites 6-7). Measurements indicate a loss of 22 ft^3/s to the Anacacho Limestone and alluvium (sites 7-8). Reasons for the increase in flow of 18 ft^3/s between sites 3 and 4 in the direct recharge area are unknown.

The measurements on June 22 indicate losses of 148 ft^3/s to the direct recharge area (sites 3-6), and 24 ft^3/s to the indirect recharge area (sites 6-7). There was a loss of 7 ft^3/s to the Anacacho Limestone and alluvium (sites 7-8).

The general decrease in specific conductance during each series of measurements indicates no significant inflow to the stream from ground-water sources.

Hondo Creek

A series of discharge measurements at six sites (fig. 17 and table 8) were made May 27, 1981, beginning at the streamflow station 08200000 Hondo Creek near Tarpley (site 1) and ending at the streamflow station 08200700 Hondo Creek at King Waterhole near Hondo (site 6). Site 4 was at the contact between the direct recharge area and the indirect recharge area.

The measurements followed the high discharge on May 24-25, 1981, as shown on the discharge hydrographs for the two stations (fig. 18). Tributary draws had ceased to flow at the time of the investigation.

The measurements indicate a net loss of 158 ft^3/s in the reach with 140 ft^3/s to the direct recharge area (sites 1-4) and a loss of 19 ft^3/s to the indirect recharge area (sites 4-5). The slight gain of 1.3 ft^3/s in flow

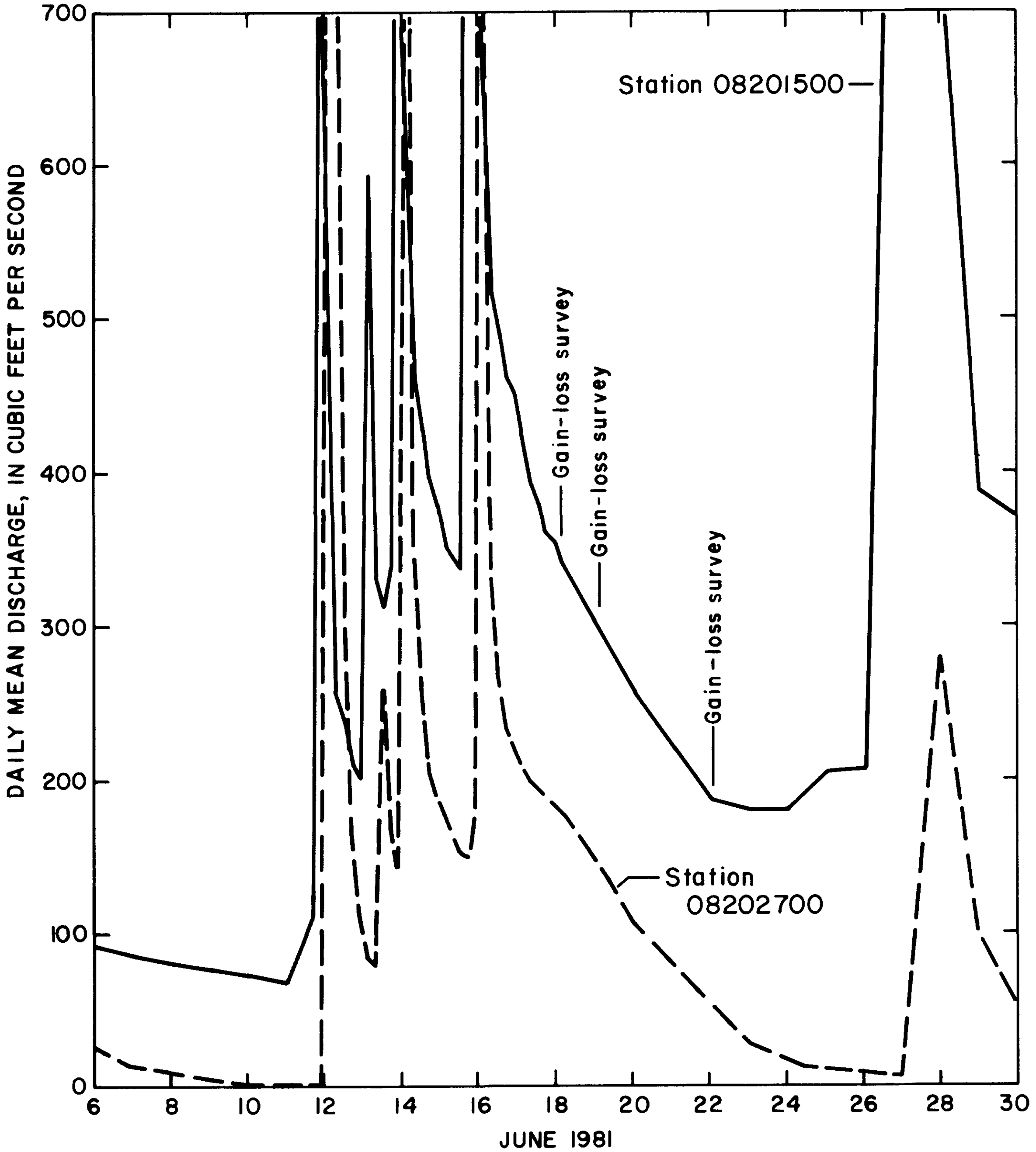

Figure 16.-Discharge hydrographs for Seco Creek, June 1981.

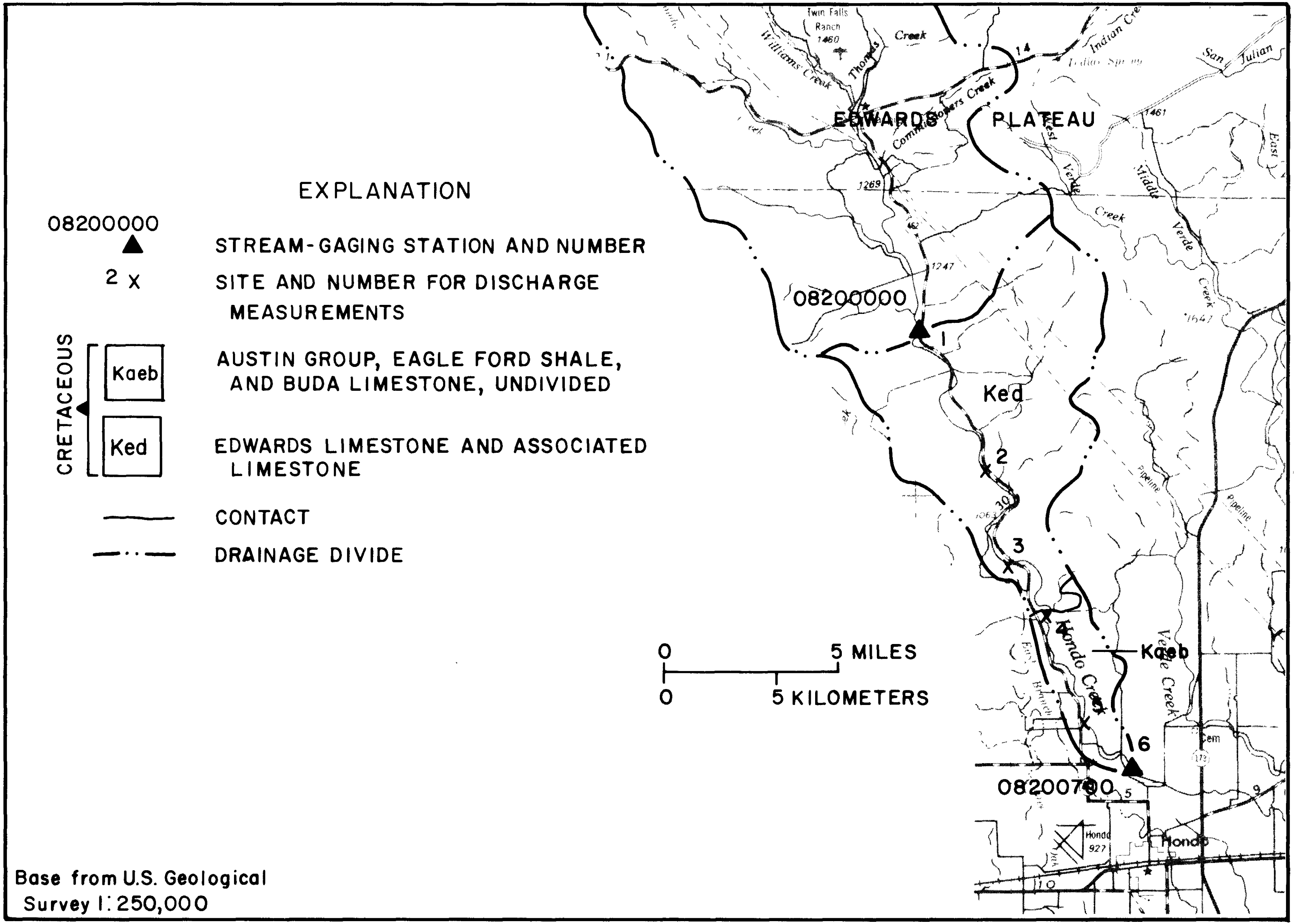

Figure 17.-Locations of discharge measurement sites in the Hondo Creek basin.

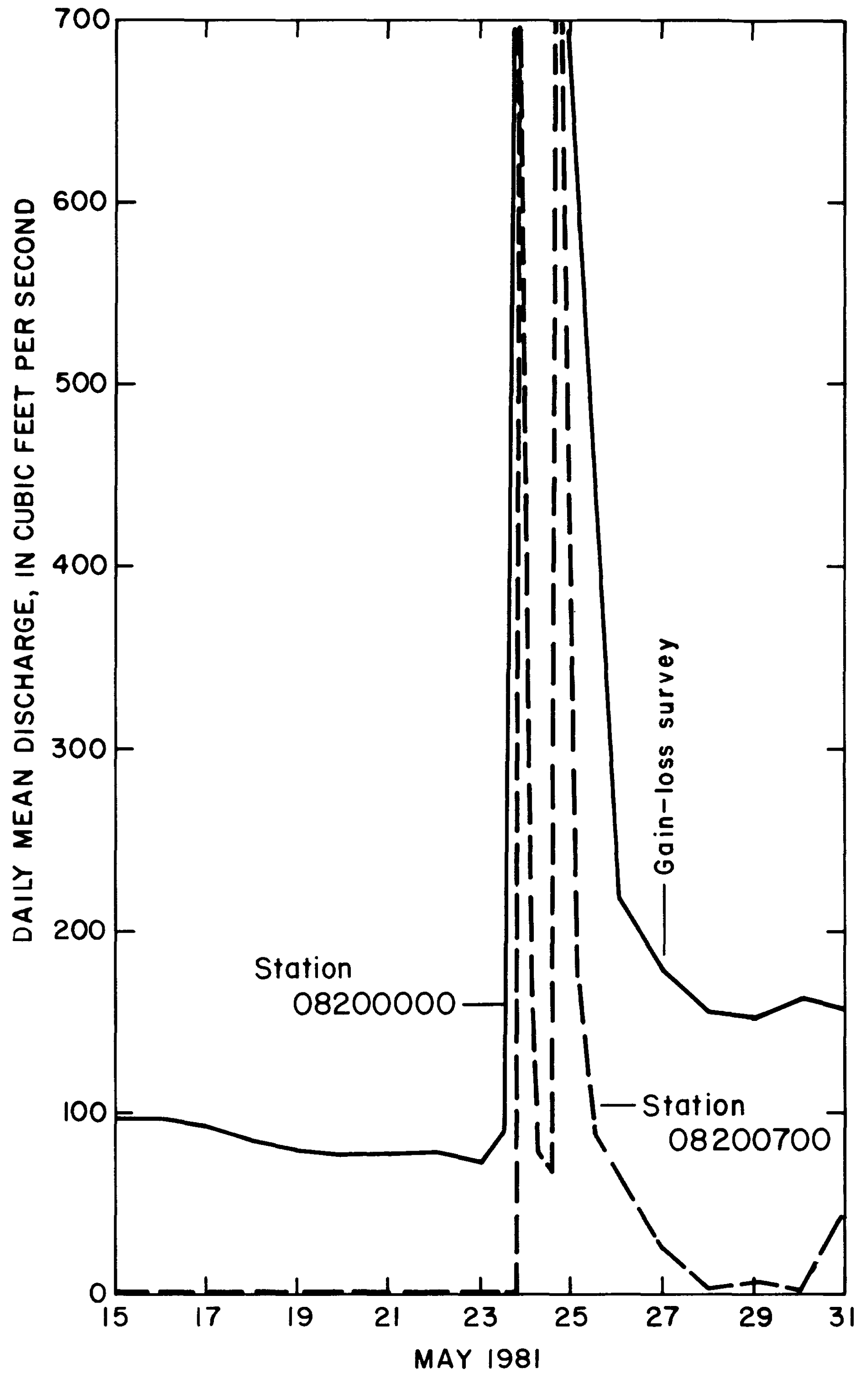

Figure 18.-Discharge hydrographs for Hondo Creek, May 1981.

Table 8.--Hondo Creek survey data

Site no.	Stream	Location	River mile	May 27, 1981 Dis-charge (ft^3/s)	Specific conduct-ance (µmho)	Water temper-ature (°C)	Flow losses (-) or gains (+) (ft^3/s)	Streambed material
1	Hondo Creek.	Lat 29°34'10", long 99°14'47", at gaging station 08200000.	0	179	454	--	--	Gravel and bedrock.
2	do.	Lat 29°31'17", long 99°13'12", 0.7 miles upstream from Twin Hollow and 10.4 miles north of Hondo.	5.7	101	432	28.0	-78	Do.
3	do.	Lat 29°28'23", long 99°12'16", at low-water crossing on FM 462, 7.6 miles north of Hondo.	9.7	59.3	400	29.5	-42	Do.
4	do.	Lat 29°27'06", long 99°11'12", at discontinued gaging station, 08200500, 5.9 miles north of Hondo.	12.4	39.0	395	30.5	-20.3	Do.
5	do.	Lat 29°24'17", long 99°10'22", 500 feet upstream from culvert on drainage ditch on FM 462, 2.4 miles north of Hondo.	16.8	19.6	375	30.5	-19.4	Do.
6	do.	Lat 29°23'26", long 99°09'04", at gaging station 08200700.	18.9	20.9	323	30.0	+1.3	Do.

between sites 5 and 6 could be either return flow from bank storage or from errors introduced by stream travel time in the reach.

