HYDROLOGY OF THE ARBUCKLE MOUNTAIN AREA, SOUTH-CENTRAL OKLAHOMA

U.S.GEOLOGICAL SURVEY

Open-File Report 82-775

Prepared in cooperation with the

OKLAHOMA GEOLOGICAL SURVEY

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UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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By Roy W. Fairchild, Ronald L. Hanson and Robert E. Davis

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Oklahoma City, Oklahoma
1982

UNITED STATES DEPARTMENT OF THE INTERIOR
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FACTORS TO CONVERT INCH-POUND UNITS TO METRIC UNITS

Inch-pound units used in this report may be converted to metric (SI) units by the following conversion factors:

Inch-Pound unit	Multiply by	To obtain SI (metric) units
in. (inch)	25.4	millimeter
ft (foot)	0.3048	meter
ft^2 (square foot)	0.0929	square meter
mi (mile)	1.609	kilometer
mi^2 (square mile)	2.590	square kilometer
gal/min (gallon per minute)	0.0631	liter per second
Mgal/d (million gallon per day)	0.04381	cubic meter per second
acre-ft (acre-foot)	1,233	cubic meter
ft^3/s (cubic foot per second)	0.0283	cubic meter per second
(gal/min)/ft (gallon per minute per foot)	0.207	liter per second per meter

The conversion from temperature in degrees Fahrenheit (°F) to temperature in degrees Celsius (°C) is expressed by: °C = (5/9)(°F-32).

GLOSSARY

The following definitions are from Langbein and Iseri, (1960), Lohman, (1972), Lohman and others, (1972), and Meinzer, (1923).

Aquifer.--A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Base flow.--The discharge entering stream channels from ground water.

Diffusivity, hydraulic, $T/S(L^2T^{-1})$.--The conductivity of the saturated medium when the unit volume of water moving is that involved in changing the head a unit amount in a unit volume of medium.

Evapotranspiration, ET(L).--Water withdrawn from a land area by evaporation from water surfaces and moist soil and plant transpiration.

Flow-duration curve.--A cumulative frequency curve that shows the percent of time during which specified discharges were equaled or exceeded in a given period.

Ground water, confined.--Ground water which is under pressure significantly greater than atmospheric and having as its upper limit the bottom of a bed of distinctly lower hydraulic conductivity than that of the material in which the confined water occurs.

Ground water, unconfined.--Ground water in an aquifer that does not have a confining layer over it and that is in direct contact with the atmosphere.

Ground-water divide.--An imaginary line on a water table on each side of which the water table slopes downward in a direction away from the line.

Head, static, h(L).--The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

Homogeneity.--Uniformity. A material is homogeneous if its properties are identical everywhere in space. Although no known aquifer is homogeneous in detail, models based upon the assumption of homogeneity have been shown empirically to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

Hydraulic gradient (dimensionless).--The change of static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Isotropy.--That condition in which all significant properties are independent of direction. Although no aquifers are isotropic in detail, models based upon the assumption of isotropy have been shown to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

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.

Permeability, instinsic, $k(L^2)$.--A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient.

Phreatophyte.--A plant that obtains its water supply from the zone of saturation or through the capillary fringe and is characterized by a deep root system.

Porosity,n (dimensionless).--The property of a rock or soil containing interstices or voids and may be expressed quantitatively as the ratio of the volume of its interstices to its total volume.

Porosity, secondary.--Porosity developed after the formation of a deposit (rock or soil) and resulting from subsequent fracturing, replacement, solution, or weathering.

Potentiometric surface.--The potentiometric surface is a surface which represents the static head. As related to an aquifer, it is a surface defined by the levels to which water will rise in tightly cased wells. The water table is a particular potentiometric surface.

Recurrence interval.--As applied to streamflow, the average interval of time within which a flood of a given magnitude will be equaled or exceeded once.

Riparian vegetation.--Plants that grow in the flood plain of a stream or along its banks.

Specific capacity (L^2T^{-1}).--The rate of discharge of water from a well divided by the drawdown of wter level within the well.

Specific yield, Sy(dimensionless).--The ratio of (1) the volume of water which the rock or soil, after being saturated, will yeild by gravity to (2) the volume of the rock or soil. The definition implies that gravity drainage is complete.

Storage coefficient, S(dimensionless).--The volume of water an aquifier releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Stream, gaining.--A stream or reach of a stream for which flow is being increased by inflow of ground water.

Stream, losing.--A stream or reach of a stream that is losing water to the ground.

Transmissivity, $T(L^2T^{-1})$.--The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Water table.--That surface is an unconfined water body at which the pressure is atomospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exits.

HYDROLOGY OF THE ARBUCKLE MOUNTAIN AREA, SOUTH-CENTRAL OKLAHOMA

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ABSTRACT

Rocks that make up the Arbuckle-Simpson aquifer crop out in about 500 square miles in the Arbuckle Mountain province in south-central Oklahoma. The aquifer consists of limestone, dolomite, and sandstone of the Arbuckle and Simpson Groups of Upper Cambrian to Middle Ordovician age and ranges from about 5,000 to 9,000 feet thick. The rocks were subjected to intensive folding and faulting associated with major uplift of the area during Early to Late Pennsylvanian time.

Water in the aquifer is confined in some parts of the area while in others it is unconfined. The average saturated thickness of the aquifer is about 3,500 feet in the outcrop area. Water levels in wells measured fluctuated from about 8 to 53 feet each year, primarily in response to recharge from rainfall.

Recharge to the aquifer is estimated at about 4.7 inches per year.

The average storage coefficient of the aquifer is estimated at 0.008 and the average transmissivity is estimated at 15,000 square feet per day. Based on an average saturated thickness of about 3,500 feet and a storage coefficient of 0.008, the volume of ground water within 500 square miles of outcrop area is approximately 9 million acre-feet. An undetermined amount of fresh water probably exists in the aquifer around the periphery of the aquifer outcrop.

Base flow of streams that drain the aquifer accounts for approximately 60 percent of the total annual runoff from the outcrop area and is maintained by numerous springs. The close hydraulic connection between streams in the outcrop area and the aquifer is shown by a close correlation between base flow in Blue River and the fluctuation of ground-water levels in five wells in the Blue River basin. This correlation also exists between the discharge by Byrds Mill Spring and the fluctuation in water level in a nearby observation well; increase and decrease in spring discharge correspond to rise and fall of the water level in the well.

The chemical quality of water from the Arbuckle-Simpson aquifer is suitable for most industrial and municipal uses. The water is hard and of the bicarbonate type; average hardness is 340 milligrams per liter and average dissolved solids is 360 milligrams per liter. Because springs issue from the aquifer and discharge to streams in the area, the quality of water from springs and base flow in streams is similar to that of ground water. The average dissolved solids concentration of stream water is slightly less than that of water from wells and springs.

INTRODUCTION

Urbanization, economic growth, and improved standards of living in rural areas of south-central Oklahoma require ever-increasing amounts of water; a potential source of this water is the Arbuckle-Simpson aquifer. Basic information on the availability and potability of water from the aquifer is needed to provide water managers, planners, and consumers with adequate information for orderly development and wise use of this vital resource. Recognizing the need for such information, the Oklahoma Geological Survey requested the U.S. Geological Survey to make an appraisal of the Arbuckle-Simpson aquifer; this report presents the results of that appraisal.

Purpose and scope

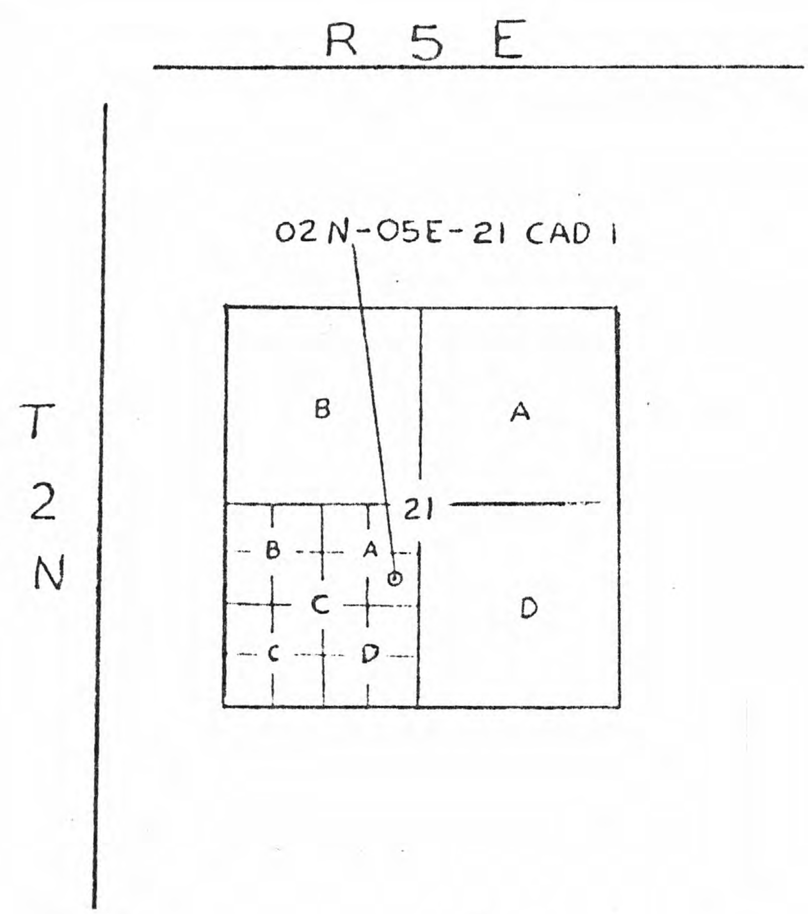
This report describes the hydrology of the Arbuckle Mountain area including the geologic framework and the hydrologic characteristics of the Arbuckle-Simpson aquifer, ground water-surface water relationships, and the chemical characteristics of ground water and surface water. Data used in preparing this report were obtained from field and laboratory analyses and from published and unpublished records of the U.S. Geological Survey and State and local agencies. Field data include records of wells, springs, streams, ground-water levels, precipitation, and selected chemical parameters of ground and surface waters. Water samples from wells, streams, and springs were analyzed in the laboratories of the U.S. Geological Survey.

Previous Studies

Ham (1955, 1969) and Ham, McKinley, and others (1954) have described the geology of the Arbuckle Mountains. Information on the geohydrology of the Arbuckle-Simpson aquifer is provided by Fay (1968 and 1969) and Hart (1966, 1972, and 1974).

Local Numbering System

The method used in this report to assign a number to a data-collection site is based on its location in a particular township, range, and quarter-quarter-quarter section. As shown in the diagram below, the location of a site indicated by the dot would be given the number 02N-05E-21 CAD 1. The fractional parts of the section are given from larger to smaller areas of the section. The final digit (1) is the sequential number of a site within the smallest fractional subdivision (10 acres).



Acknowledgments

The authors are indebted to many people throughout the area for their cooperation and assistance by supplying the information on wells, use of water, and other pertinent data.

Especially appreciated is the cooperation and assistance extended by members of the Oklahoma Geological Survey who were the source of literature and many helpful suggestions.

GEOGRAPHIC SETTING

The Arbuckle-Simpson aquifer underlies an area of about 500 mi^2 in the Arbuckle Mountain physiographic province of south-central Oklahoma (fig. 1). The term "mountain" is misleading because the topography of the area consists of gently rolling hills separated from plains by the Washita River. The river follows part of the Washita Valley fault zone. The topography reflects the degree of structural deformation of the undelying rocks. The western part of the mountains, referred to as the Arbuckle Hills, is characterized by a series of northwest-trending ridges formed on resistant rocks that are intensely folded and faulted. The eastern part of the mountains, referred to as the Arbuckle Plains, is characterized by a gently rolling topography formed on relatively flat-lying, intensely faulted limestone beds. Neither the eastern nor the western parts of the area have a well-developed karst topography but a few small features have developed in the western part of the area as a result of solution of the underlying carbonate rocks.

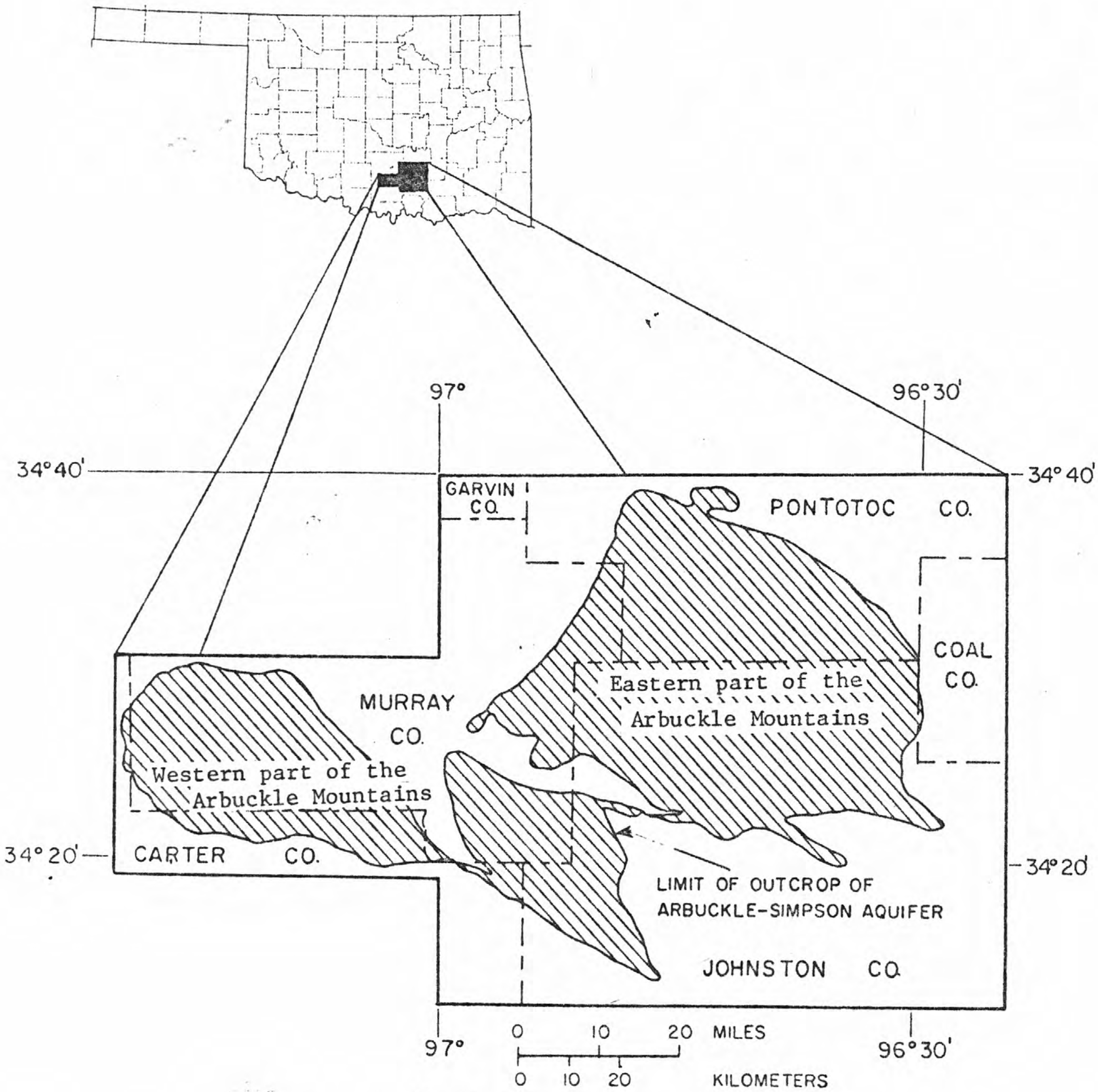


Figure 1.--Location of study area.