The general decrease in specific conductance from 454 to 323 μmho between sites 1 and 6 indicates no significant inflow from ground water in the reach.

Verde Creek

Three series of measurements at 10 sites (fig. 19 and table 9) were made on Verde Creek and its tributaries on September 8, 1980, April 24, 1981, and June 17, 1981, beginning on the Middle Verde Creek about 70 feet upstream from State Highway 172 (site 1), about 15.6 miles north of Hondo and ending on Verde Creek at State Highway 173 crossing at Vandenburg Community (site 10), about 4.5 miles north of Hondo. The reach covered 16.5 miles and involved the Verde, Middle Verde, East Verde Creeks, and Martin Creek. The direct recharge area includes sites 1 to 9 and the indirect recharge area is between sites 9 and 10.

Some tributaries were flowing during the studies and are accounted for by measurements made at or near their confluences with Verde Creek as shown in table 9. The main stem in the basin is considered to be Middle Verde Creek above its confluence with South Verde Creek where Verde Creek begins.

Measurements on September 8, 1980, indicate that the combined upstream flow of 88 ft^3/s from Middle Verde and East Verde Creeks was lost to the aquifer between sites 1 and 9. The major losses were 78 ft^3/s to the portion of the direct recharge area between sites 1 and 5. It is possible that flows between sites 7 and 10 were intermittent. The measurements indicate a net gain in flow of 1.1 ft^3/s between sites 9 and 10.

Measurements on April 24, 1981, show that the combined upstream flow of 158 ft^3/s was lost to the aquifer between sites 1 and 10.

Measurements on June 17, 1981, were made during higher flows than existed for the previous gain-loss studies on Verde Creek. Two measurements were made at each of the tributary sites upstream from the recharge area. Losses shown in table 9 are based on the earlier of the measurements at each site. Total upstream flow on Middle and East Verde Creeks was 415 ft^3/s. The measurements define a total net loss of 274 ft^3/s of which 225 ft^3/s is in the direct recharge area (sites 1-9) and 49 ft^3/s is in the indirect recharge area (sites 9-10).

Specific conductance was measured during the June 17, 1981, investigation. The general decrease in specific conductance from 486 to 370 μmho between sites 1 and 10 indicates no significant inflow in the reach.

Historical Data Analyses

The process used in analyzing flow and recharge for streams in the study area produced, in addition to regression equations for downstream flow, results that are significant in identifying and understanding the influence of various parameters on recharge to the ground-water system. The correlation coefficents

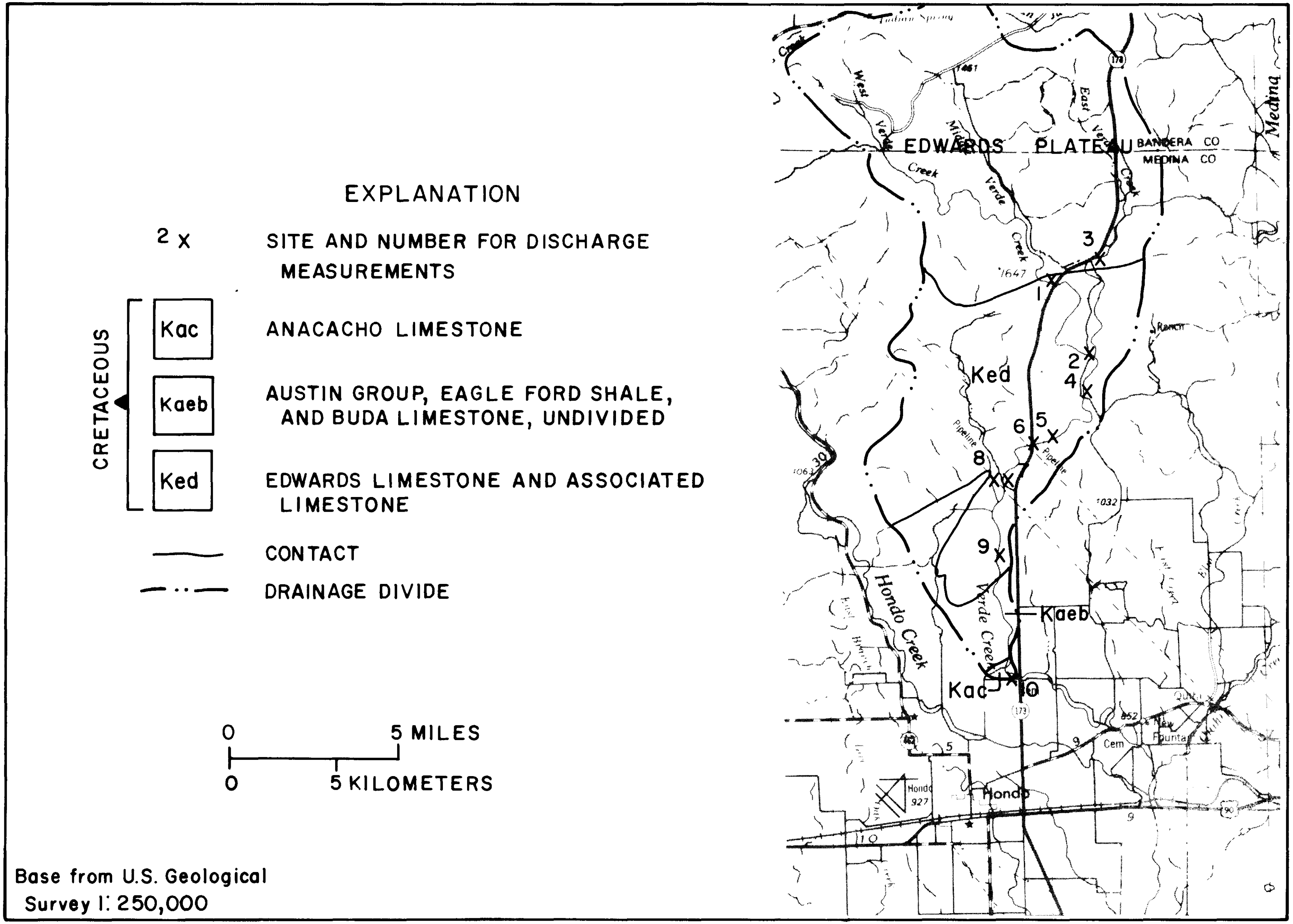

Figure 19.–Locations of discharge measurement sites in the Verde Creek basin.

Table 9.--Verde Creek survey data

Site no.	Stream	Location	River mile	September 8, 1981 Dis-charge (ft^3/s)	September 8, 1981 Specific conduct-ance (µmho)	September 8, 1981 Water temper-ature (°C)	September 8, 1981 Flow losses (-) or gains (+) (ft^3/s)	April 24, 1981 Dis-charge (ft^3/s)	April 24, 1981 Specific conduct-ance (µmho)	April 24, 1981 Water temper-ature (°C)	April 24, 1981 Flow losses (-) or gains (+) (ft^3/s)	June 17, 1981 Dis-charge (ft^3/s)	June 17, 1981 Specific conduct-ance (µmho)	June 17, 1981 Water temper-ature (°C)	June 17, 1981 Flow losses (-) or gains (+) (ft^3/s)	Streambed material
1	Middle Verde Creek.	Lat 29°34'08", long 99°05'55", 700 feet upstream from bridge on State Highway 173, 15.6 miles north of Hondo.	0	71.2	-	24.0	--	1/146 3/144	--	19.0	--	2/320 4/284	486 483	21.0 22.5	--	Limestone and some thin gravel bars.
2	do.	Lat 29°32'17", long 99°05'04", 200 feet upstream from county road crossing, 800 feet upstream from East Verde Creek, and 13.7 miles north of Hondo.	3.7	46.9	--	24.0	-24.3	102	--	20.5	-44	299	474	21.0	-21	Gravel.
3	East Verde Creek. 5/	Lat 29°34'41", long 99°04'48", at county road crossing 16.0 miles north of Hondo.	6/3.0	16.4	--	24.0	--	11.9	--	--	--	7/95.4 8/85.6	497 500	21.0 23.0	--	Do.
4	Middle Verde Creek.	Lat 29°31'17", long 99°05'04", at county road crossing 12.7 miles north of Hondo.	5.1	9/30	--	--	-33	104	--	22.0	-10	366	467	22.5	-28	Concrete low-water crossing on limestone.
5	do.	Lat 29°30'11", long 99°06'02", 40 feet downstream from Middle Verde recharge reservoir, 11.1 miles north of Hondo (station 08200990).	7.4	9.02	--	24.0	-21	39.4	--	21.0	-65	--	--	--	--	Gravel and limestone.
6	do.	Lat 29°30'05", long 99°06'31", 30 feet downstream from bridge on State Highway 173, 10.9 miles north of Hondo.	8.1	8.63	--	27.0	-0.39	34.3	--	21.0	-5.1	252	451	21.5	-114	Gravel.
7	Verde Creek.	Lat 29°29'01", long 99°07'31", 200 feet downstream from county road crossing 9.7 miles north of Hondo.	10.0	3.70	--	27.0	-4.93	22.3	--	--	-12.0	204	442	22.0	-48	Limestone with thin gravel bars.
8	Martin Creek. 10/	Lat 29°30'26", long 99°07'52", 1,800 feet upstream from mouth, 9.2 miles north of Hondo.	--	0	--	--	--	--	--	--	--	0	--	--	--	Limestone.
9	Verde Creek.	Lat 29°27'00", long 99°07'30", at Seifert Branch, 7.2 miles north of Hondo.	12.6	9/0.05	--	--	-3.65	8.42	--	23.5	-13.9	190	428	23.0	-14	Gravel.
10	do.	Lat 29°24'16", long 99°06'59", 100 feet downstream from bridge on State Highway 173, 4.5 miles north of Hondo.	16.5	1.16	--	25.0	+1.11	0.36	--	23.0	-8.06	141	370	24.0	-49	Do.

1/ 1205 hours.
2/ 1220 hours.
3/ 1610 hours.
4/ 1550 hours.
5/ Tributary to Middle Verde Creek.
6/ Site located 3.0 miles upstream from mouth.
7/ 1250 hours.
8/ 1645 hours.
9/ Estimated discharge.
10/ Tributary to Verde Creek.

and scatter diagrams using selected daily data show that of the variables examined, upstream discharge has the highest correlation with downstream discharge. There is some scatter of data points in the high-flow regime, but a common characteristic for most streams is a horizontal band of points in the very low downstream-flow regime that is below and to the left of the typical diagonal band of data points as illustrated in figure 20.

The upstream discharges for the points in the horizontal band are considered to be less than the through-flow threshold, the flow required at the upstream site to sustain flow downstream from the recharge zone. Below this threshold, all upstream flow is assumed to be lost to recharge. For each stream, this flow was determined by eliminating the data points in the horizontal band with use of the scatter diagrams, determining the linear-regression equation of the diagonal band using only the upstream discharges as the independent variables, and computing the upstream threshold discharge as that for the zero intercept of the downstream discharge. All additional statistical analyses were made only after eliminating the data points in the horizontal band, which was identified as all points with downstream discharges at and below a selected value, generally 1.0 or 2.0 ft^3/s. All of the ranges in the independent variables are given for the reduced (diagonal band) data set.

The correlation of downstream discharge to ground-water levels is generally very weak. There is substantial scatter and generally very few or no data points in the high-discharge, low ground-water level regime. Antecedent conditions are represented by the base 10 logarithm of the number of days to accumulate selected flow volumes at the upstream stations or by the 5-day antecedent flow volumes at the upstream sites. The correlations between downstream discharge and antecedent conditions generally show a scatter of points in the low-discharge, long time-period regime, very little discharge variability for very long time periods, and subtantial scatter throughout the discharge range for low and median time periods. The typical relation of downstream flow and the days to satisfy antecedent flow volumes is shown in figure 21.

Because of the low-discharge variability for very long time periods, an upper limit was set for the time period for the regression analysis. This limit was selected from the scatter diagrams and implies that any additional time will not have any additional influence on the streamflow losses.

The stepwise regression produced an equation for some streams that included two presumably independent variables that represented antecedent flow volumes. Close examination of how these variables were used in the equations indicated that together they did not support the conceptual model. The inclusion of one antecedent flow variable usually supported the reasoning that as the time to satisfy accumulated flow volume increased, ground-water content in the shallow formations decreased causing lesser discharge downstream from the study reach. An additional antecedent flow variable, when used in the relation, however, did not support this reasoning. Examination of correlation coefficients of the independent variables themselves indicated that the variables representing antecedent flow were highly correlated with each other; this multicollinearity produced instability in the regression coefficients when more than one such variable was used in the regression equation. Consequently, only

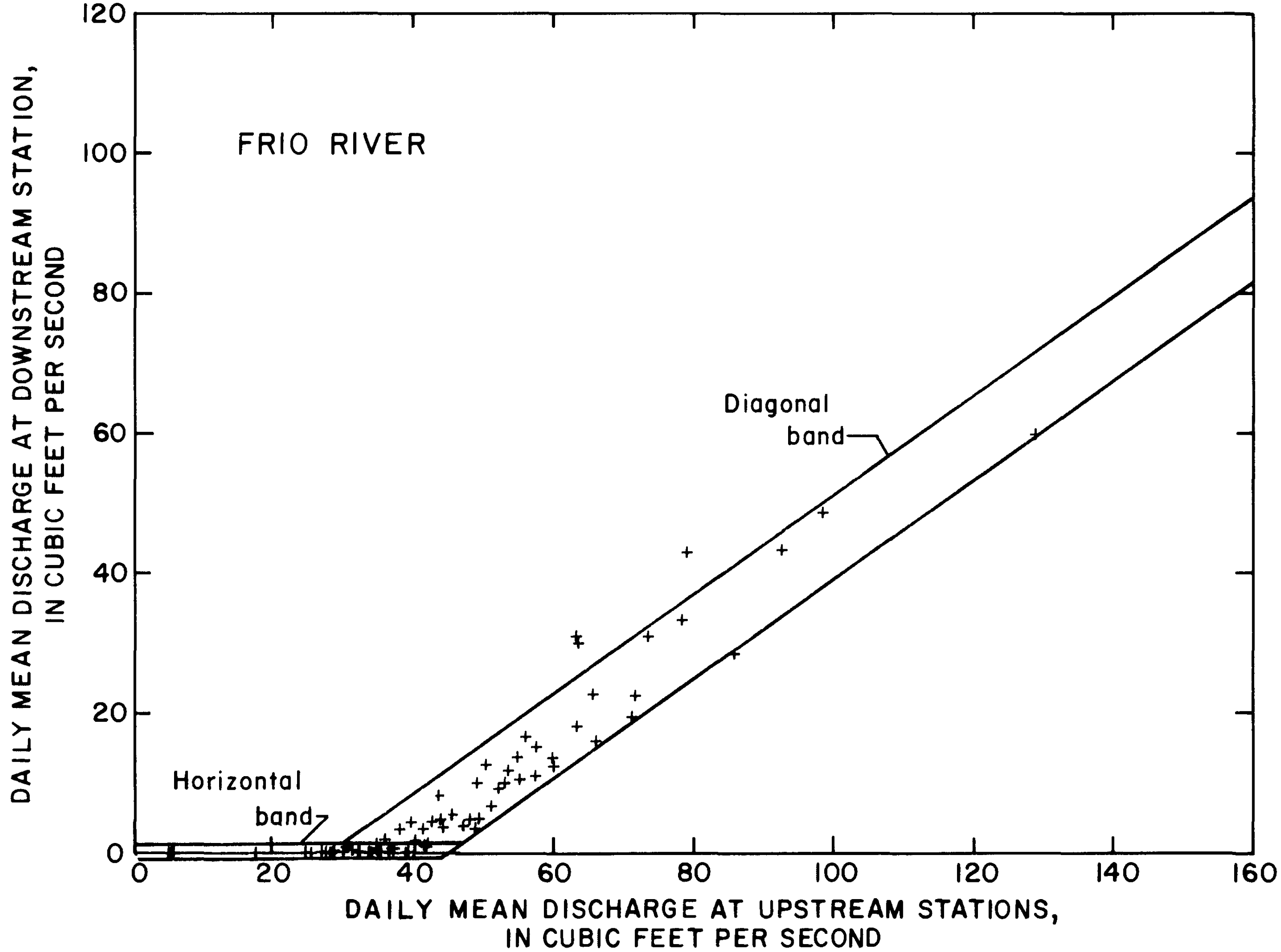

Figure 20.—Characteristic relationship of upstream to downstream discharge of streams crossing the Balcones Fault Zone.

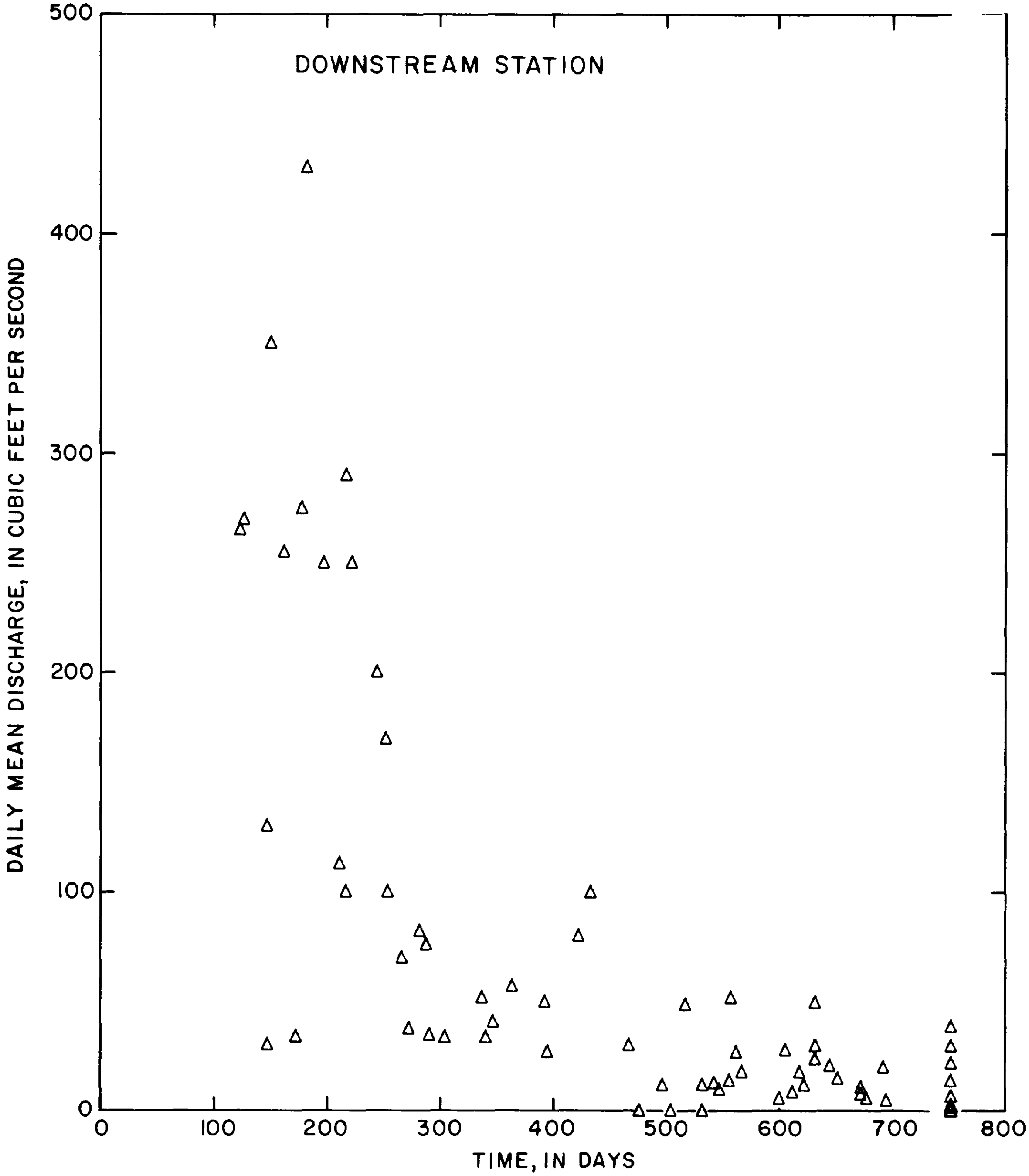

Figure 21.-Scatter diagram showing typical relationship between daily mean discharge at the downstream station and the number of days to accumulate a given flow volume at the upstream station.

the most significant antecedent condition variable was included in the data set when the regression technique was applied to develop the final equations.

Similarly, the regression analysis produced, in some instances, regression coefficients for some variables that did not support the conceptual model and were contradictory to the correlation coefficients of downstream discharge and the respective independent variable. Examination of the correlation coefficients between the independent variables themselves lent insight into the combined effect of these variables on the downstream flow and dictated excluding the lesser significant independent variable from the data set in developing the final regression equation even though the statistical analysis showed the variable to be significant.

The range of application for the regression equations is expected to cover the range of the independent parameters in the data set. However, the interrelationship of the two or more parameters in an equation can predict a negative downstream discharge, which is unreasonable and should be set to zero.

The following sections of this report present the results of the statistical analyses conducted for gaged streams in the study area. Included are the developed relationships for flow downstream from the recharge zone, statistics that indicate the accuracies of the developed equations, discussion of the hydrologic implications drawn from the analyses, and illustrative materials such as discharge hydrographs for years of hydrologic extremes, plots showing the relationships of selected variables, and plots of observed versus predicted values of flow. Also presented are illustrations and discussions describing the sensitivity of the independent variables retained in the equations.

Nueces River

Data used in the analyses of downstream station discharge from the Nueces River were selected from historic records for 1941-81. Flow in the West Nueces River at the upstream boundary of the recharge zone was combined with the upstream flow of the Nueces River prior to conducting the analysis. Although flow in the West Nueces River is negligible during low flow periods, this tributary does contribute to downstream discharge during higher flow periods. The relationship of downstream discharge to the combined upstream discharges is illustrated in figure 22. There are 103 data points in the data set. The horizontal band of points is not prevalent in the scatter diagram (fig. 22); therefore no points were omitted in the statistical analyses. Combined upstream discharges range from 22 to 866 ft^3/s.

Ground-water levels were provided by records of well YP-69-50-302 located in the city of Uvalde as shown in figure 2. No datum adjustment was made to normalize the ground-water levels, which range from 19.8 to 73.4 feet (depth to water). The days required to accumulate flow volumes of 5,000 and 60,000 ft^3/s-days at the upstream station were compiled for use in the analysis. Values for these antecedent condition indices range from 5 to 150 days for volumes of 5,000 ft^3/s-days and from 19 to 910 days for volumes of 60,000 ft^3/s-days.

A linear regression analysis that used the flow downstream from the recharge zone as the only independent variable produced the following equation:

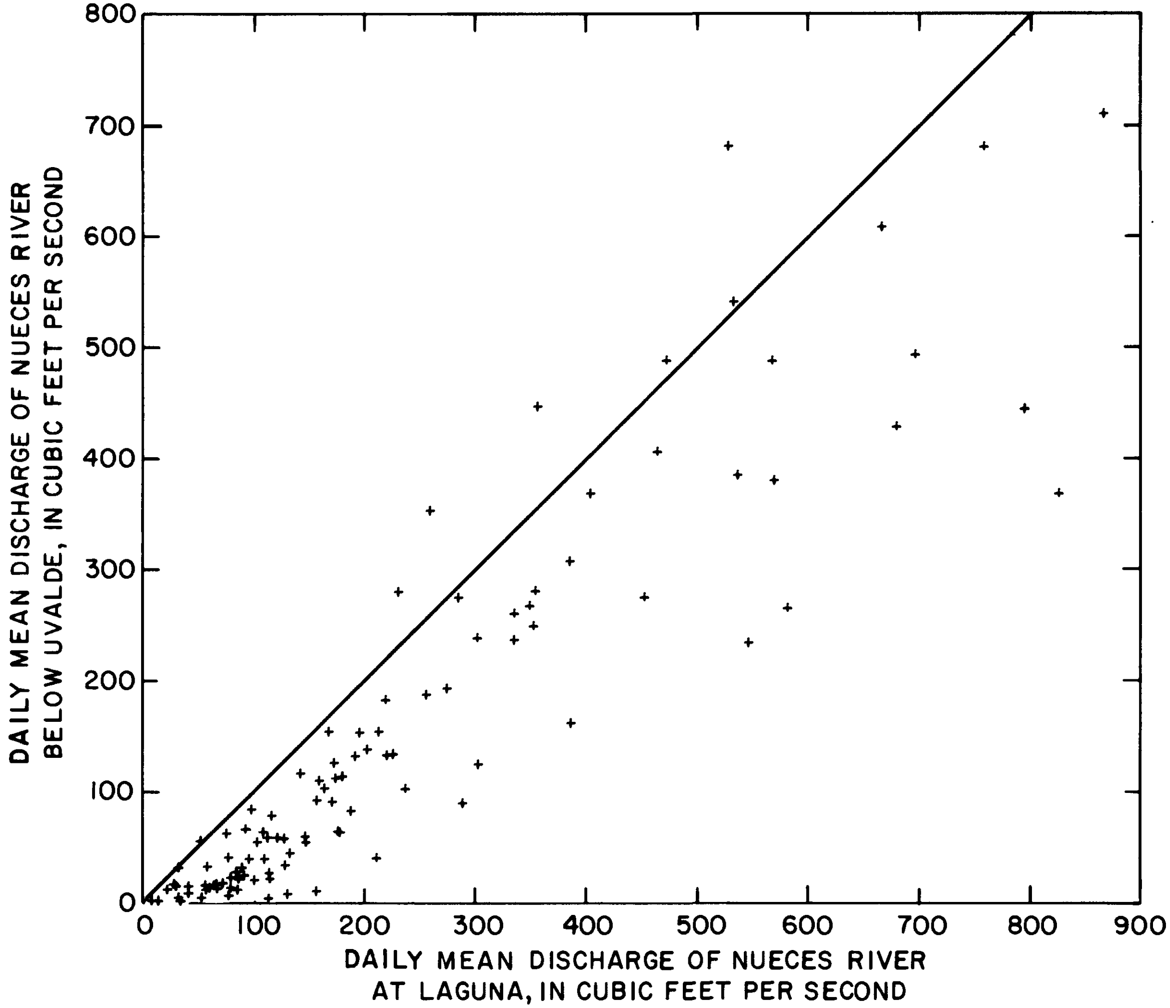

Figure 22.-Scatter diagram showing relationship of combined discharges of the Nueces River at Laguna and West Nueces River near Brackettville (upstream stations) to discharge of Nueces River below Uvalde (downstream station).

$$Q_{dn} = -25.7 + 0.77\ Q_{up} \tag{2}$$

where Q_{dn} is daily mean discharge, in cubic feet per second, at stream-gaging station 08192000 Nueces River below Uvalde; and
Q_{up} is combined daily mean discharge, in cubic feet per second, at stream-gaging stations 08190000 Nueces River at Laguna and 08190500 West Nueces River near Brackettville.

The equation indicates that combined flows of about 33 ft^3/s at the gages upstream from the recharge zone are required to produce flow at the downstream gage site. The regression equation also indicates that about 23 percent of the combined upstream flow above this threshold is also lost to recharge. The equation has an R-square value of 0.83 and a standard error of estimate of 73.0 ft^3/s. The wide scatter in the plotted observations (fig. 22) shows that recharges much greater than 50 ft^3/s are not uncommon and indicates that other factors strongly influence the portion of upstream flow that is recharged to the aquifer.

The discharge hydrographs and ground-water levels shown in figures 23 and 24 illustrate extremes in recharge to the Edwards aquifer from the Nueces River and indicate the influence of ground-water levels on recharge and on downstream flow. During the 1958 drought recovery, ground-water levels were still depressed, and although upstream flows in the Nueces River as large as 480 ft^3/s occurred for a sustained period, downstream flows remained very low. During 1977, when ground-water levels were high, downstream flow exceeded upstream flow for a significant period of time.

The correlation coefficients of downstream discharge and the independent variables are:

Dependent variable	Independent variables			
	Q_{up}	Gwl	$\log_{10}(t_{5,000})$	$\log_{10}(t_{60,000})$
Q_{dn}	0.91	-0.27	-0.79	-0.50

where Q_{dn} and Q_{up} are as defined previously;
Gwl is depth to water, in feet, in well YP-69-50-302; and
$t_{5,000}$ and $t_{60,000}$ are time, in days, to accumulate flow volumes of 5,000 and 60,000 ft^3/s-days, respectively, at station 08190000.

The correlation coefficients show that the upstream discharge has the highest linear relationship to downstream discharge and would be the main factor in estimating downstream flow. The coefficients support the conceptual model regarding the impact of the independent variables on downstream flow.