Blue River, Pennington Creek, Mill Creek, Rock Creek, Delaware Creek, Oil Creek, and Sycamore Creek drain the eastern part of the area (fig. 2) and flow generally toward the southeast into the Washita River and Red River. Colbert Creek, Lick Creek, Hickory Creek, Garrison Creek, Honey Creek, Tulip Creek, Henryhouse Creek, Spring Creek, and West Spring Creek drain the western Arbuckle Mountains (fig. 3). These streams are sustained throughout the year by springflow. Many of the small tributary streams are intermittent and cease to flow in late summer.

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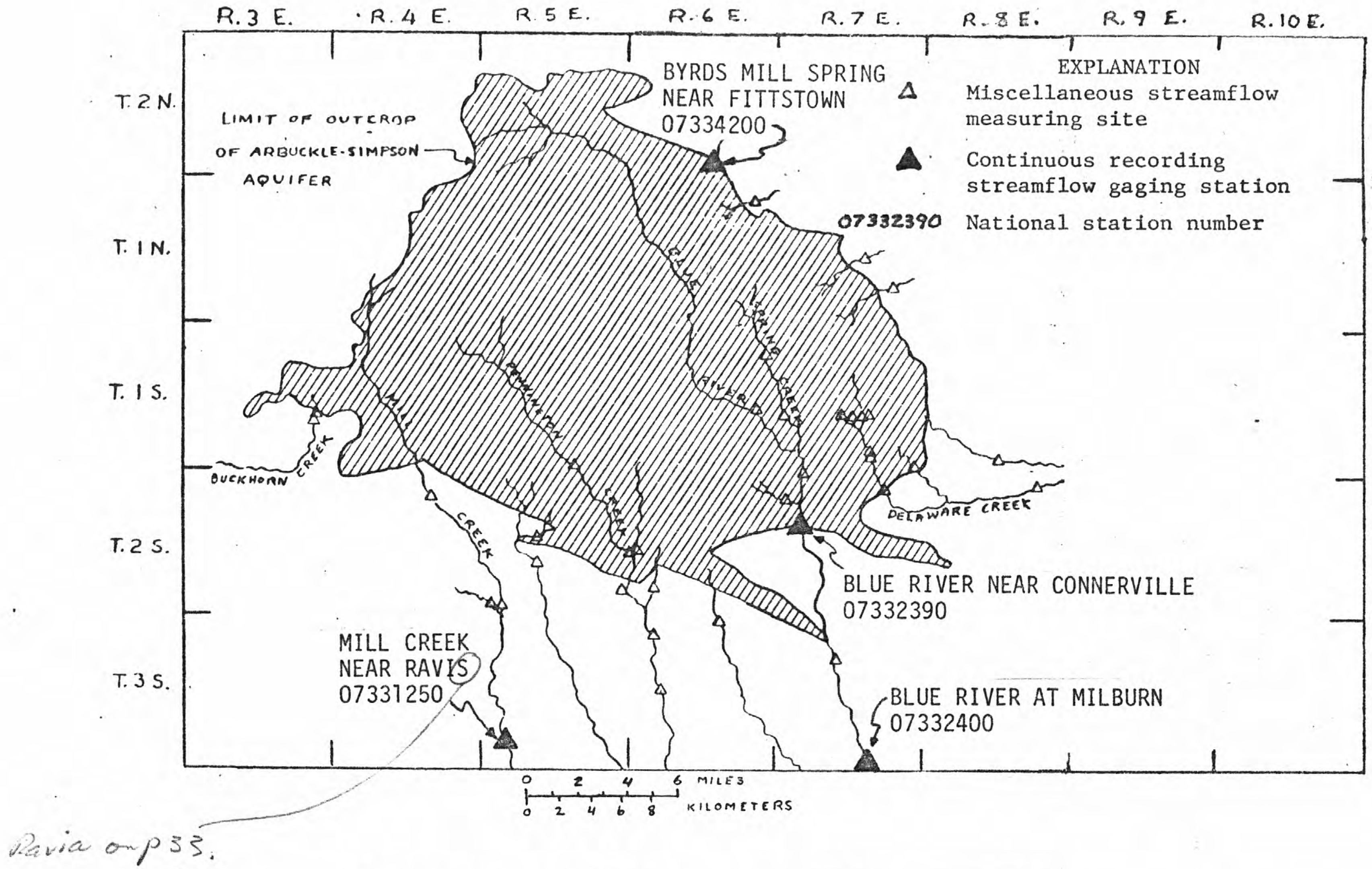

Figure 2.--Location of streamflow measuring sites in the eastern part of the study area.

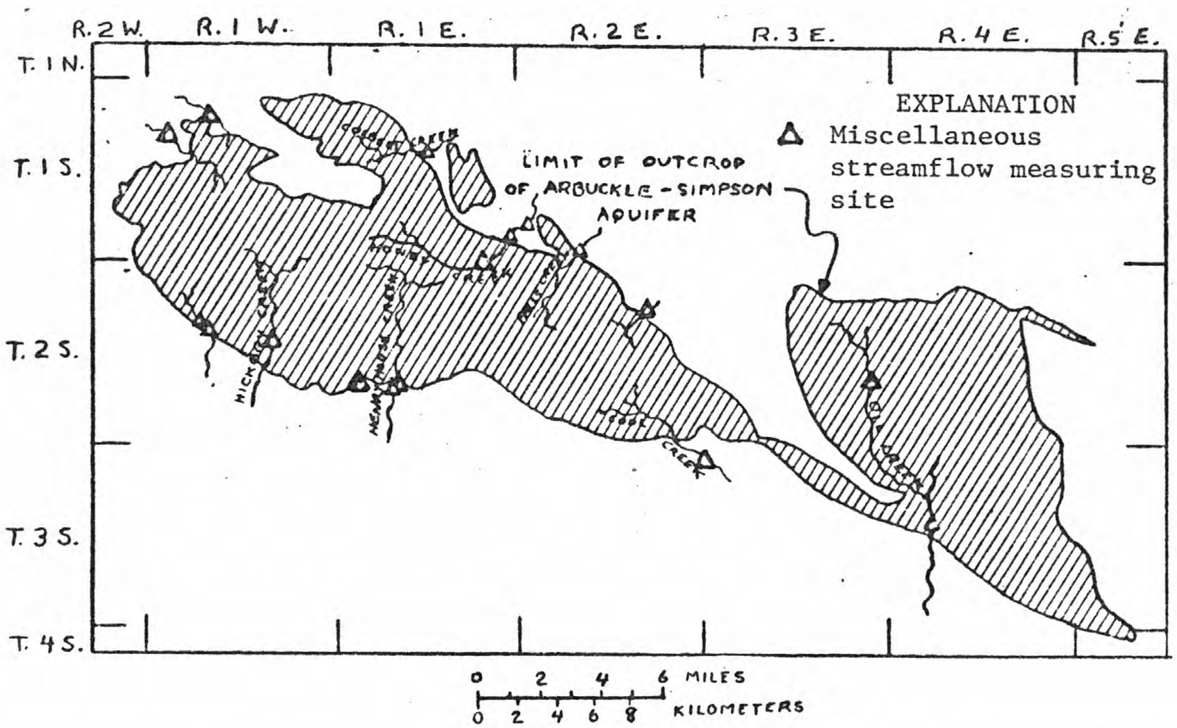

Figure 3 .--Location of streamflow measuring sites in the western part of the study area.

CLIMATE

The study area is in a moist subhumid zone. Most of the precipitation occurs as rainfall with some light snow or sleet during the winter.

Long-term percipitation data from National Weather Service stations located in and adjacent to the study area (table 1) give a time-weighted average precipitation of 38.2 in. per year. Precipitation records at these sites during the 3-year study period, October 1976 - September 1979, indicate that the 1978 water year (table 2) was about 84 percent of both the 6-year and long-term average precipitation.

Three additional recording rain gages were operated during the study period to determine the variation in precipitation within the area. These short-term records were used in conjunction with the long-term records at Ada (10 miles north of the study area), Sulphur, and Pontotoc to aid in evaluating recharge rates to the aquifer and an areal hydrologic budget. Monthly precipitation at the three short-term stations is listed in table 3; the total precipitation varies greatly in any given month in different parts of the study area.

Table 1.--Average calendar-year precipitation in and adjacent to the study area

Station	Period of Record	Average (inches)
Ada	1941-70	39.45
Pontotoc	1931-78	38.21
Sulphur	1931-78	37.53
Time-weighted Average		38.25

Table 2.--Annual precipitation for six water years in and adjacent to the study area

Station	Precipitation (inches) Water years					
	1969	1970	1971	1977	1978	1979
Ada	43.43	44.05	41.51	38.31	32.92	36.31
Pontotoc	34.33	41.87	33.39	37.00	31.90	50.41
Sulphur	36.70	44.18	41.69	34.69	31.86	35.97
Average	38.15	43.37	38.86	36.67	32.23	40.90

Six Year Average = 38.36

Table 3.--Precipitation at three locations in the study area.

Month	02S-04E-23 CAB *	01N-06E-08 BBA	01S-01E-36 AAC	02S-04E-23 CAB *	01N-06E-08 BBA	01S-01E-36 AAC	02S-04E-23 CAB *	01N-06E-08 BBA	01S-01E-36 AAC
	1977			1978			1979		
J	--	--	--	1.00	1.05	0.70	2.23	1.70	1.87
F	--	--	--	1.8e	2.12	1.57	1.68	1.46	1.19
M	--	--	--	2.6e	3.70	1.81	4.07	5.99	4.49
A	--	--	--	2.7e	2.70	2.82	2.33	2.45	2.43
M	4.72	5.91	3.36	6.43	6.30	8.80	4.76	5.64	3.37
J	2.70	4.94	3.70	2.60	3.88	4.17	3.33	4.90	6.17
J	--	2.78	0.9	2.24	0.47	0.60	0.24	1.0e	2.62
A	3.3	4.48	2.13	1.18	0.73	0.71	2.20	3.33	4.01
S	2.45	4.00	1.30	2.99	1.17	3.18	3.36	0.57	0.59
O	2.50	1.4e	1.66	0.94	0.90	0.91	--	--	--
N	0.78	0.8e	0.68	4.00	5.06	4.57	--	--	--
D	0.2e	0.06	0.13	0.51	0.32	0.41	--	--	--

* Originally at 02S-04E-26 CCB. Moved to this site August 1, 1978.

-- No record

e Estimated

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Seasonal variations in the climate of the study area are indicated in figure 4 by the average monthly temperature and precipitation at Sulphur (near the central part of the study area) for the 30-year period 1941-70. Maximum temperatures commonly occur in July and August while minimum temperatures occur in December and January. Maximum rainfall generally occurs during the spring months, April through June and a less intense wet period in September and October, while the seasonal dry period occurs from November through February. Figure 5 shows the annual precipitation at Pontotoc in the northeastern part of the area for the 48-year period 1931-78. As indicated by the graph in figure 5, precipitation was below the annual average during the period 1976-78 which was during the study period. However, from 1967 to 1975 for 9 years prior to the study period (except for 1972), precipitation was near or above the annual average in the northeastern part of the study area.

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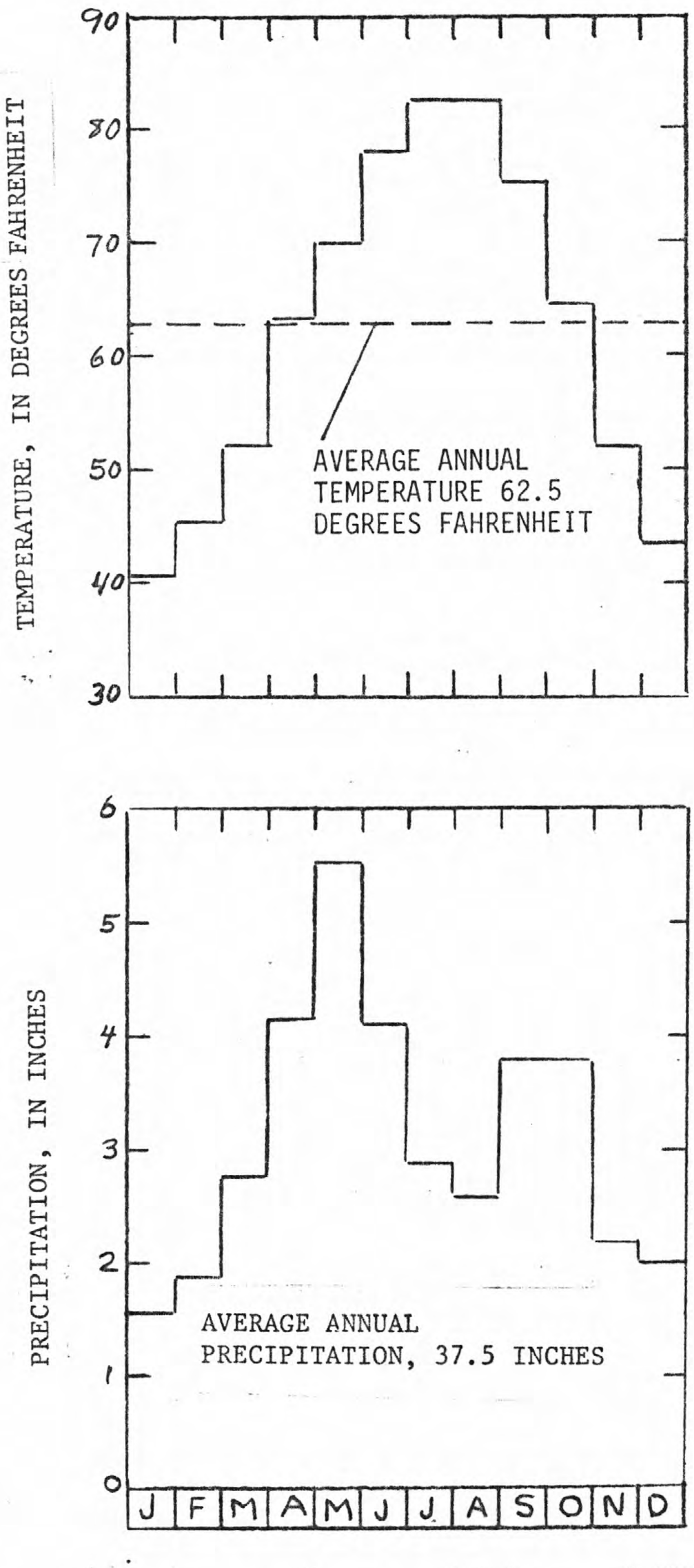

Figure 4.--Average monthly temperature and precipitation at Sulphur, 1941-70 (data from National Oceanographic and Atmospheric Administration, No. 81).