The multiple regression analysis used 103 data values to produce the following equation for flow Q_{dn} at the downstream gage, Nueces River near Uvalde:

$$Q_{dn} = 277 + 0.72\ Q_{up} - 2.96\ Gwl - 74.8\ \log_{10}(t_{60,000}) \tag{3}$$

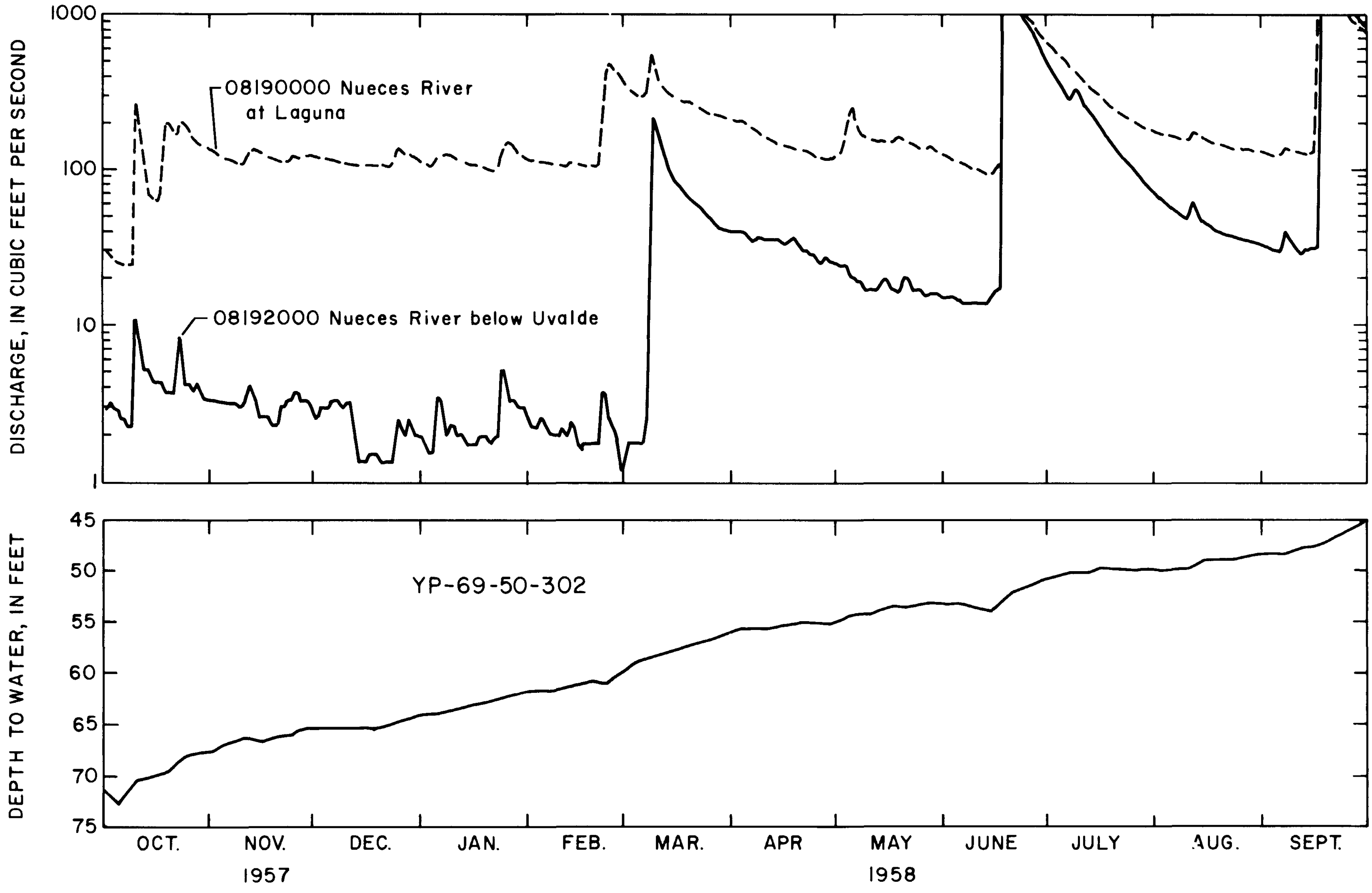

Figure 23.-Discharge and ground-water level hydrographs in the Nueces River basin for 1958, when recovering from drought conditions.

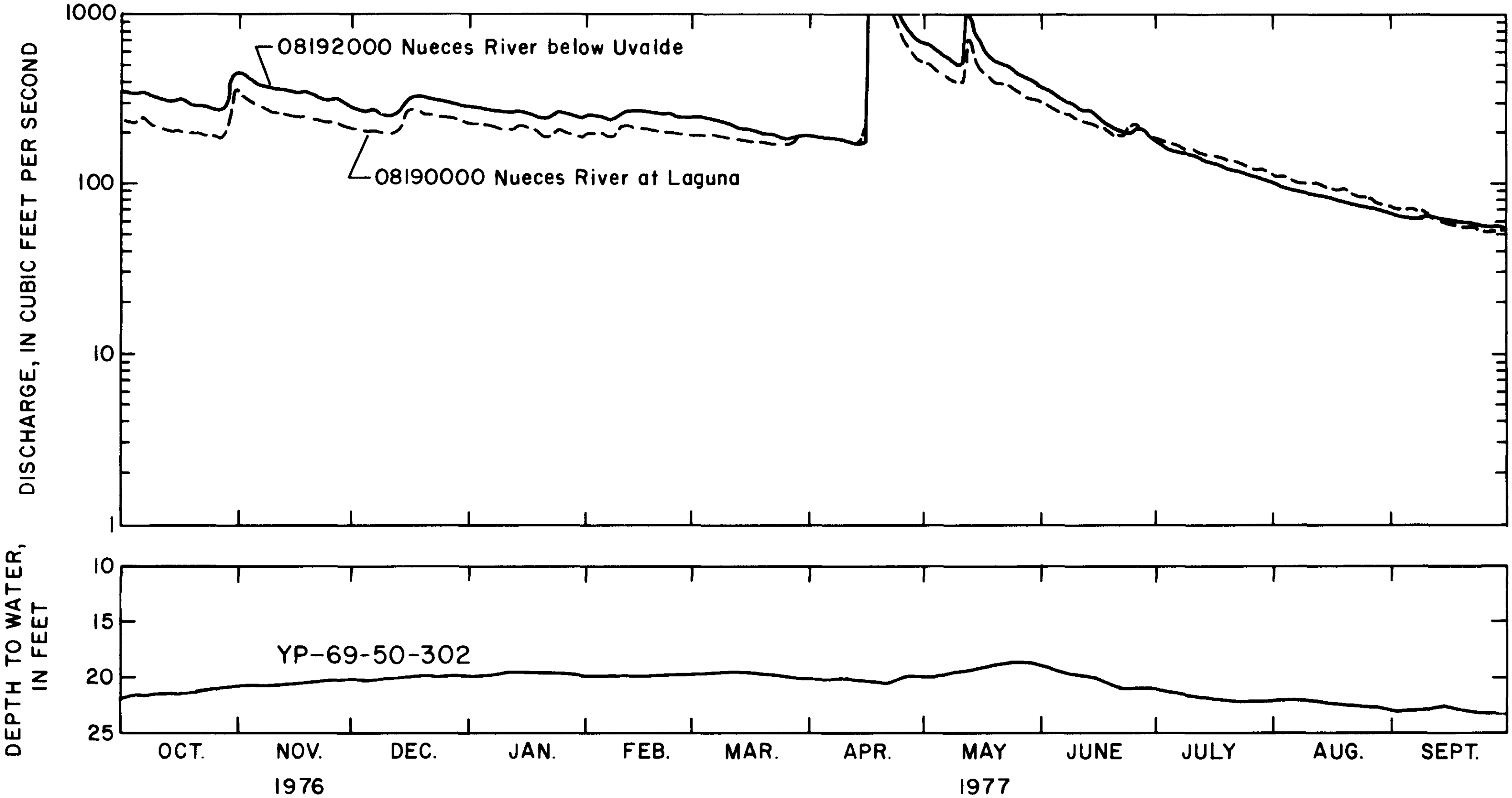

Figure 24.-Discharge and ground-water level hydrographs in the Nueces River basin for 1977, during high ground-water level conditions.

This equation has an R-square value of 0.89 and a standard error of estimate of 60.2 ft^3/s. The goodness of fit for the observed and predicted values is shown in figure 25.

The antecedent conditions provided the least amount of improvement in the relation. An examination of the equation shows that for a given upstream discharge, the downstream discharge will decrease with a lowering of ground-water levels and the drier antecedent conditions. This response confirms the conceptual model discussed earlier.

The sensitivity of the independent variables in the above equation is illustrated in figure 26. The range of downstream discharge is 125 ft^3/s, when antecedent conditions are varied from 19 to 910 days and ground-water levels are held constant. For similarly varied ground-water levels with antecedent conditions held constant, the range of downstream flow is 159 ft^3/s.

Frio River

Data used in the analysis of flow at the downstream station were selected from discharge records for 1958-81. Because the Dry Frio River is a major tributary to the Frio River and enters the main stem in the recharge zone, it is also gaged above the recharge zone. The selected flows at the two upstream stations were combined for analysis. A scatter diagram between combined upstream and downstream discharges (fig. 27) shows a reasonably strong relationship between the two variables. The horizontal band is obvious and can essentially be eliminated by omitting the 22 data points, which have downstream discharges at or below 2.0 ft^3/s. The original data set has 77 data points. For the remaining 55 points, the combined upstream discharge ranges from 284 to 1,285 ft^3/s.

Ground-water levels are from records of well YP-69-35-501, which is located about 18 miles north-northeast of Uvalde and shown in figure 2. Ground-water levels for the reduced data set range from 23.7 to 56.2 feet (depth to water). No datum adjustment was made. The number of days required to accumulate flow volumes of 4,000 and 48,000 ft^3/s-days were used for antecedent conditions indices. These volumes were selected on the basis of the ratio of the long-term mean-annual flow between the station 08190000 Nueces River at Laguna and the station 08192000 Frio River at Concan and the two antecedent flow volumes used in the Nueces River analysis. The number of days representing antecedent conditions range from 3 to 15 for volumes of 4,000 ft^3/s-days and from 59 to 487 for volumes of 48,000 ft^3/s-days.

The following equation that expresses flow downstream from the recharge zone as a function of combined flows upstream from the recharge zone was produced by linear regression analysis:

$$Q_{dn} = -248 + 0.70\ Q_{up} \qquad (4)$$

where Q_{dn} is daily mean discharge, in cubic feet per second, at stream-gaging station 08197500 Frio River below Dry Frio River near Uvalde; and
Q_{up} is combined daily mean discharge, in cubic feet per second, at stream-gaging stations 08195000 Frio River at Concan and 08196000 Dry Frio River near Reagan Wells.

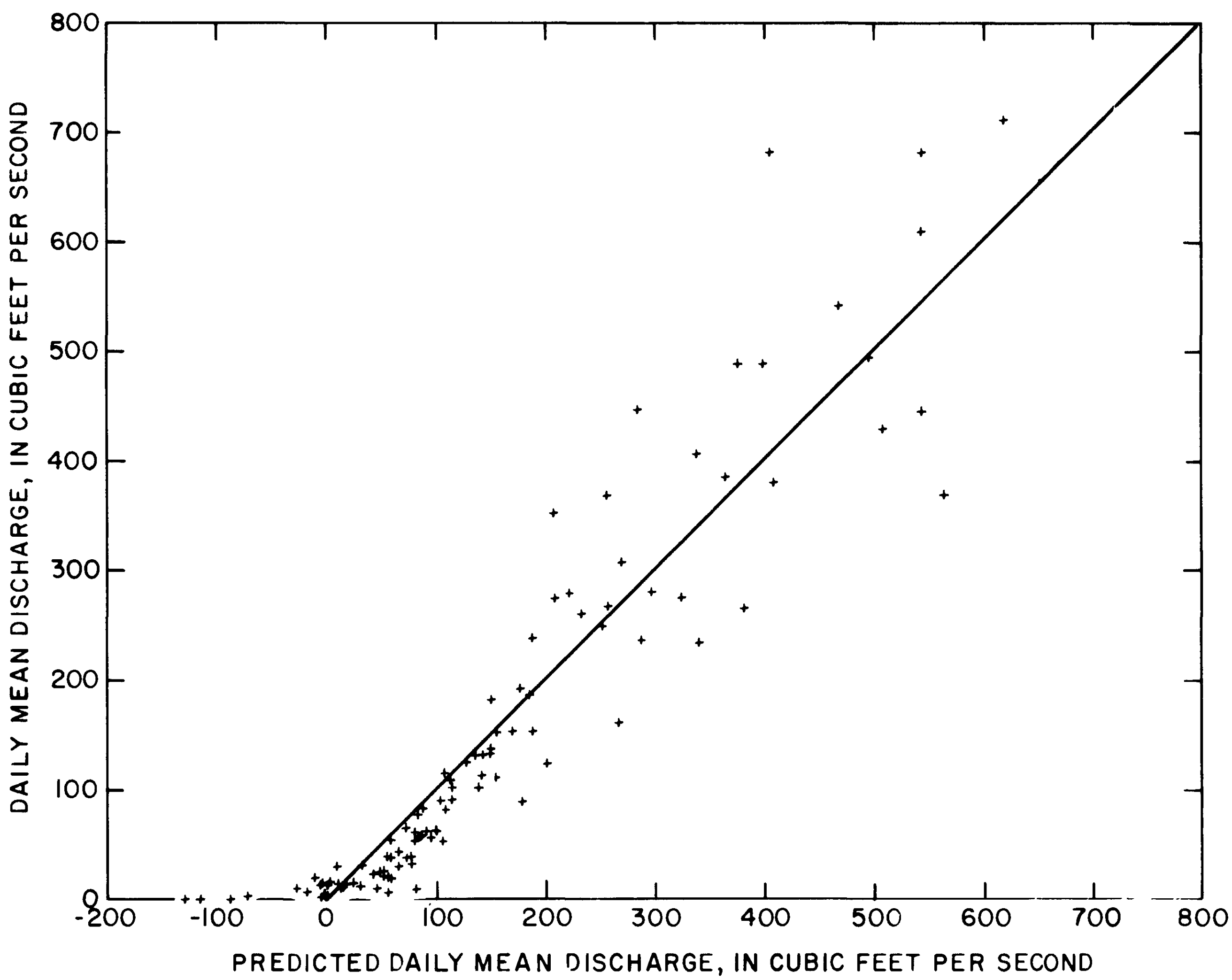

Figure 25.-Goodness of fit between observed and predicted downstream discharges in the Nueces River.