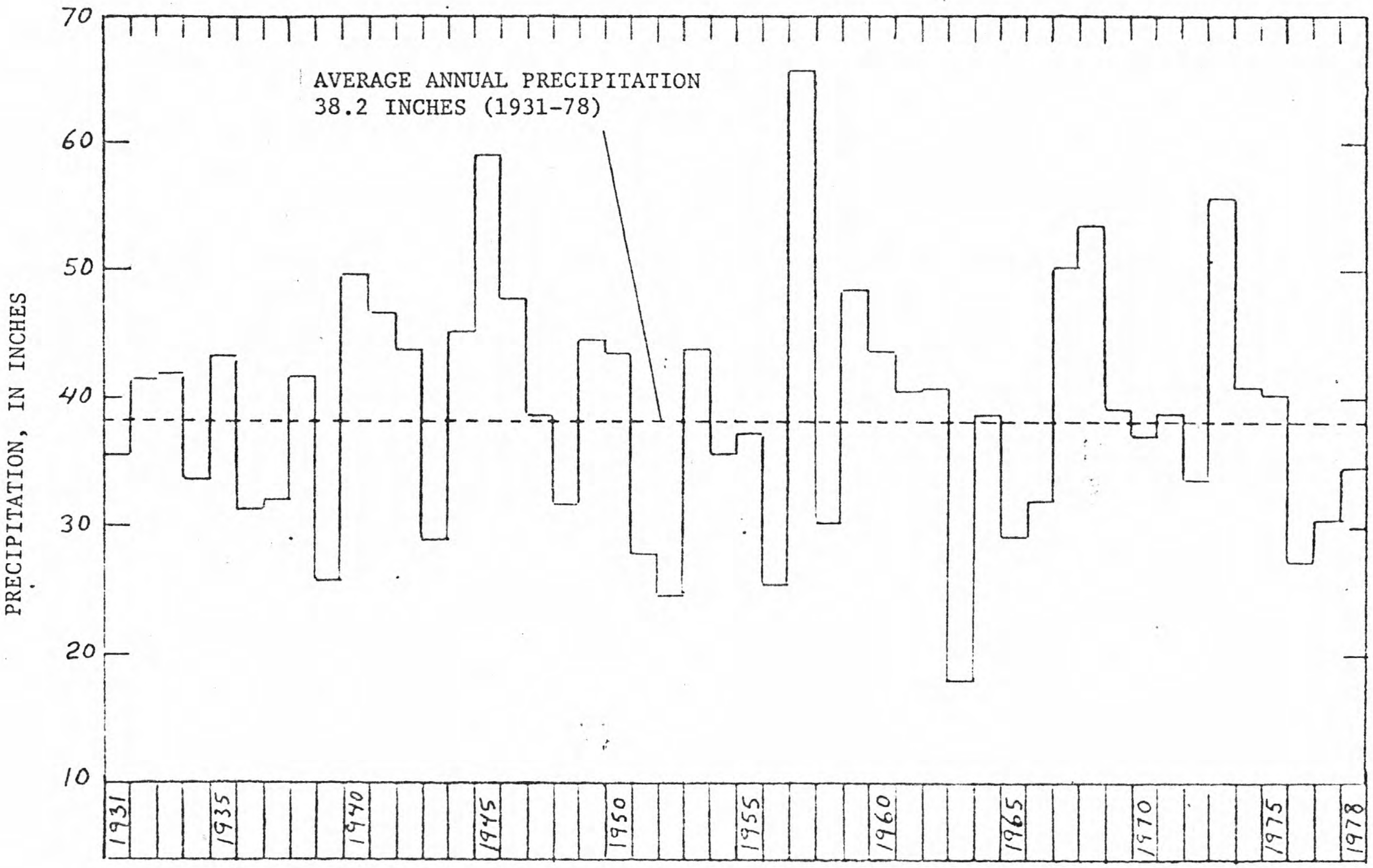

Figure 5 --Annual and average annual precipition at Pontotoc (1931-1978); (Climatological data, National Oceanographic and Atmospheric Administration).

SURFACE WATER

Description of Principal Streams in Study Area

Several perennial streams in the study area are fed by springs that issue from the limestone and sandstone that make up the Arbuckle-Simpson aquifer. The major streams include Pennington, Mill, Falls, Honey, Oil, and Delaware Creeks, and the Blue River and its tributaries.

A gaging station was established on Blue River near Connerville at the contact between the Arbuckle Group and the Tishomingo Granite (fig. 16) to be used in conjunction with a long-term station (Blue River at Milburn) already in operation 15.2 mi downstream. The two stations were used to estimate evapotranspiration rates in the area. In addition, base-flow data were collected at miscellaneous sites on all major streams that drain the outcrop area (figs. 2 and 3) to determine seepage rates and winter and summer ground-water discharge from the aquifer.

Figure 2 shows the four streams which drain 85 percent of the eastern part of the study area: the four streams and their drainage areas are, Blue River (162 mi^2), Pennington Creek (65.7 mi^2), Mill Creek (46.4 mi^2) and Oil Creek (28.6 mi^2). Continuous records of flow have been collected at Blue River at Milburn (No. 07332400, fig. 2) since October 1965 and 15.2 mi upstream at Blue River near Connerville (No. 07332390, fig. 2) since October 1977. The mean annual discharge of the Blue River at Milburn for the 14-year period of record (1966-79) is 140 ft^3/s. Mean annual discharge at this site for the three-year study period (1977-79) is 89.2 ft^3/s; runoff of the Blue River during the study period was 64 percent of the long-term average. Three years of continuous records of flow were also recorded at Mill Creek near Ravia (No. 07331250, fig. 2) from October 1968 through September 1971. In addition, 19 years (since 1958) of continuous record have been collected at Byrds Mill Spring near Fittstown (No. 07334200, fig. 2). Miscellaneous streamflow measurements have been collected periodically at several sites in and adjacent to the study area since 1949.

Because the granite acts as a barrier to ground-water flow from the Arbuckle-Simpson aquifer, streamflow at the Blue River near Connerville site approximates the total surface and subsurface water discharging from the outcrop area.

URE 6

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Figure 6 shows a fairly close relation (correlation coefficient of 0.95) of monthly mean flows at the Milburn site and the Connerville site for the common period of record (1977-79 water years) and indicates that the Milburn gage can be used to approximate the flow characteristics from the study area.

The flows at the two sites are about equal in the range 30 to 40 ft^3/s, but the river is a gaining stream between the two sites when flow at the Connerville gage exceeds 40 ft^3/s. Probably there is some inflow to Blue River between the two sites when flow is great enough to exceed 40 ft^3/s at the Connerville gage. The scatter of points in figure 6 reflects both year-to-year variation in antecedent moisture and seasonal differences in evapotranspiration. Monthly average flows at both sites did not fall below about 32 ft^3/s during the three year study period.

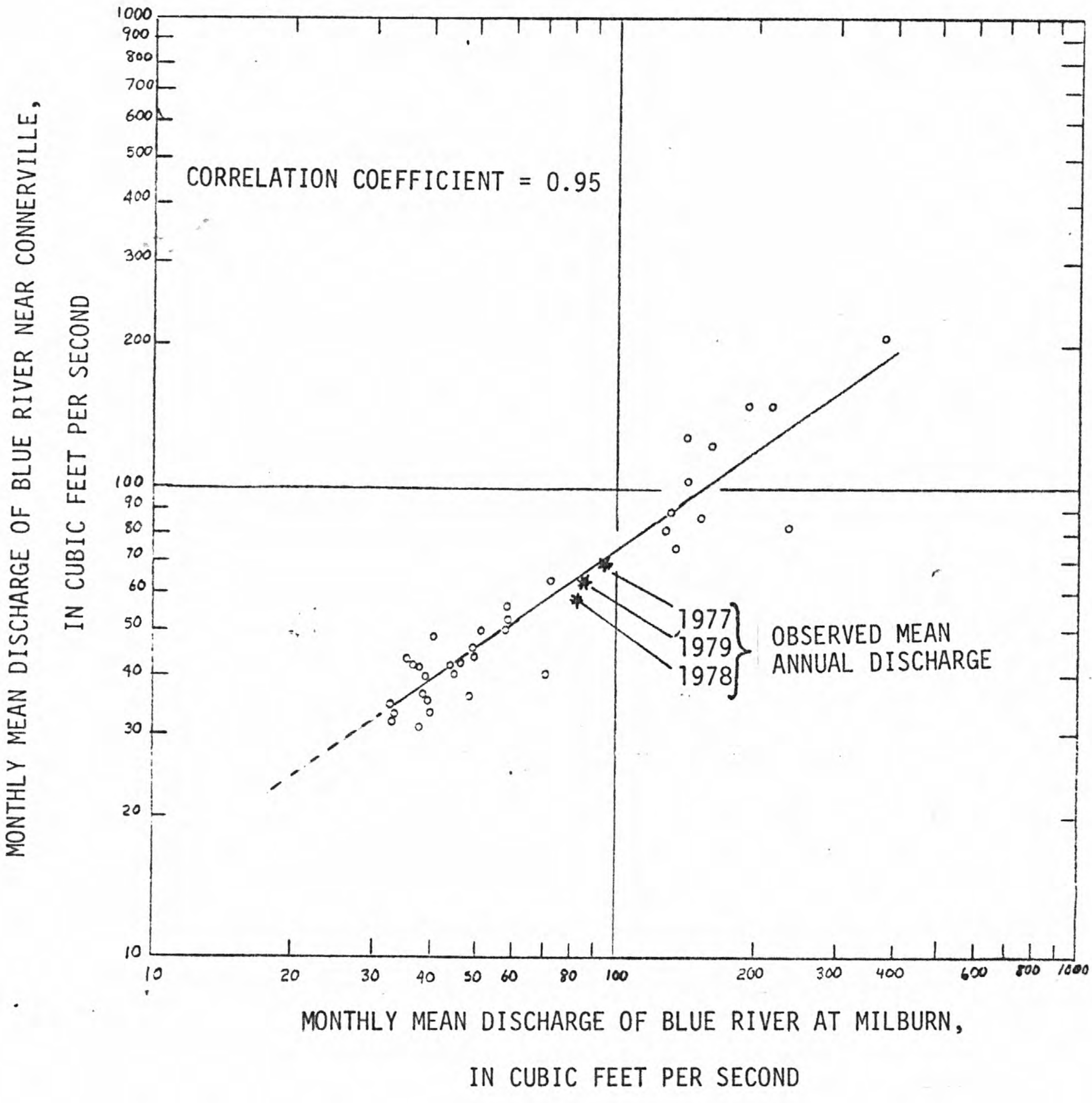

Figure 6.--Relation between the monthly mean discharge in Blue River at Milburn and Blue River near Connerville, water years 1977-79

Seasonal Fluctuations in Streamflow

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Seasonal trends in streamflow in the study area are shown by the Blue River near Connerville hydrograph in figure 7. The flow responds rapidly to significant rainfall events and is typically high during the early spring when frontal storms commonly move into Oklahoma. The flow then declines during June and July reaching base-flow levels by July or August. Base flow will continue to decline in response to declining ground-water levels and high evapotranspiration. Not until January or February does streamflow begin to increase again in reponse to winter rainfall.

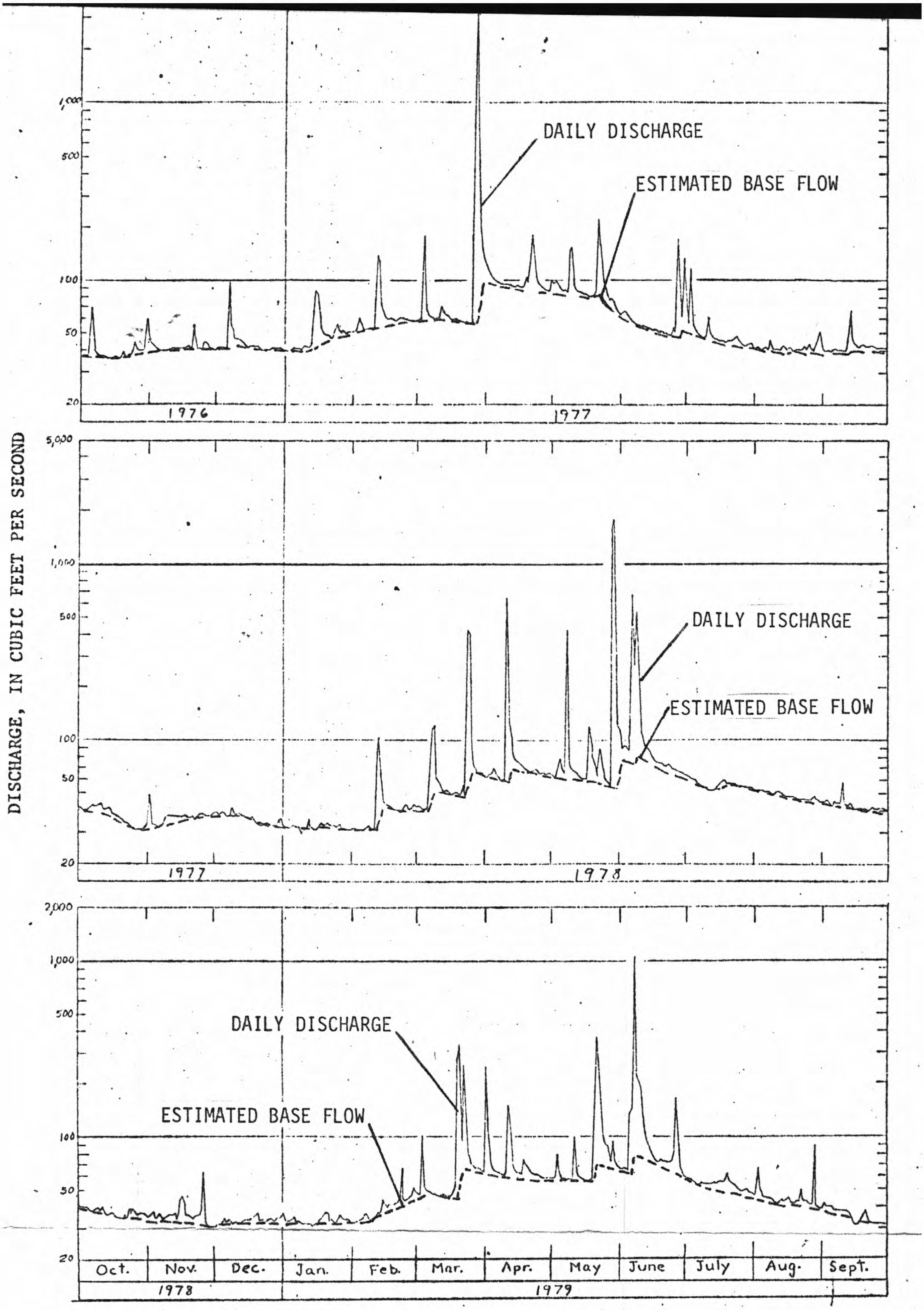

Figure 7.--Hydrograph of daily discharge of Blue River near Connerville for water years 1977-79 and estimated base flow under the total hydrograph.

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Figure 8 shows the duration curve of mean daily flow for the Blue River at Milburn and indicates the percent of time a given daily flow can be expected to be equaled or exceeded during the year. The duration curve--which was defined from 14 years (1966-79) of mean daily flow -- shows that 10 percent of the time flow equaled or exceeded 220 ft^3/s, 50 percent of the time flow equaled or exceeded 66 ft^3/s and 90 percent of the time flow equaled or exceeded 30 ft^3/s. The flat slope of the duration curve at the lower end indicates that base flow -- which represents primarily ground-water discharge from the Arbuckle-Simpson aquifer -- approaches a minimum mean daily flow of about 20 ft^3/s at the Milburn gage. However, an instantaneous low flow of 13.6 ft^3/s was observed at the Milburn site August 28, 1956 (Huntzinger, 1978). Also the low flow value occurred during a year with the second lowest annual precipitation of 48 years of record. Because the low flow value (13.6 ft^3/s) was a single instantaneous measurement and may also have been affected by upstream diversion, it is not considered to be representative of the minimum mean daily discharge at Milburn. If the relation of monthly mean discharges in figure 6 approximates the relation of mean daily flow between Connerville and Milburn, then the flow at the upstream Connerville gage would have been about 18 ft^3/s when the flow at Milburn was 13.6 ft^3/s.

Figure 8.--Duration curve of mean daily flow, Blue River at Milburn.

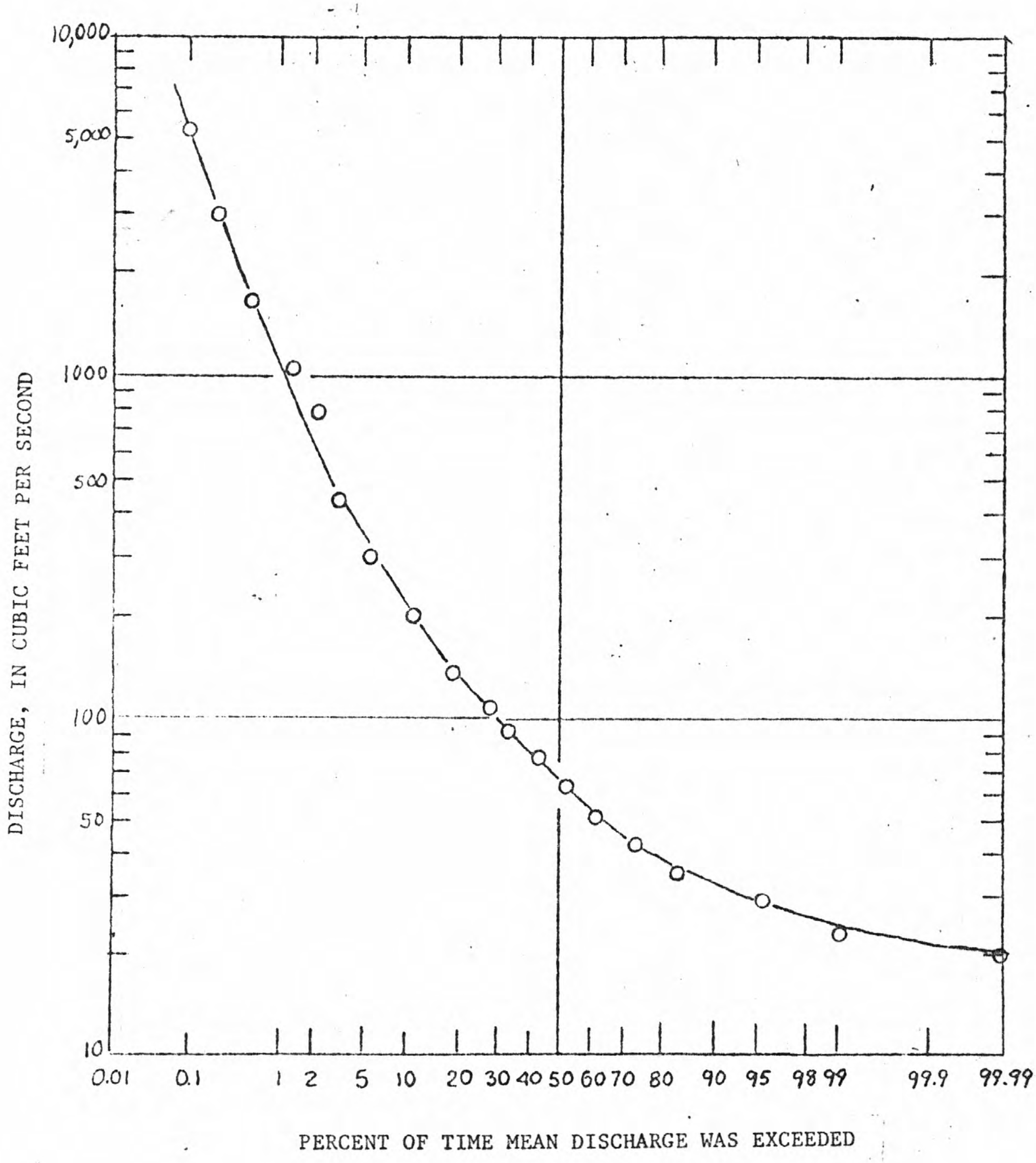

Figure 8.--Duration curve of mean daily flow, Blue River at Milburn, 1966-79.

Average Surface-water Discharge From Study Area

The mean annual runoff from the eastern part of the Arbuckle-Simpson outcrop area of 398 mi^2 was determined using estimates of runoff from three streams which drain nearly 70 percent of this area: Blue River near Connerville (162 mi^2), Mill Creek near Mill Creek (46.4 mi^2), and Pennington Creek near Reagan (65.7 mi^2).

Data used to obtain these estimates include continuous records of discharge at Mill Creek near Ravia (1969-71 water years) and Blue River near Connerville (1977-79 water years) and periodic miscellaneous discharge measurements at Mill Creek near Mill Creek (1955-79 water years) and Pennington Creek near Reagan (1955-79 water years).

The periodic miscellaneous data collected prior to 1967 are published in U.S. Geological Survey Open-File Report 78-166, "Low-flow Characteristics of Oklahoma Streams," by Thomas L.Huntzinger (1978). All other discharge data are published in the U.S. Geological Survey's Annual Water Resources Data Reports for Oklahoma.

Average Annual runoff was estimated at each gaging site for the six water years, 1969-71 and 1977-79. The annual runoff for each site is listed in table 4; the methods used to obtain these values for each gage site are described below:

Table 4.--Mean annual observed and estimated discharge for Blue River near Connerville, Mill Creek near Mill Creek, and Pennington Creek near Reagan, water years 1969-71 and 1977-79

[mi^2 (square miles); in. (inches); ft^3/s (cubic feet per second)]

Water year	Average annual precipitation [1]	Mean Annual Discharge					
		Blue River near Connerville (162 mi^2) [5]		Mill Creek near Mill Creek [3] (46.4 mi^2) [5]		Pennington Creek near Reagan [4] (65.7 mi^2) [5]	
	in.	in.	ft^3/s	in.	ft^3/s	in.	ft^3/s
1969	38.2	9.8 [2]	117 [2]	8.8	30	19.6	95
1970	43.4	8.1 [2]	97 [2]	5.6	19	13.4	65
1971	38.9	7.4 [2]	88 [2]	5.3	18	12.4	60
1977	36.7	6.1	73	3.5	12	9.7	47
1978	32.2	5.4	65	1.8	6	6.8	33
1979	40.9	4.9	58	1.8	6	6.8	33
Average	38.4	7.0	83	4.5	15	11.4	56

1 Average of Ada, Sulphur, and Pontotoc gages.

2 Estimated from relation with Blue River at Milburn.

3 Estimated from relation with Mill Creek near Ravia.

4 Estimated from relation with Mill Creek near Ravia.

5 Drainage area.

Blue River near Connerville

Annual runoff for the Blue River near Connerville for water years 1969-71 was estimated from figure 6 using the monthly observed values at Milburn to estimate monthly values at the Connerville site.

Annual runoff for water years 1977-79 was obtained directly from the continuous daily record at the Connerville site.

Mill Creek near Mill Creek

Only periodic miscellaneous discharges were available at the Mill Creek near Mill Creek site. However, continuous records of discharge were available at a downstream gage---Mill Creek near Ravia---for the period 1969-71. Therefore, a relation of monthly mean discharge between Mill Creek near Ravia and Blue River at Milburn was first defined using observed monthly discharges for the common period of continuous record at these two sites (1969-71) (fig. 9). Monthly discharges for Milburn were then entered into this relation to obtain estimates of monthly discharge and corresponding annual discharges for Mill Creek near Ravia for the period 1977-79. A relation was then defined between periodic discharge measurements at Mill Creek near Mill Creek and corresponding daily mean discharge at the Ravia gage using periodic discharge measurements at Mill Creek near Mill Creek and observed or estimated daily mean discharges at Mill Creek near Ravia for the periods 1969-71 and 1977-79 (fig. 10). Finally, the annual observed and estimated annual discharges at the Ravia site for the periods 1969-71 and 1977-79 were entered in figure 10 to obtain corresponding approximate annual discharges for Mill Creek near Mill Creek.

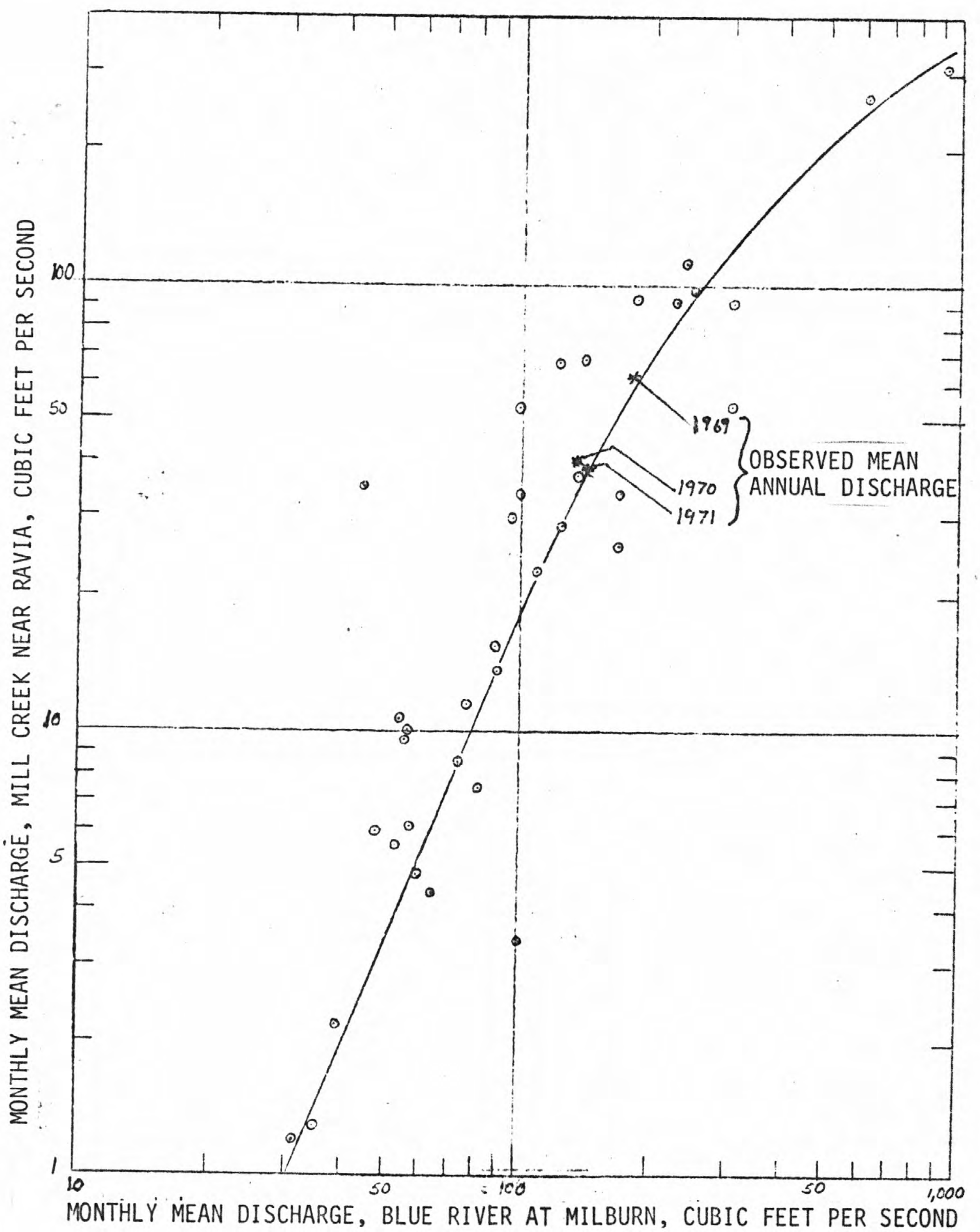

Figure 9.--Relation of monthly mean discharge, Blue River at Milburn and Mill Creek near Ravia, 1969-71 water years.

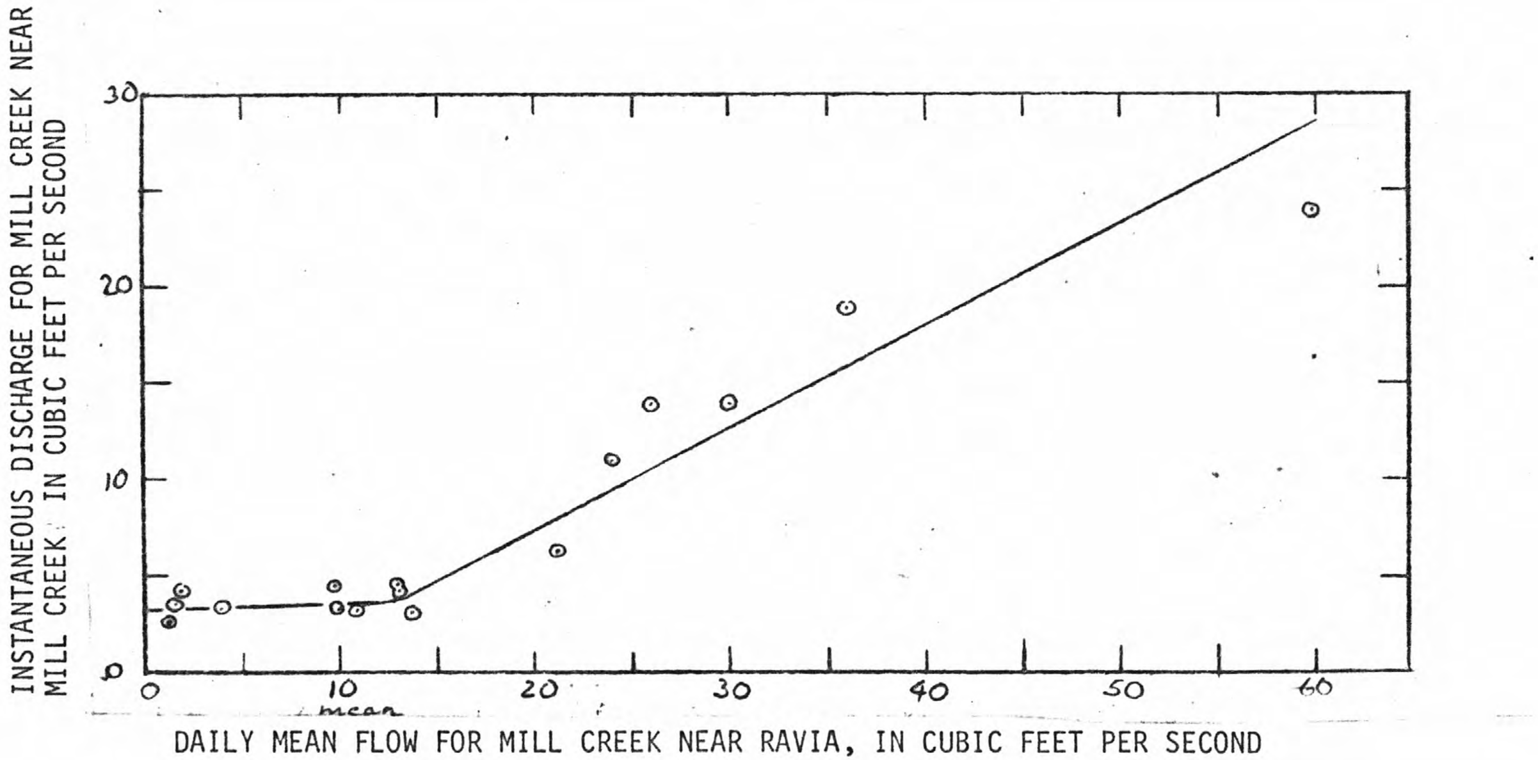

Figure 10.--Relation of periodic daily mean discharge, Mill Creek near Ravia, and instantaneous discharge, Mill Creek near Mill Creek, 1969-71 and 1977-79 water years.

Pennington Creek near Reagan

Periodic miscellaneous discharge measurements obtained at Pennington Creek near Reagan were used in the same manner as for Mill Creek to obtain estimates of annual runoff for Pennington Creek. Discharge measurements obtained during the period 1969-79 were used to define the relation between daily mean discharge at Mill Creek near Ravia and instantaneous discharge at Pennington Creek near Reagan (fig. 11). Annual runoff values for the Ravia site were then entered in figure 11 to obtain approximate annual runoff values for Pennington Creek near Reagan for the period 1969-71 and 1977-79.