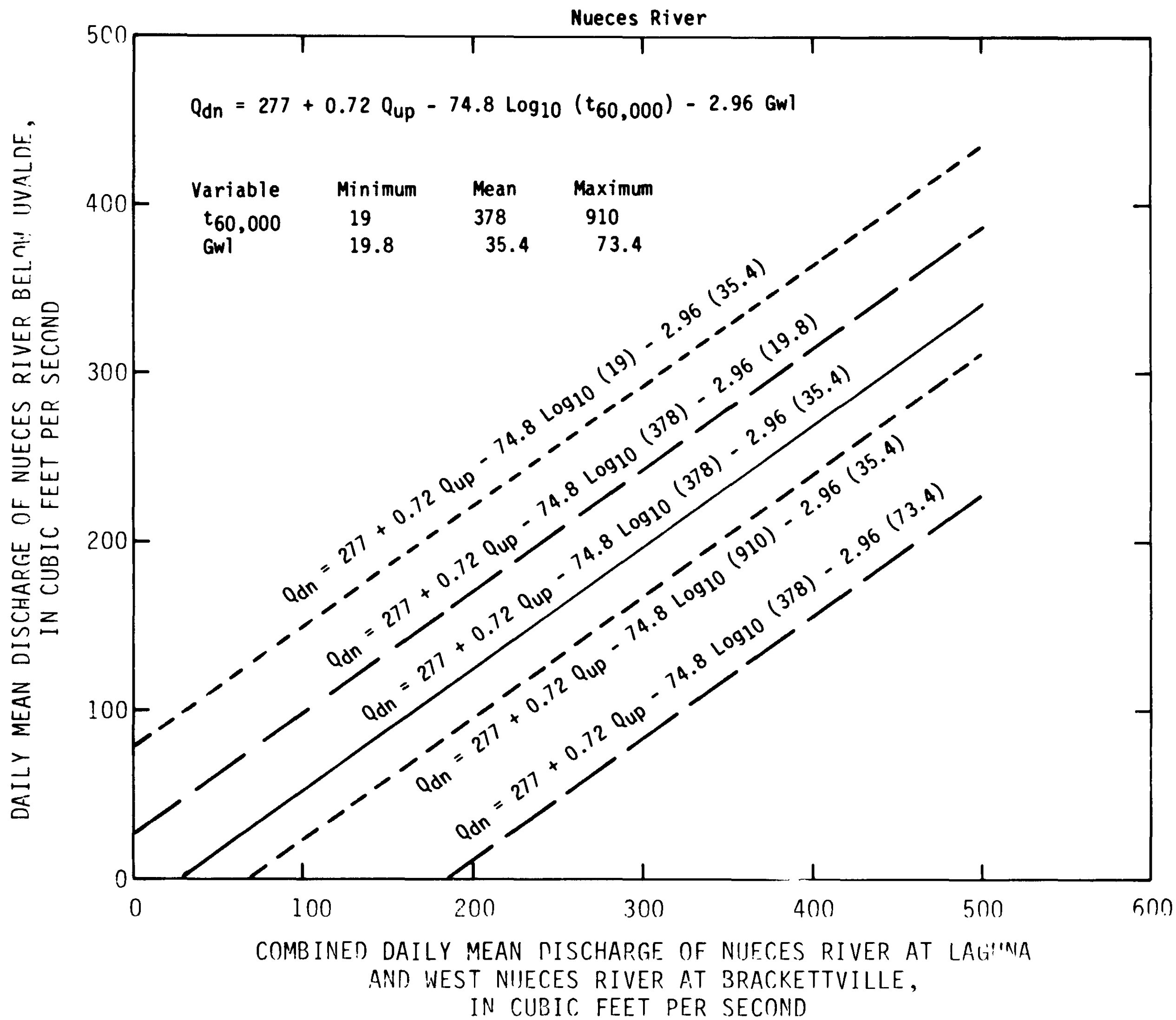

Figure 26.-Relationship of independent variables in the multiple-regression equation to downstream discharges in the Nueces River.

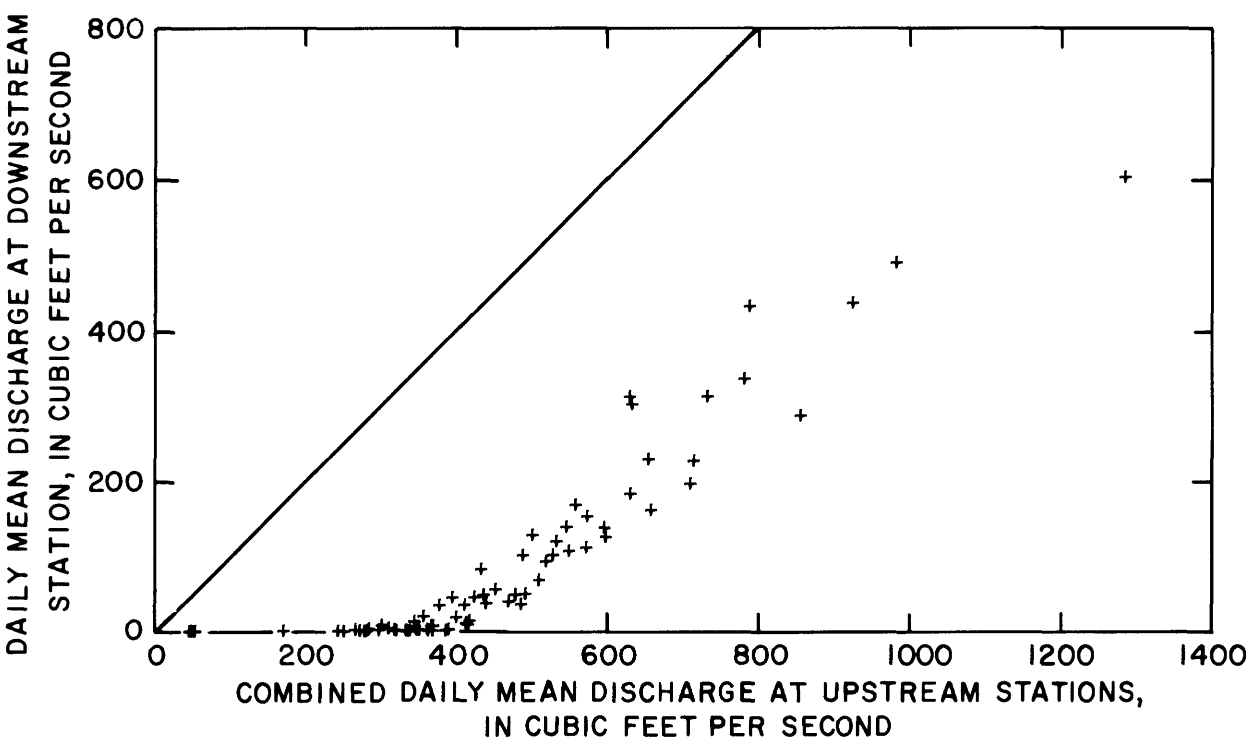

Figure 27.–Scatter diagram showing relationship of combined upstream discharges to downstream discharges in the Frio River.

This equation has an R-square value of 0.91 and a standard error of estimate of 41.7 ft^3/s. The equation indicates that combined upstream flow of 355 ft^3/s is required to have flow at the downstream site. The variation of the observed data from this through-flow threshold is caused by the other parameters that influence recharge and downstream flow. Further examination of the upstream-downstream flow relationship indicates that about 30 percent of the upstream flow above the 355 ft^3/s through-flow threshold is also lost to recharge.

Correlation coefficients of downstream discharge and the independent variables are:

Dependent	Independent variables			
	Q_{up}	Gwl	$\log_{10}(t_{4,000})$	$\log_{10}(t_{48,000})$
Q_{dn}	0.95	-0.48	-0.87	-0.06

where Q_{dn} and Q_{up} are as defined previously;
Gwl is depth to water, in feet, in well YP-69-35-501; and
$t_{4,000}$ and $t_{48,000}$ are time, in days, to accumulate flow volumes of 4,000 and 48,000 ft^3/s-days, respectively at station 08195000.

The correlation coefficients show that upstream flow is the variable most significant in determining downstream discharge. Short-term antecedent flows are also highly correlated; long-term antecedent conditions and ground-water levels are poorly correlated. The coefficients all support the conceptual model impact of each variable on downstream flow.

The multiple regression analysis produced the following equation for downstream flow:

$$Q_{dn} = 25.5 + 0.57\, Q_{up} - 174 \log_{10}(t_{4,000}). \qquad (5)$$

The equation has an R-square value of 0.92 and a standard error of estimate of 39.2 ft^3/s. The other independent variables either did not significantly improve the model or produced coefficients, when used in conjunction with Q_{up} and $\log_{10}(t_{4,000})$, that did not support the conceptual model. This was attributed to the intercorrelation of the independent variables. The coefficients of the independent variables in the above equation support the conceptual model; downstream flows will decrease in response to decreased upstream flows and to longer times to satisfy antecedent flow volumes.

The goodness of fit of the observed and predicted values for the analyzed data set is illustrated in figure 28. A sensitivity test of the developed relation shows that varying the antecedent condition over the 3 to 15-day range of the data set and holding upstream flow constant, produces a variation in downstream flow of 122 ft^3/s. This test is illustrated in figure 29.

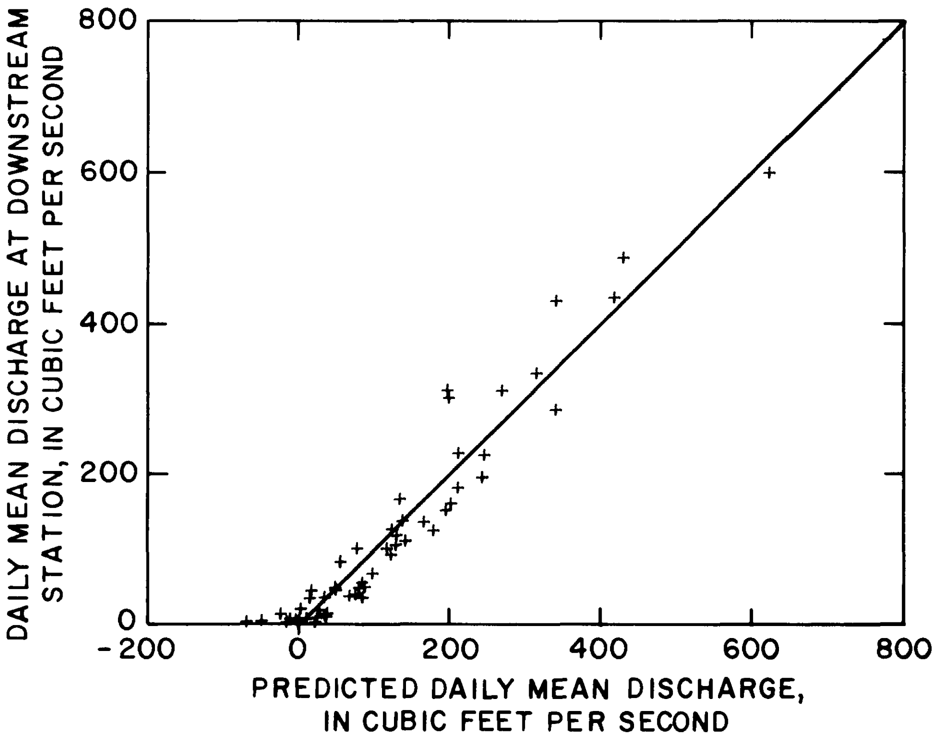

Figure 28.-Goodness of fit between observed and predicted downstream discharges in the Frio River.

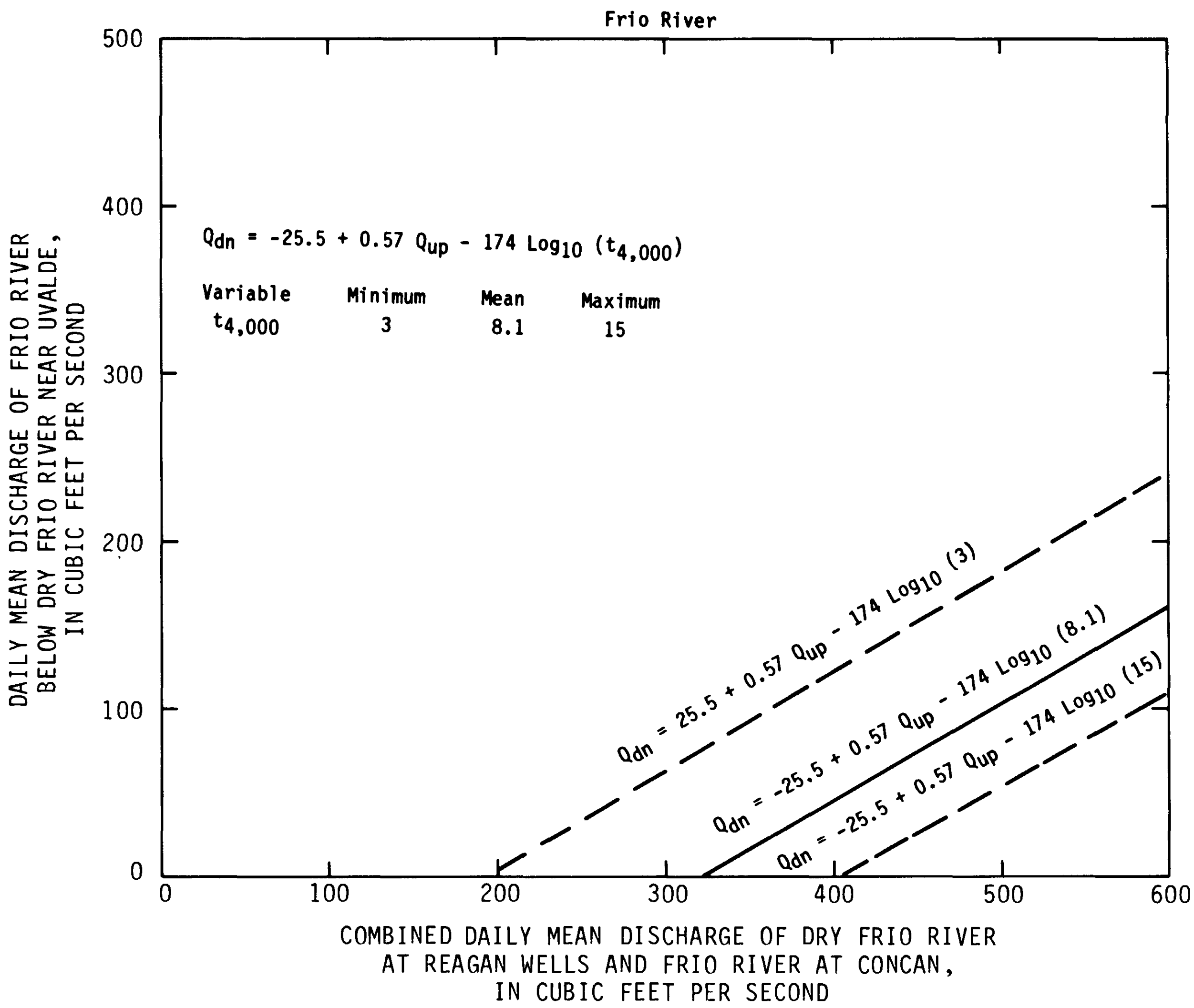

Figure 29.–Relationship of independent variables in the multiple-regression equation to downstream discharges in the Frio River.