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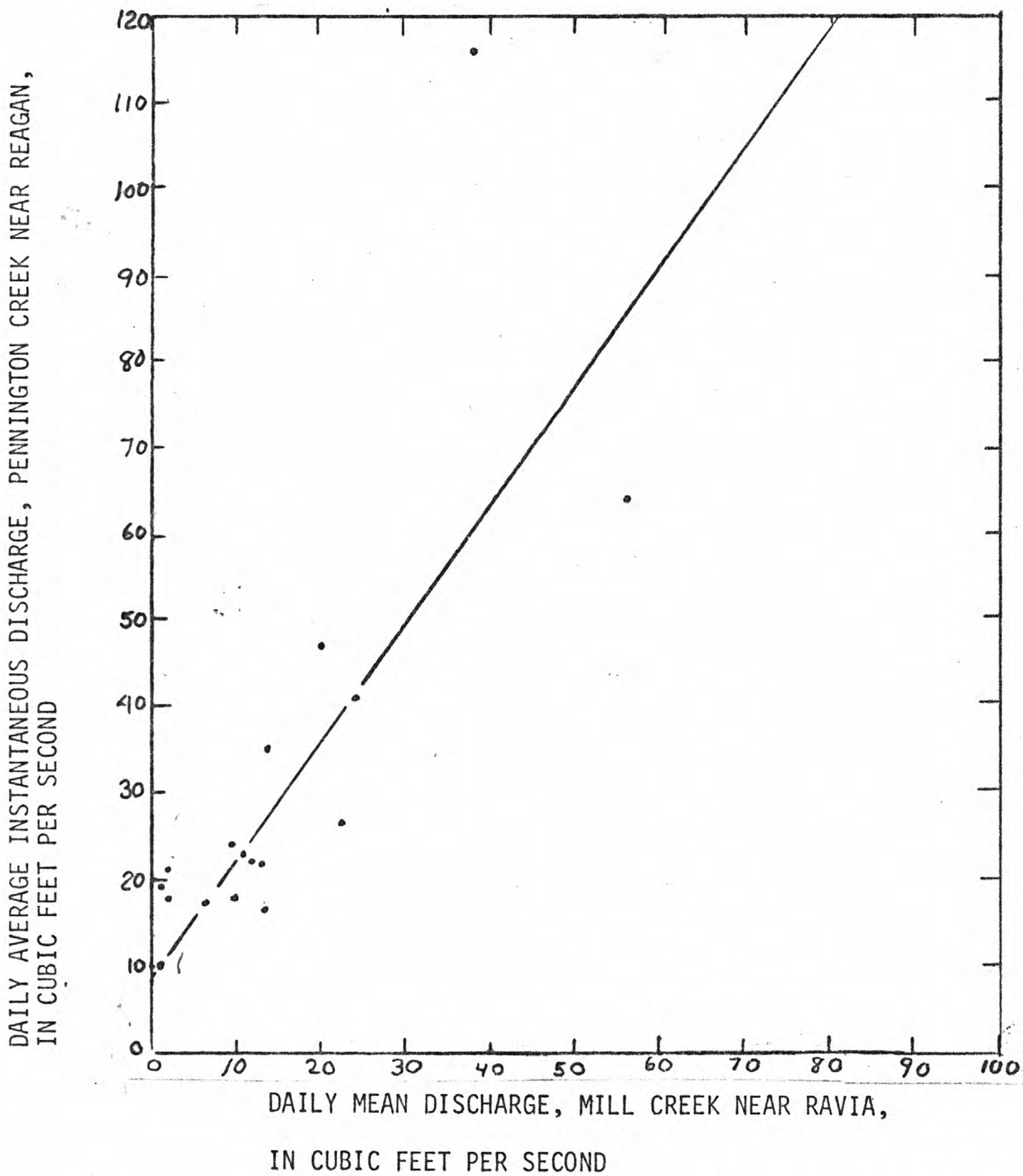

Figure 11.--Relation of periodic daily mean discharge, Mill Creek near Ravia and instantaneous discharge, Pennington Creek near Reagan, 1969-79 water years.

The estimates of annual discharge derived from figures 10 and 11 assume that instantaneous measured discharges represent the daily average discharge for the gaging site. This assumption is not correct if there is a significant change in stage in the stream during the discharge measurement. A greater source of possible error in the derived annual discharge is the assumption that the relation of mean daily discharges in the figures approximates the relation for annual discharges. To check the reliability of the derived estimates of annual discharge for Mill Creek and Pennington Creek, the 6-year mean values of 15 ft^3/s and 56 ft^3/s, respectively, (see table 4) were plotted on a graph (not included in this report) of drainage areas verses 6-year mean discharges (1969-71 and 1977-79) for selected streams in south-central Oklahoma. The scatter of points in this plot is quite large; however, the Mill Creek and Pennington Creek 6-year means plot well within this scatter.

Table 4 shows that the combined average annual runoff from Blue River, Mill Creek, and Pennington Creek for the six water years 1969-71 and 1977-79 was 154 ft^3/s from a total drainage area of 274 mi^2 or 7.6 in./yr. A comparison of this runoff with the average of the Ada, Sulphur, and Pontotoc annual precipitation of 38.4 in. during this 6-year period indicates that surface runoff from the outcrop area accounts for about 20 percent of the precipitation.

The average annual precipitation of 38.4 in. during the 6-year period agrees closely with the long-term average of 38.2 in./yr (table 2). The average annual precipitation for the 14-year period (1965-79) was 40.0 in. (fig. 5). Streamflow records for the Blue River at Milburn for the 14-year (1965-79) and 6-year (1969-71, 1977-79) periods show average annual flows of 140 ft^3/s and 120 ft^3/s, respectively. A comparison of the corresponding average precipitation and annual flows indicates that runoff during the 6-year period was probably about average and runoff during the 14-year period was above average.

Low-flow Characterisitcs

Springs provide base flow to all of the larger streams in the study area throughout the year. Generally, streams from the smaller basins (less than 10 mi^2 of drainage area) cease to flow during the summer months. The minimum flows observed in each of the principal streams in the study area are listed in table 5.

Knowledge of the amount and duration of low flow is necessary for a reliable evaluation of year-round water supply. A study of the frequency of low flow was made for Blue River at Milburn, Pennington Creek near Reagan, and Mill Creek near Mill Creek. Low-flow frequency curves were computed for the late summer period of high water demand when flow typically reaches a seasonal minimum and for the winter season when flow may reach extreme lows due to an intensive freeze or a prolonged drought carried over from the previous summer and fall.

Summer 7-day low-flow curves for the Blue River at Milburn site were computed by selecting the lowest mean discharge for 7 consecutive days during the July-September period of each of the 14 water years of record (1966-79). The values were then assigned order numbers beginning with the smallest 7-day low flow ranked as 1. The recurrent interval (RI) of each value was then computed from RI = $(n+1)/m$ where n is the number of values (14 in this instance) and m is the order number. Each flow value and its corresponding RI were then plotted on extreme-log paper as shown in figure 12.

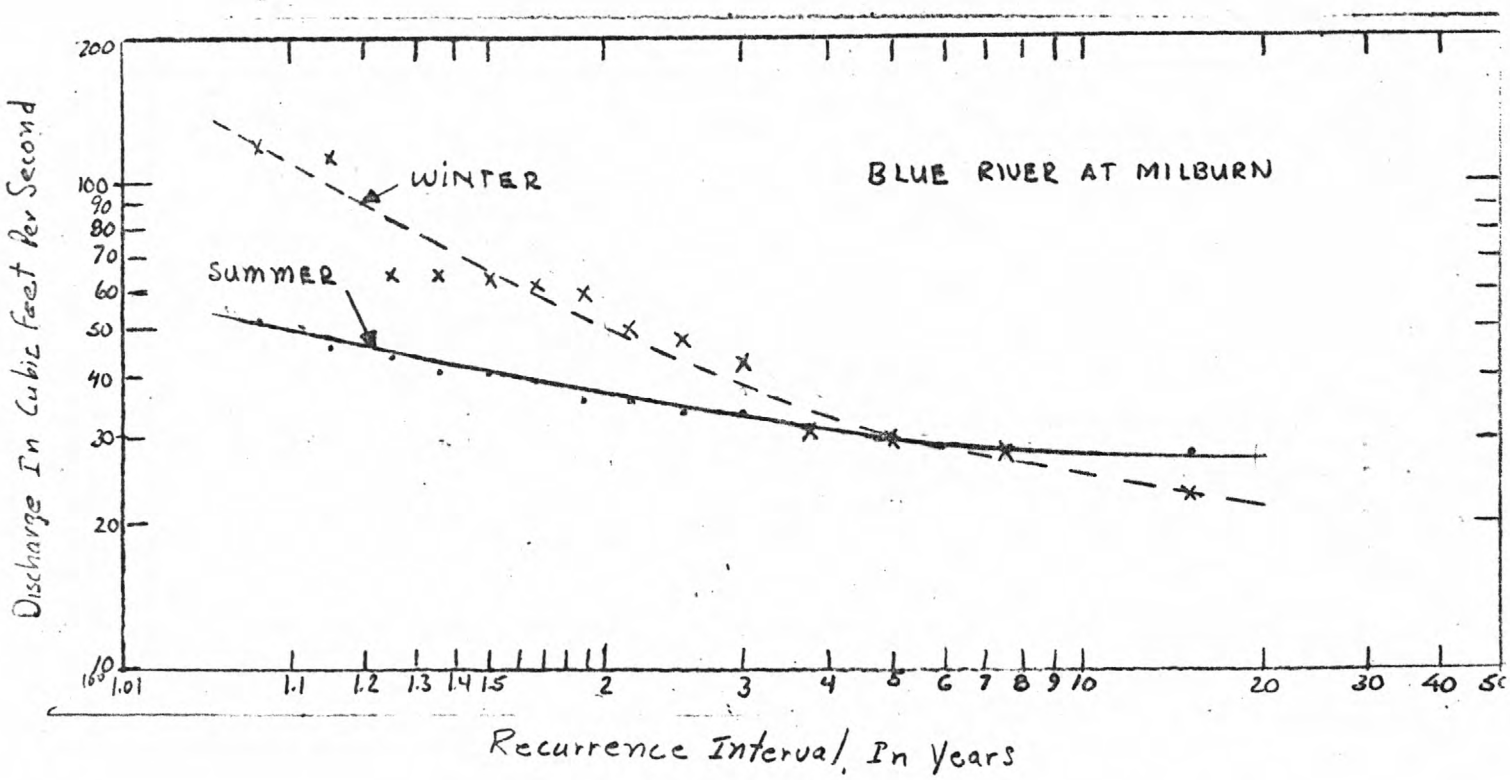

Figure 12.--Summer and winter 7-day low-flow frequency curves for Blue River at Milburn, 1966-79.

Table 5.--Minimum streamflow observed in principal streams draining the Arbuckle-Simpson outcrop area

Stream	Drainage area (square miles)	Measurement date	Discharge (cubic feet per second)	Period of record [1] (water years)
Blue River near Connerville	162	1/08/78	29.0	1976-79
Blue River at Milburn	203	8/28/56	13.6	(1955-61), 1966-79
Pennington Creek near Reagan	65.7	2/20/67	6.30	(1951-55, 1958-73, 1976-79)
Mill Creek near Mill Creek	46.4	9/21/55	0.95	(1951-55, 1958-63, 1965-71, 1962-79)
Mill Creek near Ravia	89.2	9/16-18/71	0.09	(1949-50, 1955), 1969-71, (1976-79)

[1] Years in parentheses represent periods of intermittent measurements.

A similar procedure was used to define the winter low-flow frequency curve using the minimum 7-day low flows for the November-February period of each of the 14 water years.

These curves indicate that, on the average, the summer flow for Blue River at Milburn will be equal to or less that 37 ft^3/s for 7 consecutive days once every two years (RI = 2) and less than 27 ft^3/s for 7 consecutive days once every 20 years (RI = 20). Similarly, the winter low-flow frequency curve shows that the 7-day 2-year low flow is 50 ft^3/s and the 7-day 20-year low flow is 22 ft^3/s.

The intersection of the curves at RI = 5 indicates that winter low flows fall below the summer low flows only once every 5 years on the average.

The asymptotic trend of the summer curve suggests that 7-day summer low flows at the Milburn site are sustained at about 25 ft^3/s. The probability of the 7-day low flow during the extreme low daily value of 13.6 ft^3/s observed on August 28, 1956, at the Milburn site is unknown but does correspond to a historically dry period. Possibly, the August 28, 1956, low flow may have been affected by upstream diversion.

The Connerville gage did not have a sufficient number of years of data to define winter and summer frequency curves similar to those for the Milburn site shown in figure 12. However, relations of the winter and summer 7-day low flows could be defined between these two sites for the common period of record (1977-79). These 7-day low flow relations are not included here but are similar to the monthly mean discharge relation shown in figure 6. The 7-day low flows for Milburn from figure 12 were therefore used in the 7-day low flow relations to obtain estimates of the 7-day low flows for Connerville.

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Table 6 lists the summer and winter 7-day low-flow values corresponding to recurrence intervals of 2, 10, and 20 years for the Blue River at Milburn and 7-day low flows for recurrence intervals of 2 and 10 years at Blue River near Connerville.

Table 6.--Summer and winter 7-day low flows at recurrence intervals of 2, 10, and 20 years for Blue River at Milburn and 2 and 10 years for Blue River near Connerville

Station	Period of record (water years)	Summer Recurrence interval (years) 2	10	20	Winter Recurrence interval (years) 2	10	20
		Seasonal 7-day low flows (cubic feet per second)					
Blue River at Milburn	1966-79	37	28	27	50	25	22
Blue River near Connerville	1977-79	40	35	--	45	25	--

Table 7.--Summer and winter 1-day low flows for recurrence intervals of 2 and 10 years for Mill Creek near Mill Creek and Pennington Creek near Reagan

Station	Period of record (water years)	Summer Recurrence interval (years) 2	Summer Recurrence interval (years) 10	Winter Recurrence interval (years) 2	Winter Recurrence interval (years) 10
		Seasonal 1-day low flows (cubic feet per second)			
Mill Creek near Mill Creek	1952-79 1/	2.1	0.8	3.6	0.9
Pennington Creek near Reagan	1951-79 1/	15	7.0	16	6.0

1/ Partial record only.

FIGURE 13
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Figure 13 shows summer and winter one-day low-flow frequency curves for Pennington Creek near Reagan and Mill Creek near Mill Creek which were computed using periodic miscellaneous low-flow measurements obtained at these sites. The frequency curves were computed in a manner similar to that used for Blue river at Milburn; however, the low-flow values in this instance represent daily values approximating the minimum low flow for the season rather than a continuous 7-day minimum low flow for the season. Only partial data are available during the periods of record at Pennington Creek and Mill Creek.

The accuracy of the low-flow frequency estimates is dependent on the number of years of record used to define the curve and how representative the low flows during this period of record are of the long-term low-flow characteristics. The results may not be reliable if the period of record is interrupted by significant upstream regulation or diversions. No significant regulation occurs on streams in the study area and the only diversion occurs on Pennington Creek at the Fish Hatchery near Reagan. This diverted water was measured and is included in the low-flow computations.

The occurence of an extreme and unusual drought (such as indicated by the August 28, 1956, low flows in the area) or a significant wet year during the period of record may adversely affect the low-flow frequency estimates.