Sabinal River

Data used in the analysis of downstream station discharge on the Sabinal River were selected from historic discharge records for 1957-81. Data that are considered suitable for analysis are extremely limited and therefore nearly all flow periods that reasonably satisfied steady flow criteria were used in the analysis. The scatter diagram of upstream and downstream discharges (fig. 30) shows a reasonably good relationship in the medium-flow range, few points and high scatter in the high-flow regime, and the common characteristic of a wide range in upstream discharge for very low downstream flows. To eliminate data for which all of the upstream flow may be lost in the reach, all observations with a downstream discharge of 2.0 ft^3/s or less are omitted for the regression analysis. From the original data set of 108 points, the remaining 78 points have an upstream discharge ranging between 21 and 652 ft^3/s. Ground-water levels are from records of well YP-69-45-401, which is located in the town of Sabinal as shown in figure 2. A datum adjustment of 100 feet was subtracted from the ground-water level records to normalize the minimum value. Ground-water levels (depth to water) range from 22.0 to 165.5 feet after adjustment. The number of days required to accumulate flow volumes of 2,000 and 25,000 ft^3/s-days were used for antecedent condition indices and range from 2 to 35 and from 22 to an upper limit of 700, respectively. These volumes were selected based on the antecedent flow indices used in the Nueces River analysis and the ratio of long-term flows at the Nueces River at Laguna station to the Sabinal River near Sabinal station.

A linear-regression analysis shows that approximately 50 ft^3/s of base flow at the upstream site is usually required to maintain flow throughout the reach. The regression equation is:

$$Q_{dn} = -36.8 + 0.73\ Q_{up} \qquad (6)$$

where Q_{dn} is daily mean discharge, in cubic feet per second, at stream-gaging station 08198000 Sabinal River at Sabinal; and
Q_{up} is daily mean discharge, in cubic feet per second, at stream-gaging station 08198500 Sabinal River near Sabinal.

The regression equation indicates that about 27 percent of all the additional flow at the upstream site is lost before reaching the downstream station. The equation has a R-square value of 0.91 and a standard error of estimate of 21.8 ft^3/s. The goodness of fit of the observed and predicted values is shown in figure 31.

The scatter of the points in figure 30 indicates that other factors may also influence downstream flow. Correlation coefficients of downstream discharge and the independent variables are:

Dependent variable	Independent variables			
	Q_{up}	Gwl	$\log_{10}(t_{2,000})$	$\log_{10}(t_{25,000})$
Q_{dn}	0.95	-0.13	-0.83	-0.46

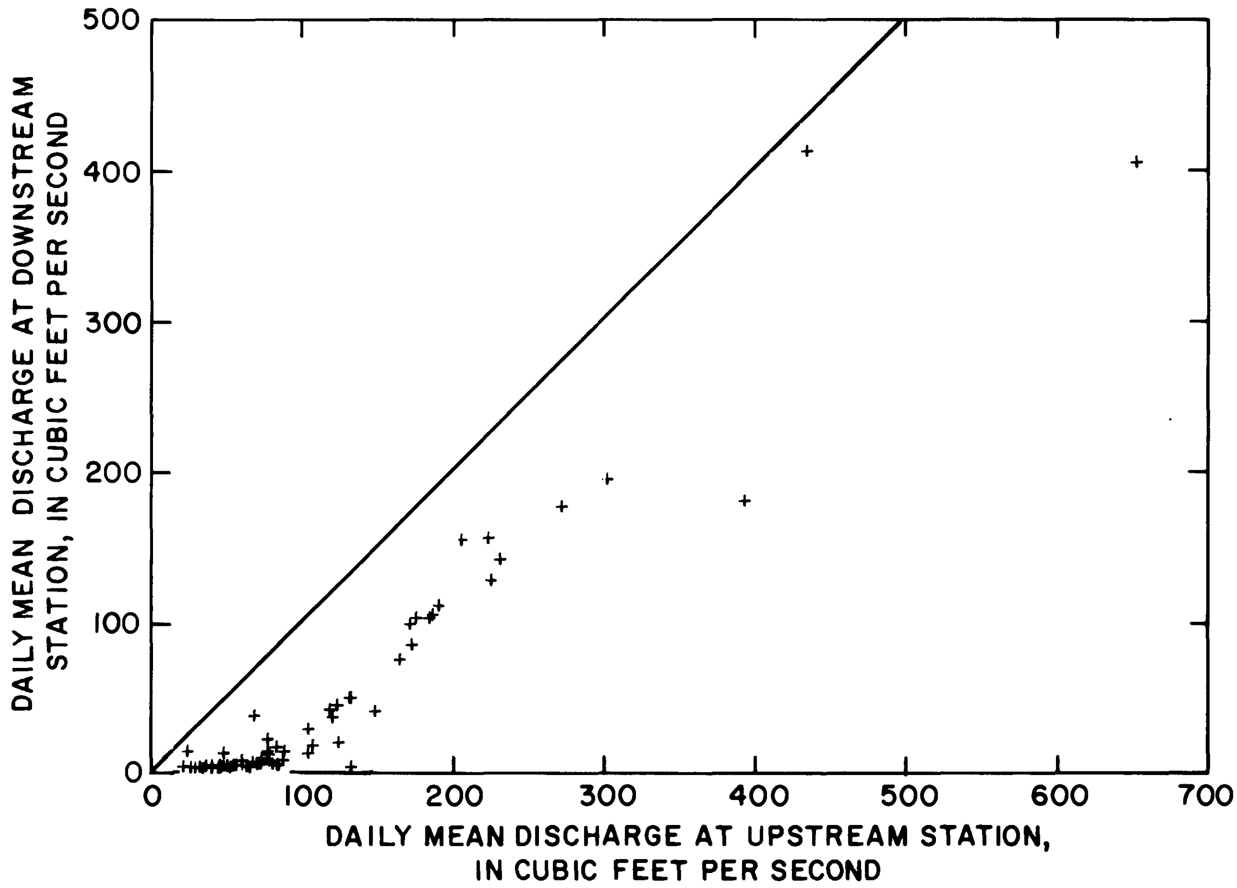

Figure 30.–Scatter diagram showing relationship of upstream and downstream discharges in the Sabinal River River.

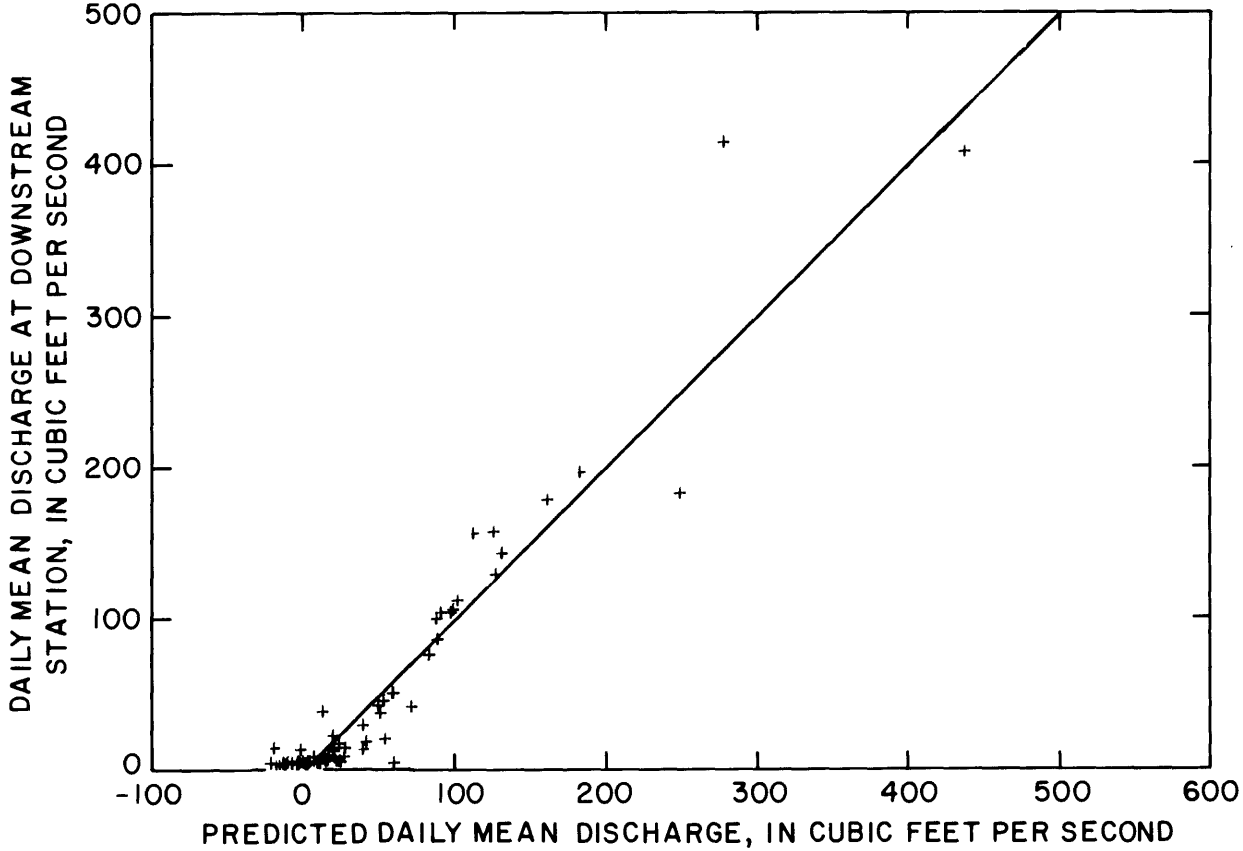

Figure 31.-Goodness of fit between observed and predicted downstream discharges in the Sabinal River.

where Q_{dn} and Q_{up} are as defined previously; and

Gwl is depth to water, in feet, in well YP-69-45-401, less 100 feet; and

$t_{2,000}$ and $t_{25,000}$ are time, in days, to accumulate flow volumes of 2,000 and 25,000 ft^3/s-days, respectively, at station 08198500.

Each of these coefficients represents agreement with the conceptual model, although ground-water levels are relatively insignificant probably because of the depth below stream channels. As expected, upstream discharge is the variable most significantly related to downstream flow.

A multiple regression analysis using all independent variables did not produce an improved expression of downstream flow. Although other independent variables also were significantly correlated with downstream flow, only the upstream discharge was significant in predicting the downstream discharge. This is attributed to multicullinearity between the independent variabales.

Seco Creek

Data used in the analysis of recharge from Seco Creek were selected from historic records for 1961-81. The relationship of upstream and downstream discharges presented in figure 32 shows a very high degree of scatter of the data above the very low downstream flow regime. During very low downstream discharge, a high variability of upstream discharge can occur. To eliminate data that may represent instances when flow was not sustained throughout the recharge zone, the 43 observations with a downstream discharge of 1.0 ft^3/s or less are omitted for the regression analysis. The remaining 34 points of the original data set have an upstream discharge ranging from 37 to 493 ft^3/s.

Ground-water levels are provided by records from well TD-69-38-601 located 8 miles north of the town of D'Hanis and shown in figure 2. A datum adjustment of 50 feet was substracted from the ground-water level records to normalize the minimum value. Ground-water levels (depth to water) ranged from 27.0 to 172.5 feet after adjustment. The number of days required to accumulate flow volumes of 500 and 6,000 ft^3/s-days were initially used for antecedent conditions indices. Values for these indices range from 1 to 40 and from 8 to 550, respectively. In an effort to improve developed relations for downstream flow, an additional antecedent flow index of the previous 5-day volume at the upstream site was calculated. Values for this index ranged from 150 to 4,730 ft^3/s-days.

As determined from the illustration and by linear regression analysis of upstream and downstream flows, a break in the relationship is at an upstream flow of about 100 ft^3/s, indicating that this discharge is usually required at the upstream station to have flow at the downstream station. The equation of the relationship of upstream and downstream flow is:

$$Q_{dn} = -115 + 1.19\ Q_{up} \qquad (7)$$

where Q_{dn} is daily mean discharge, in cubic feet per second, at stream-gaging station 08201500 Seco Creek at Miller Ranch near Utopia; and

Q_{up} is daily mean discharge, in cubic feet per second, at stream-gaging station 08202700 Seco Creek at Rowe Ranch near D'Hanis.

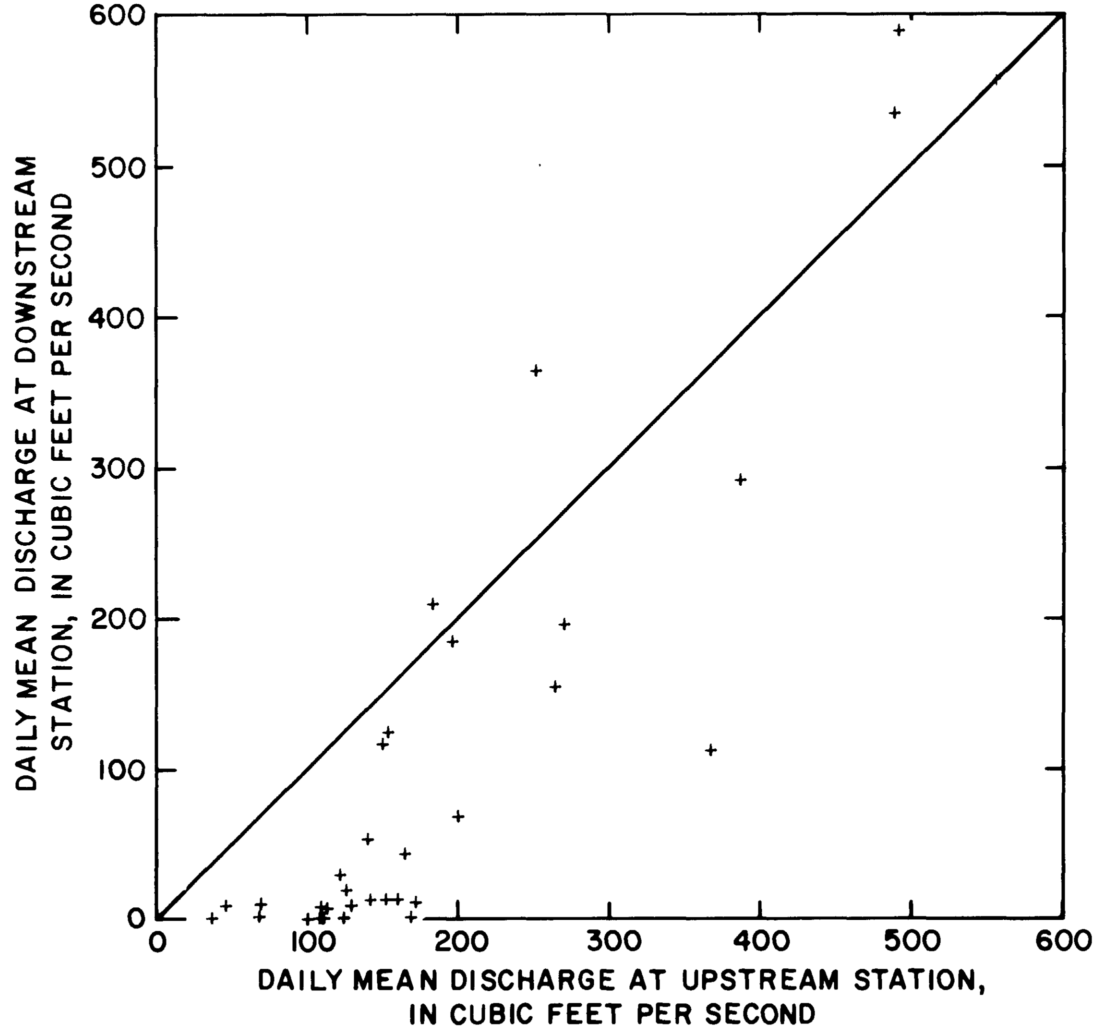

Figure 32.–Scatter diagram showing relationship of upstream and downstream discharges in Seco Creek.

This equation has an R-square value of 0.78 and a standard error of estimate of 71.6 ft^3/s. The slope of the relationship above the through-flow threshold is about 1.2, which suggests a streamflow gain between the two stations. Because the highly ephemeral nature of this stream in the study reach dictated that data be selected during recession flows, the observations probably represent times when runoff from the intervening area between the two sites was still occurring, causing apparent gain through the reach. Traveltime is fairly short through the reach and may be a factor in the indication of increased flow.

Correlation coefficients of the downstream discharge and the independent variables are:

Dependent variable	Independent variables				
	Q_{up}	Gwl	$\log_{10}(t_{500})$	$\log_{10}(t_{6,000})$	V_5
Q_{dn}	0.88	0.14	-0.47	-0.37	0.89

where Q_{dn} and Q_{up} are as defined previously;
Gwl is depth to water, in feet, in well TD-69-38-601, less 50 feet;
t_{500} and $t_{6,000}$ are time, in days, to accumulate flow volumes of 500 and 6,000 ft^3/s-days at the upstream station; and
V_5 is the 5-day antecedent flow volume, in ft^3/s-days, at the upstream station.

Because all data were selected during recession flows, it is not surprising that antecedent flow for only 5 days prior to the observations and the observed upstream flows are about equally correlated with downstream flow. Longer-term antecedent conditions are less significantly correlated with downstream flow although their correlation coefficients support the conceptual model. It was apparent from examination of a scatter diagram of downstream flow and ground-water levels, that a meaningful relationship between these two variables does not exist. This is verified by the low correlation coefficient which also is contrary to the conceptual model.

The multiple regression analysis using the significant independent variables produced the following equation:

$$Q_{dn} = -100 + 0.62\,Q_{up} + 0.070\,V_5 \qquad (8)$$

This equation has an R-square value of 0.85 and a standard error of estimate of 60.8 ft^3/s. The goodness of fit of the observed and the predicted values using the equation is shown in figure 33. The sensitivity of the equation to the 5-day antecedent flow volume is illustrated in figure 34. The downstream flow varies about 250 ft^3/s when upstream flow is held constant and the antecedent flow volume is varied over its range of 150 to 4,730 ft^3/s-days. This sensitivity test illustrates the effect of high intercorrelation of the independent variables Q_{up} and V_5. This multicollinearity causes the slope of the developed equation when V_5 is held constant to deviate significantly from the slope of the relationship of upstream and downstream flows (0.62 versus 1.20, respectively).

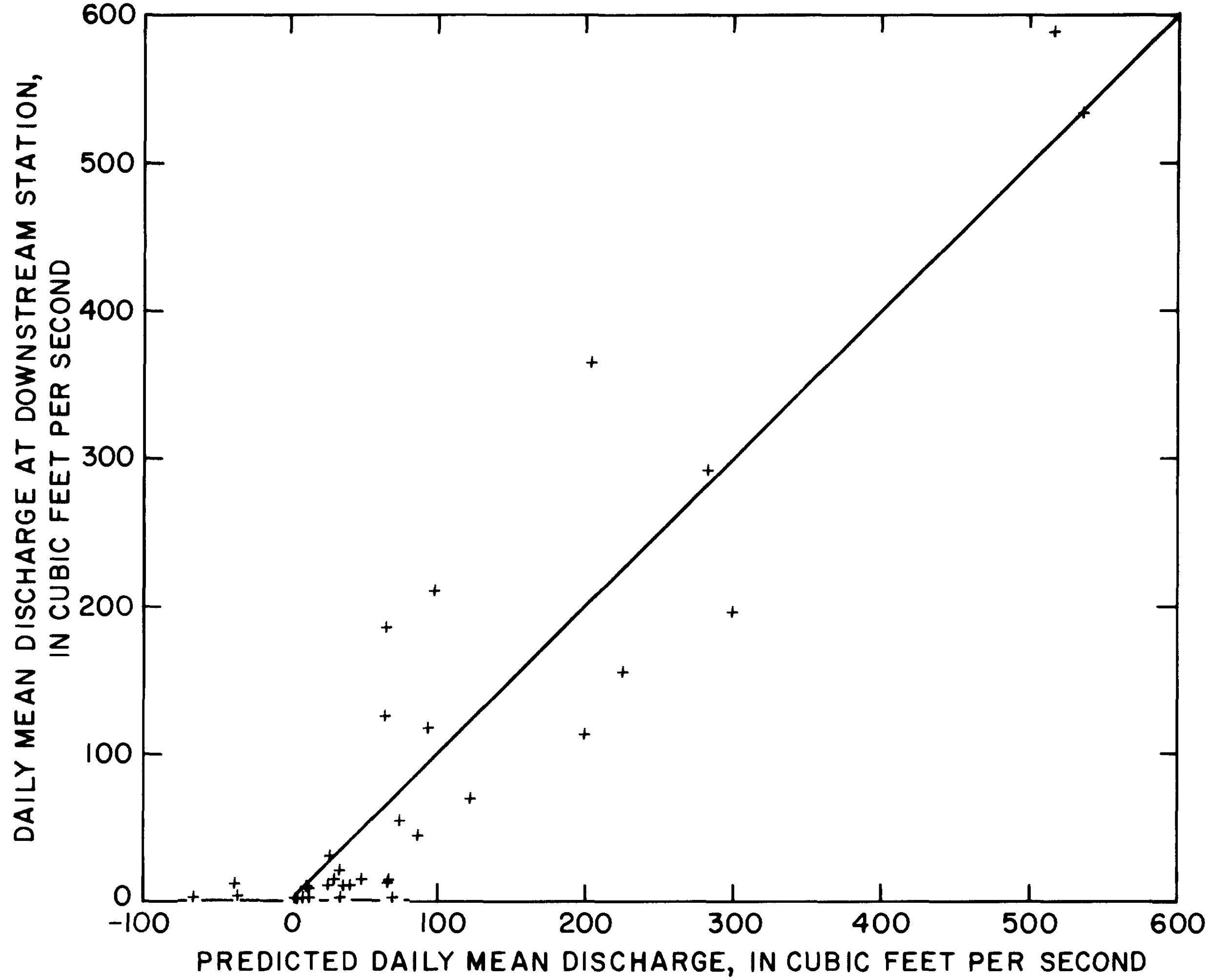

Figure 33.-Goodness of fit between observed and predicted downstream discharges in Seco Creek.

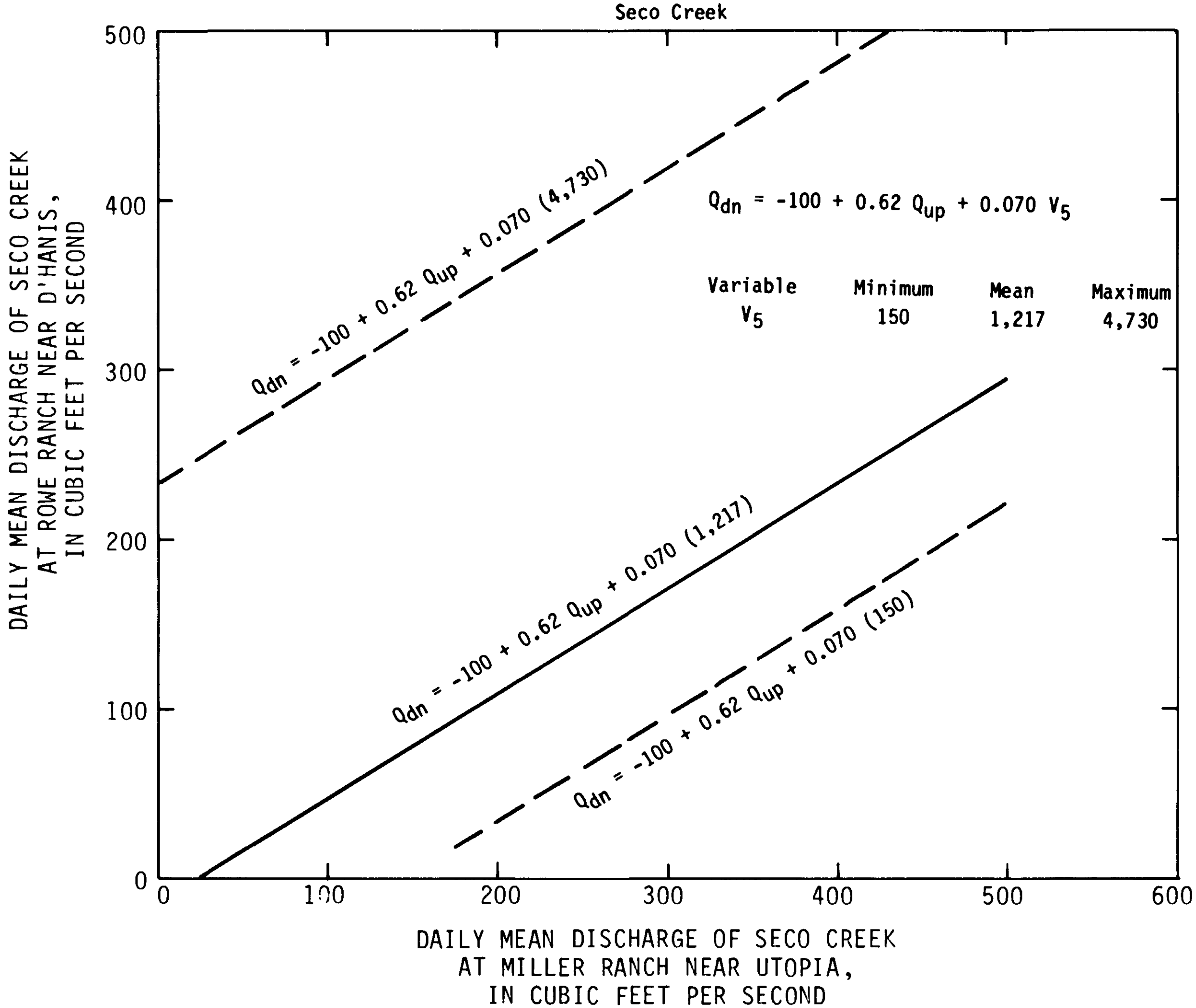

Figure 34.–Relationship of independent variables in the multiple-regression equation to downstream discharges in Seco Creek.

Although the statistics indicate reasonable reliability of the developed equation for a 100- to 493-ft^3/s range in upstream flow, the hydrologic characteristics of Seco Creek introduce questionable applicability of the relationship. The variation in drainage area from 43.1 square miles at the upstream gage to 168 square miles downstream from the recharge zone increases the likelihood that downstream discharges used in the analysis are significantly affected by intervening area runoff. This is indicated by the slope of 1.2 in the upstream-downstream flow relationship for discharges greater than the through-flow threshold. The stream is highly ephemeral; steady flows rarely, if ever, exist, which further introduces potential error in the analysis because of difficulty in accounting for travel time of flow through the study reach.

Hondo Creek

Data used in analyzing Hondo Creek flows downstream from the recharge zone were selected from records for 1961-81. Few data are available that satisfy selection criteria, and a large amount of unsteady flow data was used. A graphical relationship between upstream and downstream discharges is shown in figure 35. The illustration shows a poorly defined relation and widely scattered data in the 100- to 400-ft^3/s flow range at the upstream station and an even more poorly defined relation at higher flows. Although the relation is poorly defined, the characteristic of a wide range of upstream flows concurrent with the very low downstream flows found in the other basins is also evident from the Hondo Creek data. To eliminate data for which flow may be ephemeral, all observations with a downstream discharge of 1.0 ft^3/s or less were omitted for the regression analysis. From the original data set of 72 points, the remaining 54 points have an upstream discharge ranging from 64 to 525 ft^3/s.