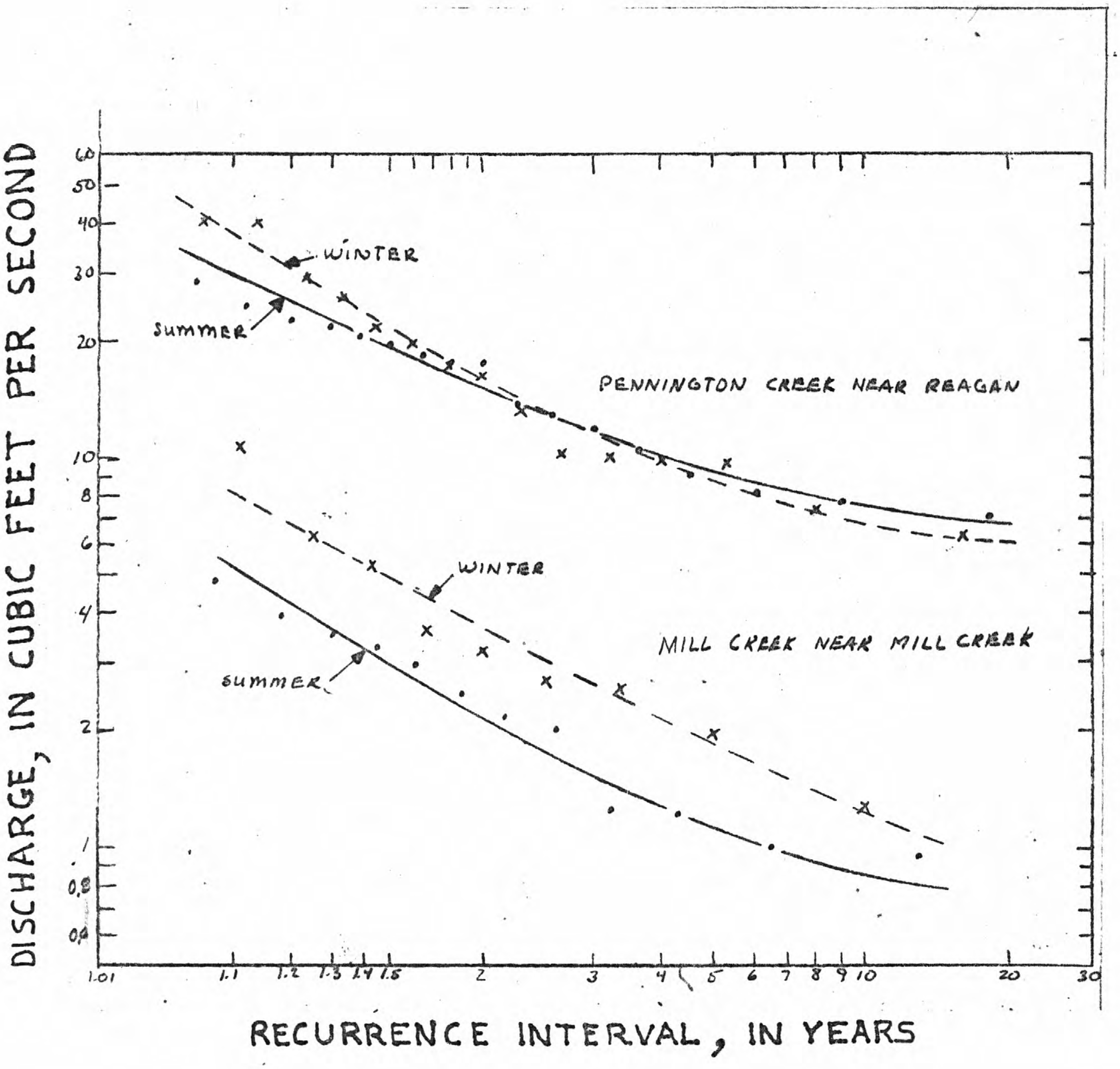

Figure 13.--Summer and winter 1-day low-flow frequency curves for Pennington Creek near Reagan (1951-79) and Mill Creek near Mill Creek (1951-79), water years.

Riggs (1972) recommends that at least 10 years of record be available to define the 20-year low flow. Thus, the 14 years of record for Blue River at Milburn are considered to provide a reliable estimate of the 2-, 10-, and 20-year low flows. When regression relations are used to define the low-flow values such as were used for the Blue River near Connerville, the correlation coefficient (r) of the relation should exceed 0.8 (Fiering, 1963). Because r for the winter and summer relations are greater than 0.8, the 7-day 2-year and 7-day 10-day low flows in table 15 are also considered reliable estimates.

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Table 7 lists the summer and winter 1-day low-flow values corresponding to recurrence intervals of 2 and 10 years for Mill Creek near Mill Creek and Pennington Creek near Reagan.

Figures 12 and 13 show that in all instances the summer low flows fall below the winter low flows in the low frequency range (RI less than or equal to 2 yrs). This reflects the effect of annual depletion of ground water due to high summer evapotranspiration rates. However, at the higher frequencies (RI greater than or equal to 10 yrs) for the Blue River and Pennington Creek, summer low flows exceed the winter values. This reflects the occasional effect of a prolonged drought extending through the fall season and into the winter months. Streamflow records show that extreme low winter flows occur in the study area as a result of an unusually severe freeze causing surface flow to go into storage in the form of ice.

The 1-day 2-year and 1-day 10-year low-flow discharges for Mill Creek near Mill Creek and Pennington Creek near Reagan are based on periodic discharge measurements obtained during selected winter and summer low-flow periods since November 1950.

Because of the number of values (n, in years) used to define the curves ranging from n = 17 (summer curve of Pennington Creek) to n = 9 (winter curve for Mill Creek) the 1-day 2-year and 1-day 10-year low-flow values are considered reliable estimates of the frequency of low flow at these sites (table 7).

Table 7.--Summer and winter 1-day low flows for recurrence intervals of 2 and 10 years for Mill Creek near Mill Creek and Pennington Creek near Reagan.

The shape of the low-flow frequency curves reflects the hydrologic characteristics of the Arbuckle-Simpson aquifer. Frequency curves which show significant breaks or changes in slope suggest that low flows were derived from more than one aquifer or from aquifers of different permeabilities. The smooth concave shape of curves in figures 12 and 13 suggests, however, that, on a regional basis, the aquifer is relatively isotropic with no significant changes in permeability as the ground-water levels decline. In fact, the slope of the frequency curves are all somewhat similar except for the summer curve for Blue River which is flatter with higher sustained flows at the larger recurrence intervals. This flat slope reflects a sustained ground-water discharge into the Blue River from the relatively permeable Arbuckle Group which outcrops in most of the basin's drainage area.

Ground-Water Surface-Water Relationship

Streams draining the outcrop area of the Arbuckle-Simpson aquifer are fed by numerous springs and seeps that discharge from the aquifer. That portion of streamflow coming from ground-water discharge is base flow and fluctuates directly in response to fluctuations in ground-water levels. Base flow may represent only a fraction of the total flow in the stream during periods of high surface runoff or may constitute the total flow during prolonged drought periods.

GURE 14
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Figure 14 shows for the 1978 water year, the relation between precipitation at Pontotoc, streamflow of the Blue River near Connerville, and ground-water levels in well 02S-06E-12 CCB 1 located 1.5 mi from the river. The streamflow hydrograph shows an immediate response to most precipitation events and in particular those events of 1 in. or more. Ground-water level changes throughout the study area generally lag behind streamflow by several days or weeks depending on the depth of the ground-water level below land surface.

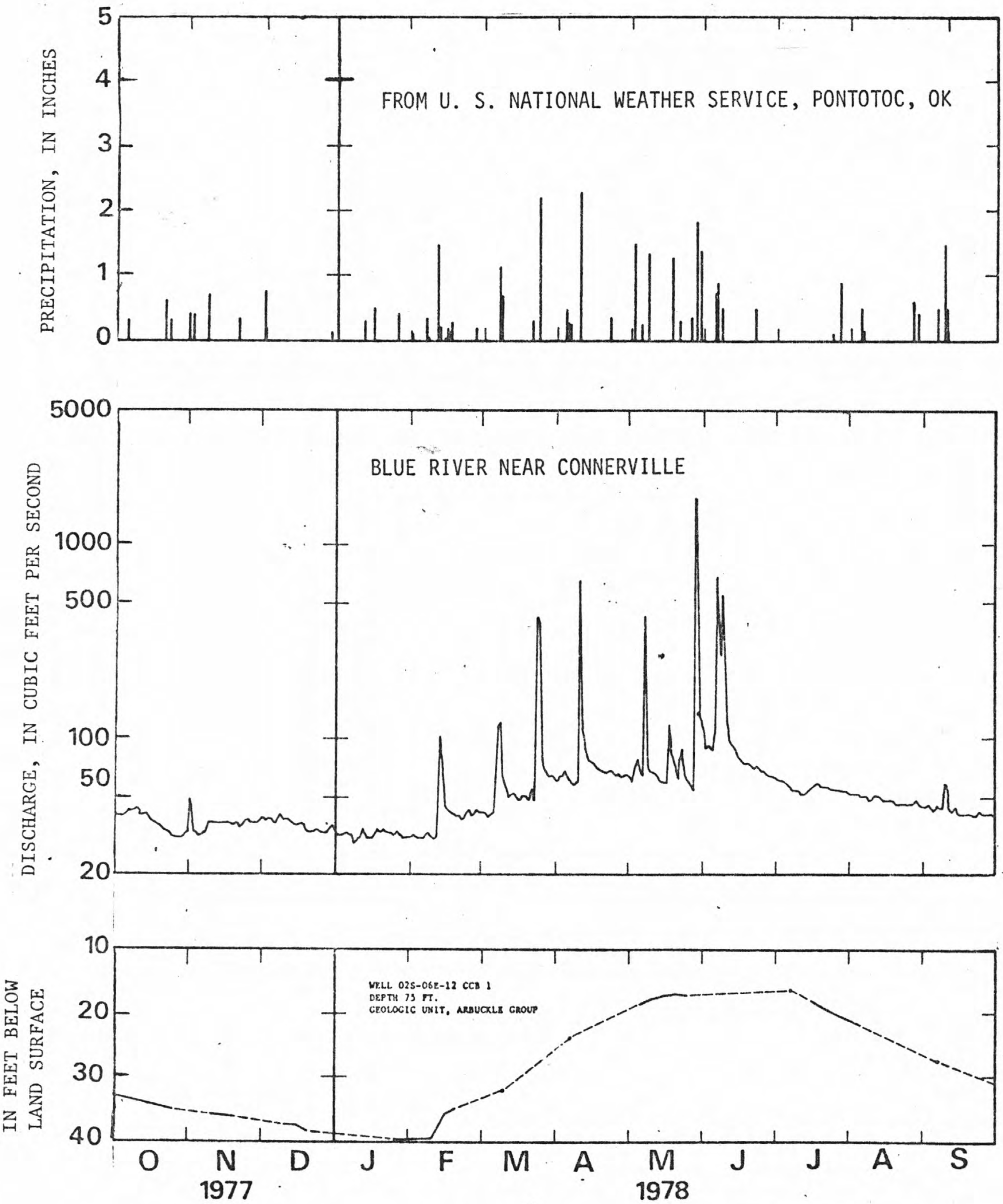

Figure 14.--Graphs showing the relation of precipitation at Pontotoc, discharge of Blue River near Connerville, and water levels in well 02S-06E-12 CCB 1.

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The average of water levels in five wells throughout the Blue River drainage basin shows a close correlation with base flow of Blue River near Connerville (fig. 15). The figure shows that ground-water levels and the corresponding base flow from Blue River are higher during the summer than during the winter. Precipitation occurs primarily in the spring and early summer causing ground-water levels and base flow to reach a maximum by early or mid-summer. The straight line in figure 15 was drawn to the right of the data points so as to represent that relation defining the minimum average ground-water level that would be expected for a given base flow in the Blue River near Connerville.

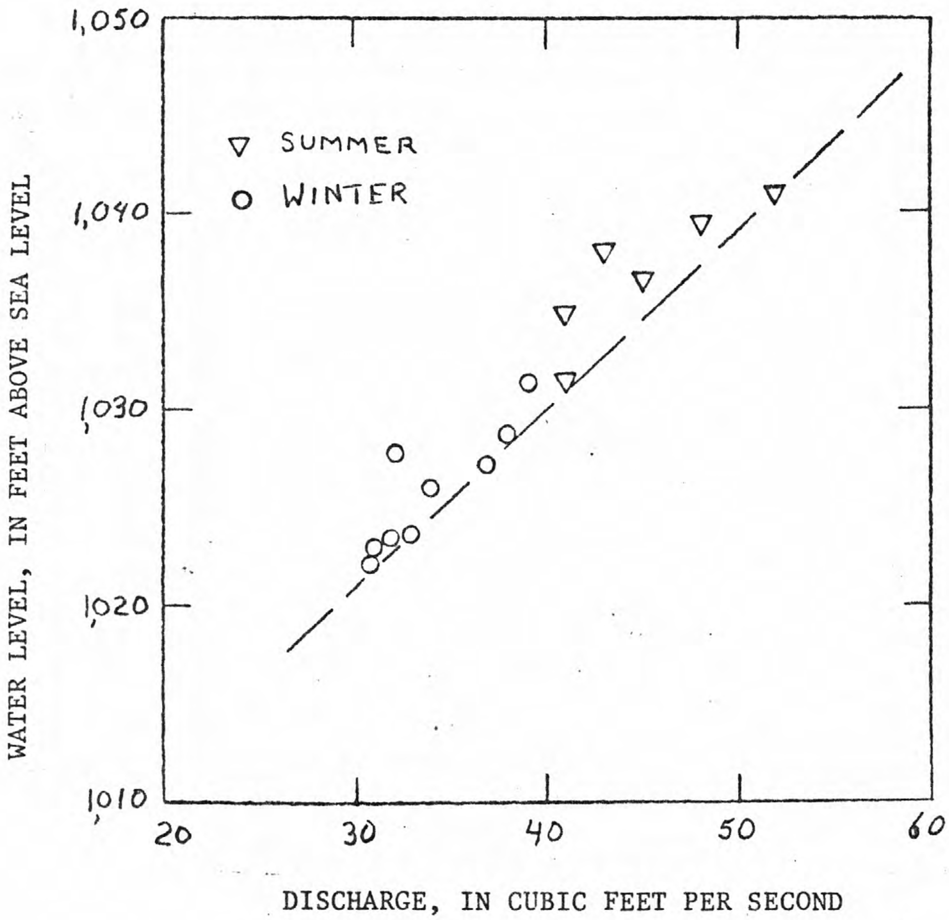

Figure 15.--Relation between average of water levels in five observation wells in Blue River basin and base flow of Blue River near Connerville.

GEOLOGIC CONTROL OF GROUND WATER

GURE 16 & 17
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Rocks ranging in age from Precambrian to Quaternary crop out in or near the Arbuckle Mountains. The distribution of these rocks is shown in figures 16 and 17; their thickness, lithology, and water-bearing characteristics are summarized in table 8.

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As shown in table 8, the Arbuckle-Simpson aquifer consists of several formations that make up the Arbuckle and Simpson Groups. Although each formation in each group may have different water-yielding characteristics, they are considered together to make up the Arbuckle-Simpson aquifer.

Rocks of the Arbuckle Group of Cambrian and Ordovician age are primarily limestone and dolomite, which are generally referred to as carbonate rocks, while those of the Simpson Group of Ordovician age are sandstone, shale, and limestone. Approximately two-thirds of the aquifer consists of limestone and dolomite.

Carbonate rocks are readily dissolved by water containing small amounts of acids derived from the atmosphere, soil, and vegetation. The total amount of acid in solution generally is small and the rate at which it dissolves the rock is very slow but over long periods of time large volumes of rock are removed.

Figure 16.--Geologic map of the eastern part of the Arbuckle Mountains.

Figure 17.--Geologic map of the western part of the Arbuckle Mountains.

Table 8.--Generalized lithologic description and water-yielding characteristics of strata in the study area

System	Series	Stratigraphic unit			Thickness (feet)	Lithologic description
Quaternary	Holocene	Quaternary Deposits			0 - 85	Gravel, sand, silt and clay.
Cretaceous	Lower Cretaceous	Cretaceous Undifferentiated			200 to 700	White to yellow, medium-grained weakly indurated sand with varicolored clay.
Permian Pennsylvanian Mississippian Devonian Silurian Ordovician	Lower Permian to Middle Ordovician	Paleozoic Undifferentiated			0 to an estimated 5,000	Shale, siltstone, sandstone or other rock types.
Ordovician	Middle Ordovician	Simpson Group	Bromide Formation Tulip Creek Formation McLish Formation Oil Creek Formation Joins Formation	Arbuckle-Simpson aquifer	1,000 to 2,300	Upper part consists of buff limestone, grayish-green shale and brown to white fine- to medium-grained sandstone. Lower part consists of gray to tan granular limestone with greenish-gray shale and brown, fine- to medium-grained sandstone.
Ordovician	Lower Ordovocian	Arbuckle Group	West Spring Creek Formation Kindblade Formation Cool Creek Formation McKenzie Hill Formation	Arbuckle-Simpson aquifer	4,000 to 6,700	Principally limestone in the west and dolomite in the east with a few thin beds of sandstone that thicken to the east.
Cambrian	Upper Cambrian	Arbuckle Group	Butterly Dolomite Signal Mountain Limestone Royer Dolomite Fort Sill Limestone	Arbuckle-Simpson aquifer		Fine-grained limestone which ranges eastward into tan to pink, fine- to coarse-grained dolomite.
Cambrian	Upper Cambrian	Timbered Hills Group	Honey Creek Formation Reagan Sandstone		175 to 675	Very glauconitic and silty, gray to to greenish-brown, fine to coarsely crystalline; limestone and brown, coarse-grained sandstone.
Cambrian	Middle Cambrian	Colbert Porphyry			Drilled thickness 4,500	Red-brown rhyolite porphyry.
Precambrian	Precambrian	Tishomingo Granite and Troy Granite			Estimated thickness 10 miles	Pink, coarse-grained granite.

Table 8.--Generalized lithologic description and water-yielding characteristics of strata in the study area.

The occurrence and movement of ground water in the Arbuckle-Simpson aquifer is strongly controlled by lithology and structure. As shown in figures 16 and 17, the area has been intensely faulted; only faults one mile or longer, from maps compiled by Ham, McKinley, and others (1954), are shown. Associated with the major fault zones are numerous minor faults and joints that occur in the more dense beds such as the Arbuckle carbonate rocks. Geologic structure is of significance because fractures caused by folding and faulting provide channels for ground-water movement. Acid water enters the fractures, joints, and bedding planes and enlarges them by solution. The result is an irregular network of openings of all sizes and shapes extending both vertically and laterally. The association of springs with faults and other fractures indicates the significance of structural control on ground-water flow. Figure 18 shows the effect of faulting on the occurrence of springs where less permeable rocks abut rocks of the Arbuckle-Simpson aquifer.

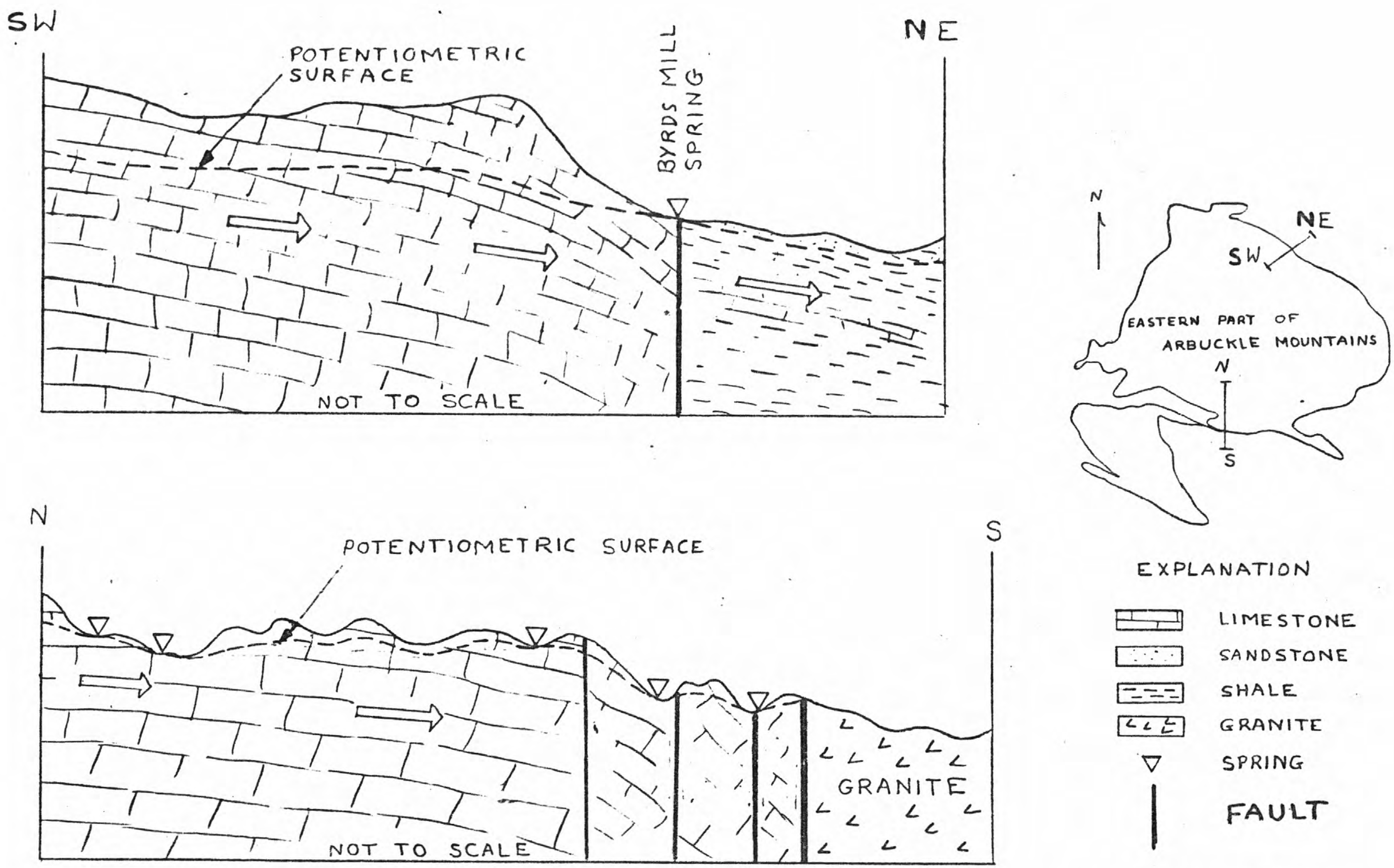

Figure 18.--Diagrammatic sections showing the relation~~ship~~ of ground water to the geology and structure of the Arbuckle-Simpson aquifer in the eastern part of the Arbuckle Mountains. Arrows indicate the general direction of ground-water flow.

Figure 18.--Diagrammatic sections showing the relation of ground water to the geology and structure of the Arbuckle-Simpson aquifer in the eastern part of the Arbuckle Mountains.

The depth to which the network of solution channels can reach is limited by the depth at which ground-water circulation took place. Caliper logs, which show the diameter of a hole with depth, indicate openings at various depths in wells as deep as 2,000 ft. Some of the openings were probably developed during drilling of the well but many may be solution openings which were developed when the water table was possibly at the level of the openings. More and larger openings are usually formed beneath the valleys where the volume and movement of water from the uplands is greatest. Larger springs occur in the eastern part of the area, which is underlain primarily by dolomite, than in the western part of the area which is primarily limestone. However, the difference in the amount of discharge from the springs could be a result of the difference in size of the catchment areas rather than a difference in lithology. The catchment area of the eastern part is much larger than the catchment area of the western part of the study area.

GROUND WATER

Rocks that make up the Arbuckle-Simpson aquifer act as a reservoir in which water is stored in numerous openings from small intergranular pores to open fractures and caverns. As water enters or leaves the reservoir, the amount in storage is changed and produces a rise or fall of the water level in a well. Because of the heterogeneity ~~and corresponding difference in the effective porosity~~ of the aquifer, the amount of water that enters or leaves the aquifer varies throughout the study area.

Occurrence and Movement

Potentiometric surface maps of the Arbuckle-Simpson aquifer in the eastern and western parts of the Arbuckle Mountain area (winter 1976-77, 1977-78) are shown in figures 19 and 20. The potentiometric surface map for the western part of the area is incomplete because wells are too sparse to adequately define the water-level surface.

Figure 19.--Potentiometric map of the eastern part of the Arbuckle Mountain area, winter 1976-77.

Figure 20.--Potentiometric map of the western part of the Arbuckle Mountain area, winter 1977-78.

The potentiometric surface roughly follows the topography. In general, recharge areas are topographically high and discharge areas are topographically low. In the eastern part of the area where ground-water levels are generally lower, the ground-water gradient is generally eastward and ranges from 20 ft/mi to 60 ft/mi. In the western part of the area, the ground-water gradient is generally toward the south at about 50 ft/mi.

Where the Arbuckle-Simpson aquifer dips beneath beds of low permeability, the water is confined and wells that penetrate below the confining layer may flow all or part of the year. Table 9 lists several wells that flow part or all of the year. Flowing wells occur in western Coal County and in Oil Creek Valley in central Johnston County near Nebo. Flowing wells also occur north of Sulphur in the valley of Rock Creek where the stream has eroded the land surface below the potentiometric surface. Hart (1972) in a study of the Sulphur area suggests that these flowing wells obtain their hydraulic head from Arbuckle rocks at depth and receive recharge at a higher altitude east of the area where the Arbuckle is at the surface.

Table 9.--Wells in the study area that penetrate the Arbuckle-Simpson aquifer and flow all or part of the year

[Water level is at or above (+) land surface. F = flowing.]

Local Number	Well depth (feet)	Water level (feet)	Observation date
01S-08E-32 CCA 1	400	F	03-09-77
01S-08E-32 CCA 2	600	F	03-09-77
01S-08E-32 CCA 3	600	F	03-09-77
01S-08E-32 CCA 4	600	F	03-09-77
01S-07E-23 BCC 1	1,400	F	02-01-77
01S-07E-34 ABC 1	90	F	02-04-77
02S-07E-03 BBB 1	84	+0.54	02-08-77
02S-07E-04 CAD 1	80	F	02-02-77
02S-06E-34 ACA 1	520	0.00	11----53
02S-03E-13 BBB 1	614	+2.10	08-24-77
02S-03E-25 DCD 1	361	+6.30	12-06-77
01S-02W-09 BCD 1	16	0.00	04-25-78

Recharge

Recharge to the Arbuckle-Simpson aquifer is from precipitation on the area. Most natural recharge takes place by infiltration of precipitation into soil cover, alluvium, or outcrops of porous rock. In some places, water enters small sink holes or solution pipes in the carbonate rocks. Some recharge to the aquifer also occurs from streamflow infiltrating through deposits and rocks fractures in the stream channel. Some recharge may percolate through overlying younger formations around the periphery of the outcrop area.

Hydrographs of water levels in wells indicate fairly rapid response of water levels in the aquifer to rainfall. However, the rate of recharge from precipitation varies from place to place because of differences in permeability ~~and porosity~~ of the aquifer and soil ~~types.~~

The recharge to the aquifer following a significant rainfall can be determined by using a method described by Rorabaugh (1964) from streamflow hydrographs. This method assumes a drainage basin underlain by an aquifer having homogeneous, isotropic characteristics; the distances from stream to ground-water divides or geologic boundaries of no flow are equal at all places in the basin; and the ground-water level is everywhere at stream level. The stream must penetrate the aquifer and must maintain flow on a perennial basis. This method was used by Rorabaugh (1964) in the case of a finite aquifer having finite boundaries. Although the method was used in the case of a sand aquifer, it is believed that the Arbuckle-Simpson aquifer may act as a uniform aquifer when considered regionally throughout the Arbuckle Mountain area. The equation used with this method is:

$$T = \frac{4Qa^2S}{\pi^2 T} \qquad (1)$$

in which

- V = volume of water recharged to the aquifer as a result of the rainfall event (L^3);
- Q = discharge in the stream resulting from the rainfall event (L^3/T);
- S = storage coefficient (dimensionless);
- a = average distance from the stream to the ground-water drainage divide (L); and
- T = transmissivity (L^2/T).

Rorabaugh and Simons (1966) have shown that the quantity a^2S/T is equal to $\Delta t/0.933$ where Δt is the time in days required for the stream-flow-hydrograph recession to pass through one log cycle when plotted on semilog coordinates. Therefore, equation (1) can be rewritten:

$$V = \frac{Q\Delta t}{2.3} \qquad (2)$$

After a recharge event, the streamflow hydrograph approaches straight-line recession when time (t), in days is equal to 0.2 (a^2S/T), or 0.2 $\Delta t/0.933$ (Rorabaugh, 1964). Also, when t equals 0.2 (a^2S/T), half of the ground water in storage from the recharge event has been depleted (Glover, 1966). To calculate the recharge from one event, the effects of all previous events must be subtracted.

Recharge to the aquifer in the Blue River basin was determined by applying this method to the streamflow hydrograph of Blue River near Connerville. The ground-water basin is thought to approximately coincide with the surface drainage basin above the Connerville station and is approximately 150 mi^2.

TABLE 10
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For the average precipitation of 4.6 in. which occurred on March 26-28, 1977, (table 10), the streamflow hydrograph shows Δt equals 160 days. The straight-line recession began on April 30 when t equals 34 days and streamflow was 72 ft^3/s. If the March 26-28 precipitation had not occurred, extrapolation of baseflow indicates that only 32 ft^3/s would have been flowing in the river on April 30. Therefore, the increase in baseflow due to the March 26-28 event was 40 ft^3/s. With Q equal to 40 ft^3/s and Δt equal to 160 days, equation 2 defines the volume of recharged ground water on April 30 due to the March 26-28 event as $V = 2.4 \times 10^8 ft^3$. However, because the amount of water recharged on April 30 is only half of the total recharge from the March 26-28 event, total recharge from the March 26-28 event was 4.8×10^8 ft^3. Distributed over the entire ground-water basin of 150 mi^2, the average recharge per unit area was 1.4 in. The results of similar calculations for several other precipitation events are included in table 10. Also shown in the table is the ratio of recharge to precipitation; the ratios ranged from 0.12 to 0.34 for the five rainfall events that were studied and depend on such variables as rainfall intensity, areal distribution, antecedent precipitation, season of the year, and evapotranspiration. The average annual baseflow draining the area is a reliable measure of the annual recharge to the aquifer; base flows are discussed in the discharge section of this report.

Table 10.--Recharge to the Arbuckle-Simpson aquifer in the Blue River basin for selected rainfall events during 1977, 1978, and 1979

[Q: discharge, in cubic feet per second, in Blue River resulting from rainfall;
Δt: time required for streamflow hydrograph to decline through one log cycle]

Date	Precipitation, in inches				Q, ft^3/s	Δt, in days	Recharge, in inches	Ratio of recharge to average precipitation
	Roff	Sulphur	Pontotoc	Average				
March 26-28, 1977	3.7	4.42	5.80	4.6	40.0	160	1.4	0.30
May 18-21, 1977	5.8	2.80	1.85	3.5	15.0	150	0.48	0.14
March 23-24, 1978	1.2	1.22	2.21	1.5	14.0	170	0.51	0.34
June 5-8, 1978	2.5	2.69	2.15	2.4	8.5	155	0.28	0.12
June 4-10, 1979	---	2.58	3.40	3.0	18.0	165	0.65	0.21
							Average	0.22

Storage and Changes in Storage

Water-level fluctuations

During the study, water levels in 29 wells that tap the Arbuckle-Simpson aquifer were measured monthly. In addition, continuous records were obtained from two wells in Johnston County and two wells in Pontotoc County (table 11). Water levels were monitored to determine annual (year to year) trends, seasonal fluctuations, and the relation between ground water storage and surface water flow. Maximum and minimum levels observed in these wells indicate that the median fluctuation is about 21 ft but fluctuations ranged from 53 ft to 8 ft for individual wells.

As indicated by the graphs in figure 21, high ground-water levels occur following periods of heaviest rainfall, and low water levels occur during the drier periods of the year. No long term declines or rises in water levels are apparent from the hydrographs other than the relation of high levels during wet years.

Of the 33 wells for which water levels were measured during the investigation, hydrographs for wells 01N-04E-02 DDA 1, 01N-05E-27 DCC 1, 01S-07E-06 BBB 1, 02S-04E-26 CBA 1, 02S-06E-12 CCB 1, and 03S-04E-06 CCD 1 are shown in figure 22. The water levels in all wells monitored during this study generally are lowest during January and February and highest during May and June.