Ground-water levels are from records of well TD-69-47-302, which is located in the town of Hondo and shown in figure 2. A datum adjustment of 150 feet was subtracted from the ground-water level records to normalize the minimum value. These values ranged from 32.3 to 106.8 feet (depth to water) after adjustment. The number of days required to accumulate flow volumes of 1,250 and 15,000 ft^3/s-days and preceding 5-day flow volumes at the upstream site were used for the antecedent condition indices. These values ranged from 2 to 20 days and from 8 to an upper limit of 600 days for the respective flow volumes. Five-day flow volumes ranged from 358 to 4,241 ft^3/s-days.

A linear-regression analysis of upstream and downstream flows shows that on the average, the through-flow threshold is about 65 ft^3/s at the upstream site. Inspection of figure 35 indicates that the upstream flow that will maintain flow through the reach may vary from about 50 to 225 ft^3/s. An approximate best-fit line through the points above the through-flow threshold has a slope of about 0.4, indicating that about 60 percent of the upstream flow greater than the through-flow threshold is also lost.

The equation of the relationship of downstream to upstream flow is:

$$Q_{dn} = -25.6 + 0.39\ Q_{up} \tag{9}$$

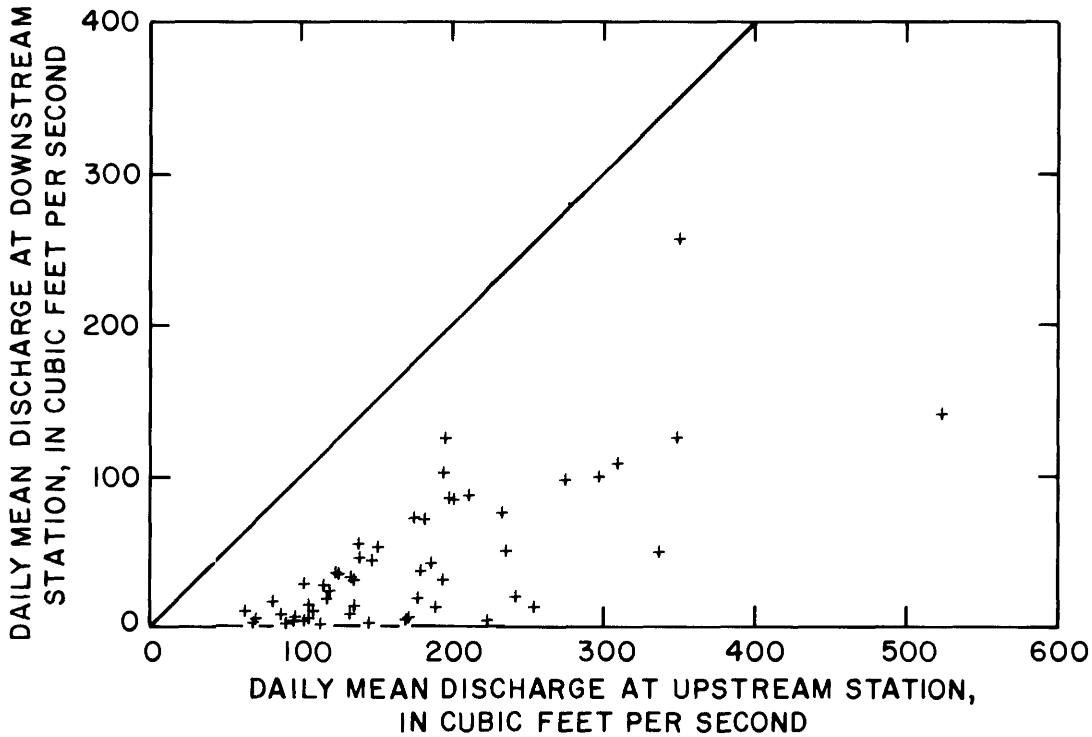

Figure 35.-Scatter diagram showing relationship of upstream and downstream discharges in Hondo Creek.

where Q_{dn} is daily mean discharge, in cubic feet per second, at stream-gaging station 08200000 Hondo Creek at Tarpley; and
Q_{up} is daily mean discharge, in cubic feet per second, at stream-gaging station 08200700 Hondo Creek at King Waterhole near Hondo.

The equation has an R-square value of 0.52 and a standard error of estimate of 33.3 ft^3/s. The goodness of fit of the observed and the predicted value of downstream discharge is illustrated in figure 36.

Correlation coefficients of downstream discharge and the independent variables are:

Dependent variable	Independent variables				
	Q_{up}	Gwl	$\log_{10}(t_{1,250})$	$\log_{10}(t_{15,000})$	V_5
Q_{dn}	0.72	0.08	-0.51	-0.30	0.62

where Q_{dn} and Q_{up} are as defined previously;
Gwl is depth to water, in feet, in well TD-69-47-302, less 150 feet;
$t_{1,250}$ and $t_{15,000}$ are time, in days, to accumulate flow volumes of 1,250 and 15,000 ft^3/s-days, respectively, at the upstream station; and
V_5 is the 5-day antecedent flow volume at the upstream station Hondo Creek at Tarpley.

The correlation coefficients support the conceptual model except for ground-water levels. No meaningful relation exists between downstream flow and ground-water levels.

The analysis of the data using multiple regression found that only the upstream discharge was significant in defining an equation for downstream flow; an improved relation could not be produced. The previously expressed relation also is poorly defined as indicated by its low R-square value. This is probably due to the highly ephemeral nature of the stream, its typical unsteady flow characteristics, as well as the inability of the selected parameters to represent moisture conditions that influence recharge.

SUMMARY AND CONCLUSIONS

Measurements of flow of streams crossing the Balcones Fault Zone in the Nueces River basin indicate that significant losses to ground water occur, and that at times some ground water returns in the lower portions of the study reaches. It was not determined whether this return flow is derived from the Edwards aquifer or from formations overlying the aquifer. Many of the streams studied are ephemeral, flowing only during or immediately following storm periods. Sustained flows seldom occur, and the measurements made during storm recession periods when unsteady flow existed are inadequate to define recharge-flow relationships over a range of flow magnitude.

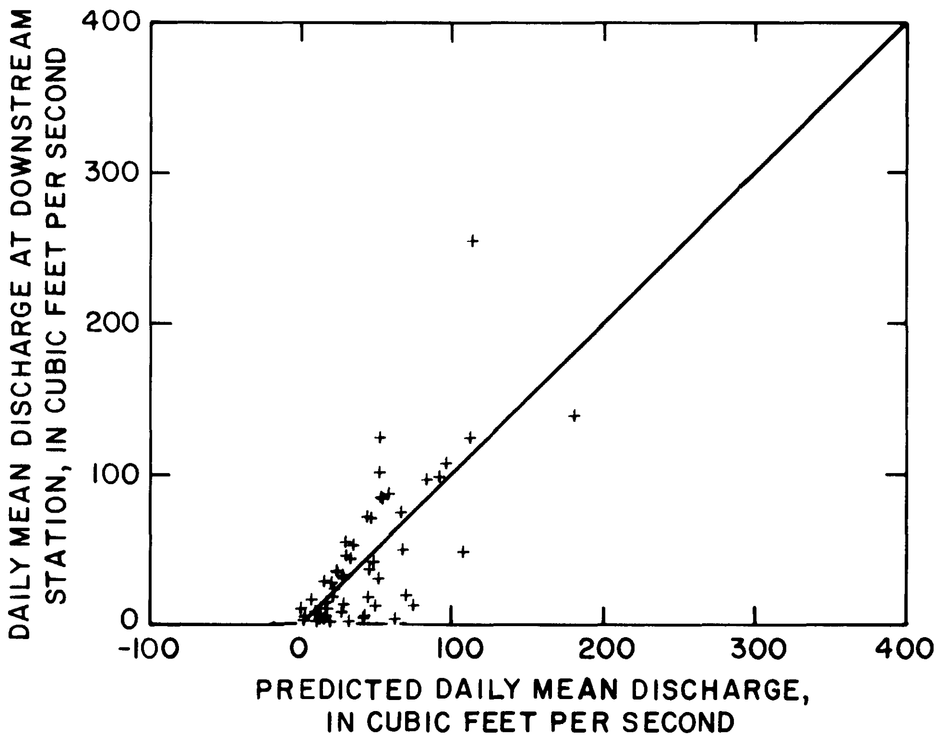

Figure 36.-Goodness of fit between observed and predicted downstream discharges in Hondo Creek.

Table 10 summarizes the losses and gains determined from streamflow measurements. In the table, direct recharge is flow that enters the Edwards aquifer through outcrops of the Edwards and associated limestones; indirect recharge is flow that eventually reaches the Edwards aquifer through outcrops of the Buda Limestone, Eagle Ford Shale, and the Austin Group. Streamflow losses or gains in the portions of the reaches upstream from the direct recharge zones, unexplained gains in the recharge zones, and gains and losses dowstream from the indirect recharge zones are collectively given as other losses and gains. Net recharge throughout each study reach for each of the surveys given in table 10 is the algebraic sum of the identified losses and gains.

The evaluation of historic discharge records of streams in the study area indicates that flows downstream from the recharge zone are most highly dependent on upstream flows. Antecedent flows at the upstream sites also significantly influence the amount of flow that passes through the recharge zone for most streams. For the Nueces River, ground-water levels also are significantly related to downstream flow. For the streams that typically are ephemeral, data representing steady flow periods are extremely limited, and less than desirable data were used in the analyses for these streams. The graphical relationships of upstream and downstream flows for these ephemeral streams illustrate the variability of flow upstream from the fault zone when downstream flows are negligible. These illustrations also identify the through-flow thresholds, the necessary upstream flows to cause flow to occur downstream from the recharge zone. For discharges greater than the through-flow thresholds, the slope of the diagonal band of observations shown in the illustrations are indicative of the percentage of additional upstream flow that passes through the study reach.

The development of relations for downstream flow as functions of other hydrologic variables utilized statistical correlation and multiple-regression techniques. For streams that have significant tributary discharge, the flows upstream of the recharge zone for the tributaries and main stem were combined for the analyses. The analyses for all streams except the Nueces River, where sustained flow data were available, used only the data when flow was expected to occur throughout the recharge zone. For purposes of this investigation, flow in the recharge zone was generally considered to be intermittent when the downstream flow was at or below 1 or 2 ft^3/s.

The equations produced in the analyses, the through-flow thresholds, the upper limit of upstream discharge test data, and statistics that indicate the reliability of the equations are given in table 11. Presented are equations that utilize upstream flow as the only independent varialbe as well as equations that include all statistically significant independent variables. The dominant independent variable in the relationships is discharge upstream from the recharge zone. This is indicated by the absence of equations using additional independent variables for some streams and by the small improvement in the R-square value in equations when additional independent variables were included.

Regression analyses to develop relationships for recharge were not conducted. Recharge is, by definition in this report, the net difference of flow upstream from the recharge zone and observed or calculated flow downstream from the recharge zone.

Table 10.--Summary of measured streamflow losses from streams in the Nueces River basin

Basin	Date of measurements	Loss to direct recharge (ft^3/s)	Loss to indirect recharge (ft^3/s)	Other losses (-) and gains (+) (ft^3/s)
West Nueces River	June 20, 1981	286	--	--
Nueces River	August 10, 1981	47	52	+75
Dry Frio River	June 18, 1981	393	33	--
Frio River	September 11, 1980	128	72	--
	April 2, 1981	153	106	--
	May 6, 1981	78	174	+23
Sabinal River	April 2, 1981	52	30	--
	August 6, 1981	40	49	- 2
Seco Creek	June 18, 1981	164	23	+20
	June 19, 1981	134	34	+ 9
	June 22, 1981	148	24	+ 2
Hondo Creek	May 27, 1981	140	19	+ 1.3
Verde Creek	September 8, 1980	88	--	+ 1.1
	April 24, 1981	150	8	--
	June 17, 1981	225	49	--

Table 11.--Summary of regression analyses of streams in the Nueces River basin

Stream and downstream gage location	Equation for downstream flow	Through-flow threshold (ft^3/s)	Maximum upstream discharge in data set (ft^3/s)	R-square	Standard error of estimate (ft^3/s)
Nueces River below Uvalde.	$Q_{dn} = -25.7 + 0.77\ Q_{up}$	33	866	0.83	73.0
	$Q_{dn} = 277 + 0.72\ Q_{up} - 2.96\ Gwl - 74.8\ \log_{10}(t_{60,000})$	--	866	.89	60.2
Frio River below Dry Frio River near Uvalde.	$Q_{dn} = 248 + 0.70\ Q_{up}$	355	1,285	.91	41.7
	$Q_{dn} = -25.5 + 0.57\ Q_{up} - 174\ \log_{10}(t_{4,000})$	--	1,285	.92	39.2
Sabinal River at Sabinal.	$Q_{dn} = -36.8 + 0.73\ Q_{up}$	50	652	.91	21.8
Seco Creek at Miller Ranch near Utopia.	$Q_{dn} = -115 + 1.9\ Q_{up}$	100	493	.78	71.6
	$Q_{dn} = -100 + 0.62\ Q_{up} + 0.070\ V_5$	--	493	.85	60.8
Hondo Creek at Tarpley.	$Q_{dn} = -25.6 + 0.39\ Q_{up}$	64	525	.52	33.3

The relationships developed are less definitive for the streams that are ephemeral and that typically have only unsteady flow. To refine the relationships developed in this report will require detailed definition and consideration of all variables that potentially influence recharge in the Balcones Fault Zone and that affect evaluation accuracy. Precise definition of travel time as recession flows pass through the recharge zone may allow significant improvement in the accuracy of the flow relationships, particularly for the ephemeral streams for which only unsteady flow data exist. Detailed geologic information and water-chemistry data will aid in identifying both the zones of highest recharge and the source and magnitude of return flow to the streams.

Data on ground-water levels in the various formations will improve the understanding of the impact of ground water on recharge and return flows. Consideration of a wider variety of antecedent flow indices may also improve the reliability of upstream-downstream flow relationships. A detailed examination of rainfall amounts and distribution in the study area would allow the selection of improved data sets for determining recharge relationships and would help in quantifying surface runoff from intervening drainage areas during storms and in determining its impact on recharge to the aquifer. A thorough knowledge and understanding of how these factors interrelate with recharge and streamflow is very important to the planning and implementation of means to enhance recharge to the Edwards aquifer.

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