Table 11.--Maximum and minimum water levels in 33 observation wells in the eastern part of the Arbuckle Mountains

Well	Depth to water (feet) Minimum	Depth to water (feet) Maximum	Range of fluctuation (feet)
01N-04E-02 DDA 1	97.66	150.72	53.06
01N-04E-25 AAC 1	85.61	118.04	32.43
01N-04E-31 CBA 1	118.75	142.01	23.26
01N-04E-33 AAD 1	103.52	127.26	23.74
01N-05E-01 AAB 1	63.79	86.86	23.07
01N-05E-09 ADA 1	79.83	116.36	36.53
01N-06E-21 ACB 1	87.34	107.12	19.78
01N-06E-04 CAD 1	105.64	120.77	15.13
01N-06E-24 CAB 1	30.29	56.75	26.46
01N-06E-29 CAB 1	70.16	89.46	19.30
02N-05E-21 DCD 1	59.93	102.04	42.11
01S-03E-22 BAC 1	38.77	47.77	9.00
01S-04E-12 ADA 1	27.50	57.16	29.66
01S-04E-22 CDC 1	35.50	49.12	13.62
01S-05E-27 AAB 1	53.35	81.64	28.29
01S-06E-05 CCC 1	61.20	77.53	16.33
01S-06E-35 BDB 1	4.24	14.85	10.61
01S-07E-02 CBB 1	89.89	99.70	9.81
01S-07E-06 BBB 1	8.11	18.04	9.93
01S-07E-08 BAA 1	13.04	45.30	30.26
01S-07E-20 CAB 1	6.10	17.32	11.22
01S-07E-23 DDD 1	47.21	95.44	48.23
01S-07E-25 CBC 1	51.09	83.49	32.40
02S-03E-13 CCD 1	9.10	23.23	14.13
02S-04E-26 CBA 1	19.74	37.67	17.93
02S-05E-03 CBC 1	93.90	103.30	9.49
02S-06E-12 CCB 1	14.75	39.53	24.78
02S-06E-04 CAB 1	83.52	132.92	49.40
02S-07E-07 AAA 1	38.44	57.20	18.76
03S-04E-06 CCA 1	15.54	27.11	11.57
03S-04E-06 CCD 1	13.00	20.78	7.78
03S-04E-23 ABB 1	18.66	35.25	16.59
Median	45.48	81.38	21.42

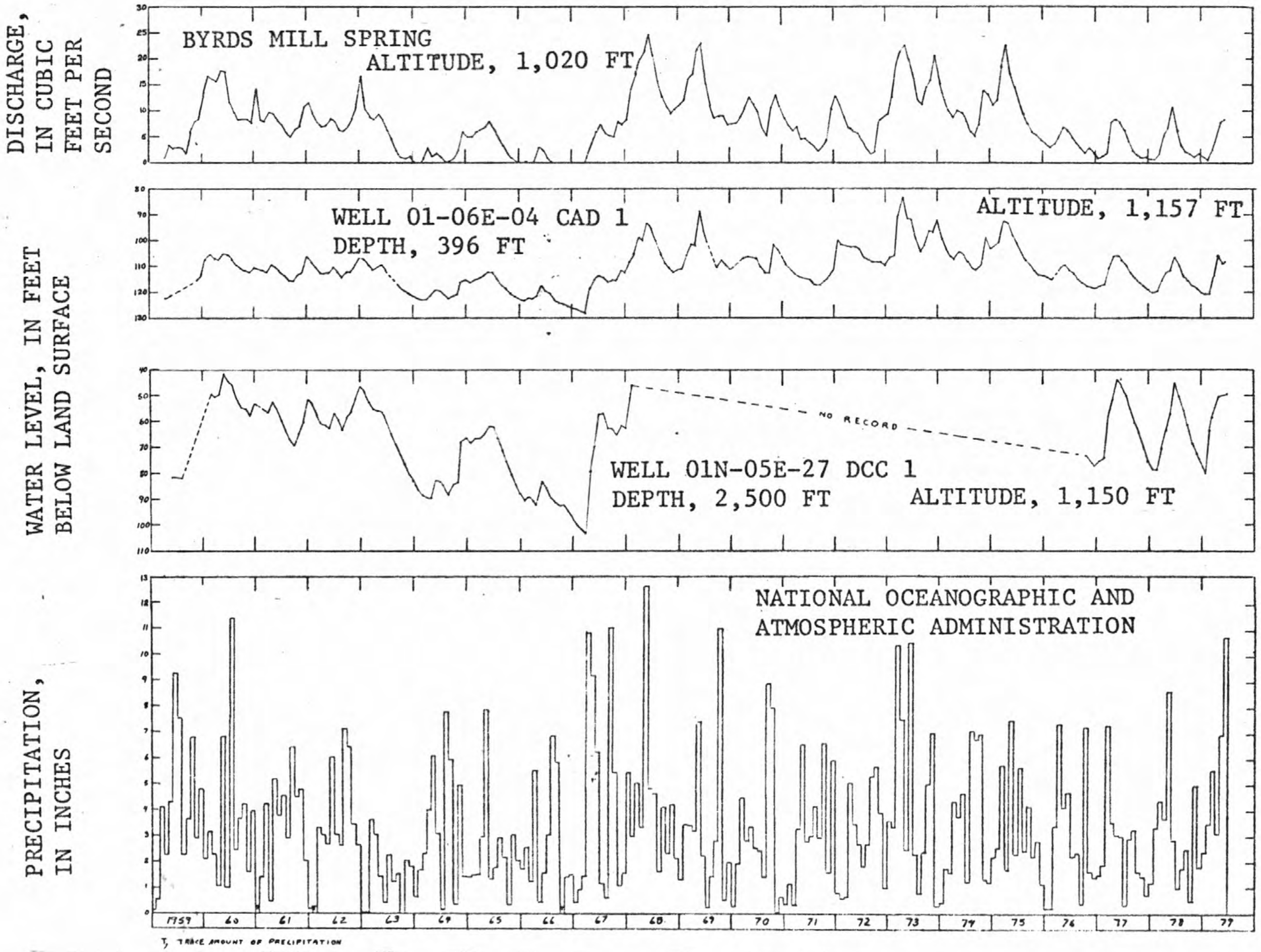

Figure 21.--Relation of water levels in wells 01N-05E-27 DCC 1 and 01N-06E-04 CAD 1 and of discharge from Bryds Mill Spring to rainfall at Pontotoc (January 1959-June 1979).

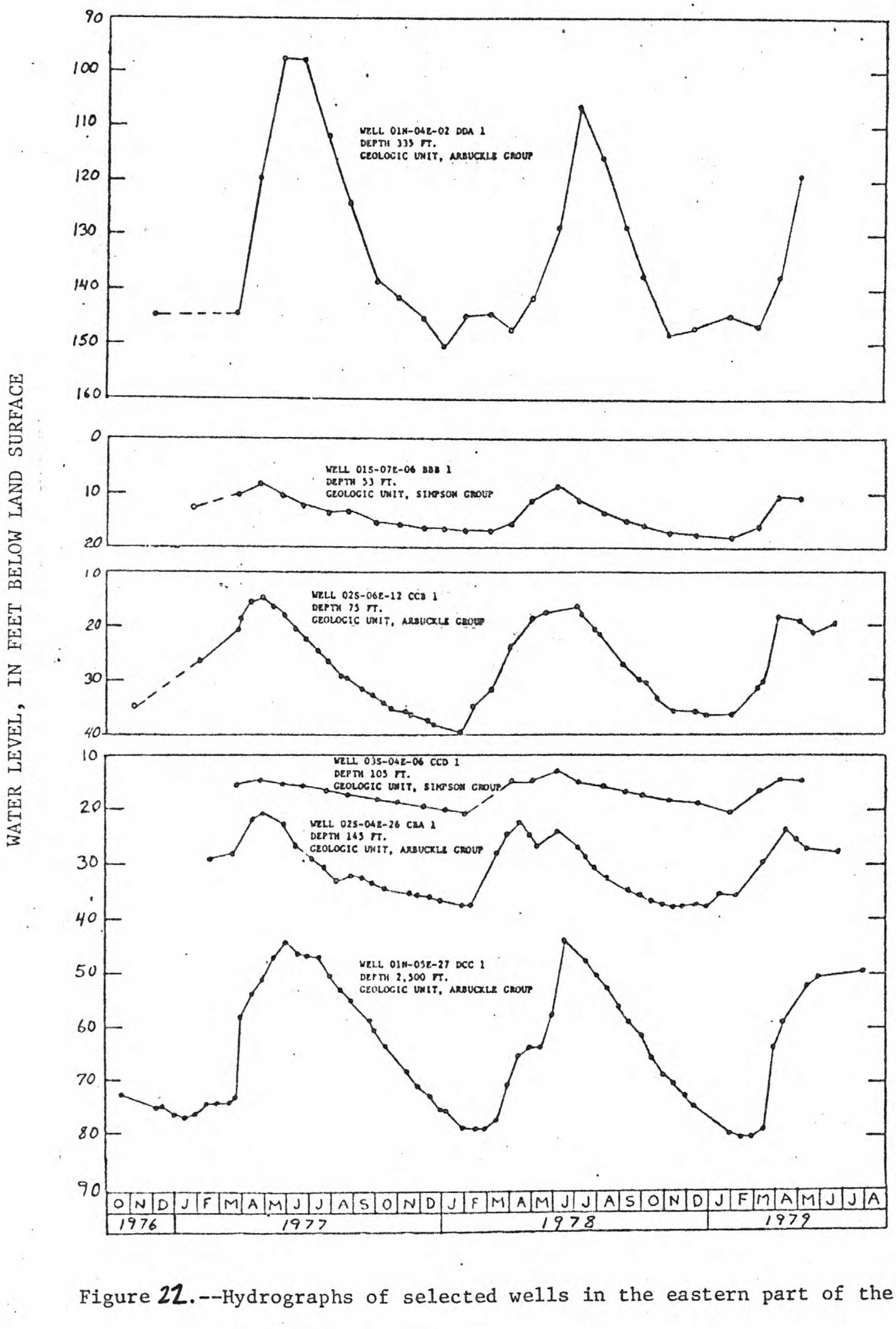

Figure 22.--Hydrographs of selected wells in the eastern part of the Arbuckle Mountains.

The rate of rise and decline of the water levels is a function of the hydraulic and geologic properties of the aquifer, the location with respect to topography, and the rate of recharge to or discharge from the aquifer.

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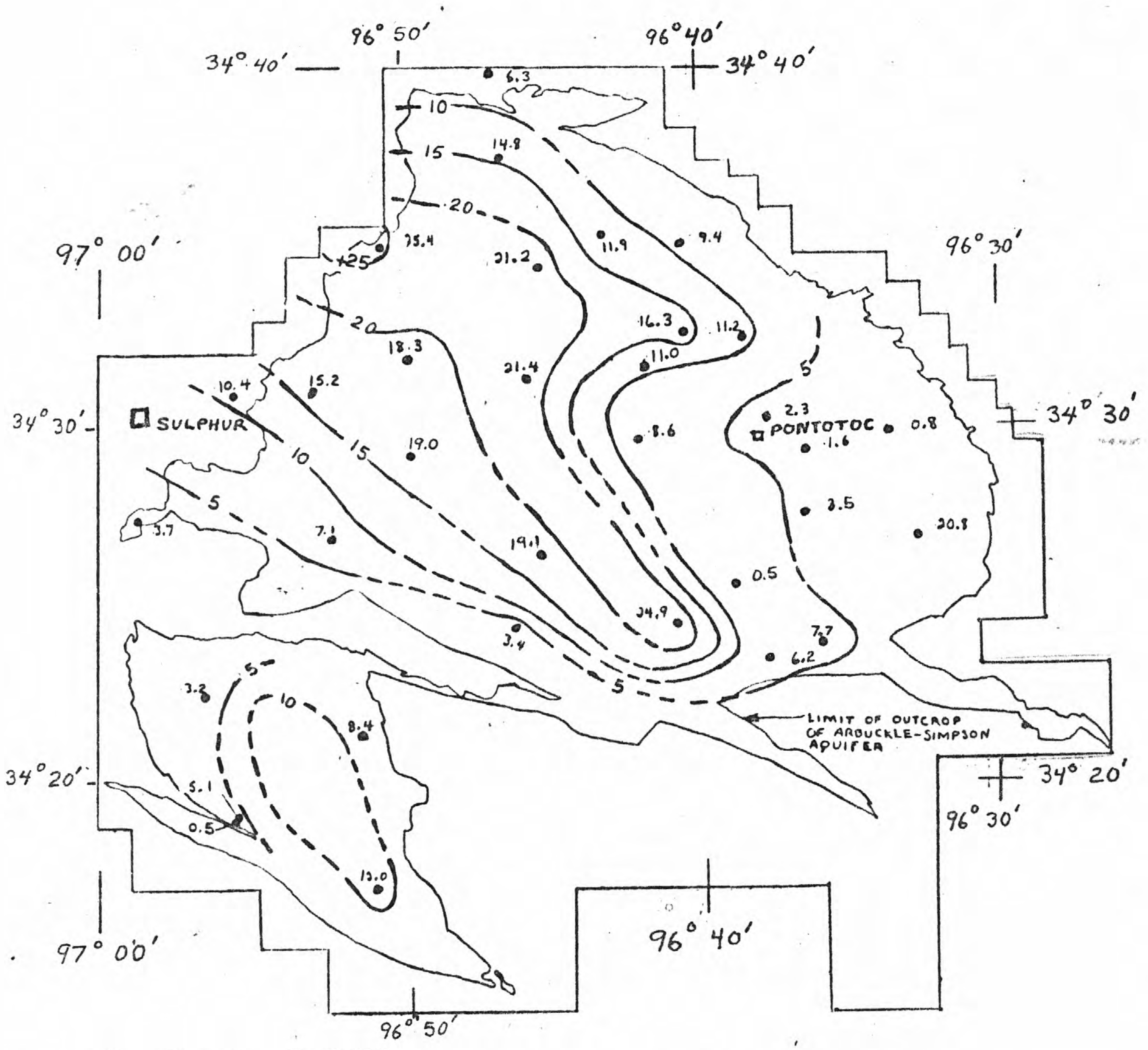
Water levels in wells respond to seasonal rainfall most of which occurs in the spring. An example of the regional (areal) effects of rainfall on water levels is shown on figure 23. From March 25 to April 25, 1977, rain amounted to an average of 8.3 in. at Pototoc and Sulphur; most of the rain occurrred in late March and during the third week of April. Water levels in wells rose from 0.5 to 25.4 ft in response to this rainfall. The greatest amount of water-level rise occurred in wells in the Arbuckle outcrop area. Water-level fluctuations are usually greatest in recharge areas and less in discharge areas.

Discharge

Although some discharge from the Arbuckle-Simpson aquifer is by evapotranspiration and pumping from wells, by far the largest amount is from springs which provide base flow to streams.



0 2 4 6 MILES

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EXPLANATION

• 7.1 WELL. Number shows rise of the water table, in feet.

— — 10 —— LINE OF EQUAL WATER-LEVEL RISE--Dashed where approximately located. Interval 5 feet.

Figure 23.--Map of the eastern part of the Arbuckle Mountains showing the rise of the water table in response to rainfall from March 25 to April 25, 1977.

Pumpage

Presently (1980) withdrawal of water from the Arbuckle-Simpson aquifer by pumpage accounts for only a minor part of the discharge. Wells that tap the aquifer in the study area produce from less than 1 gal/min to about 500 gal/min. Some wells are capable of yielding higher amounts of water (up to 2,500 gal/min) but were not in use during this study. The total amount of withdrawl from the aquifer by pumpage was not determined during this study but is estimated to be less than 2 Mgal/d.

Springs

Numerous springs discharge water from the Arbuckle-Simpson aquifer in the study areas. Information was obtained on 96 springs that issue from the aquifer in its outcrop area (fig. 24 and 25). Most of the springs in the study area are gravity springs, ~~caused by an "outcrop" of the~~ potentiometric surface ~~at~~ the land surface. The locations of the springs correspond to the natural discharge areas from the aquifer.

Most springs are located near faults or other fractures. In many places the fractures have been enlarged by solution. The enlarged fractures serve as channels for water that enters the aquifer in the recharge area and moves down-gradient where it issues from springs at lower altitudes. In places, springs occur on the up-gradient side of a fault and discharge water that flows a short distance down a stream channel. The water enters an opening, such as a fracture, or seeps into sand in the stream-channel bottom. Many are "wet weather" seeps or springs that discharge during and for a short time after the rainy season. Such springs probably occur where the water table is perched, and go dry when the perched water table recedes below the spring outlet.

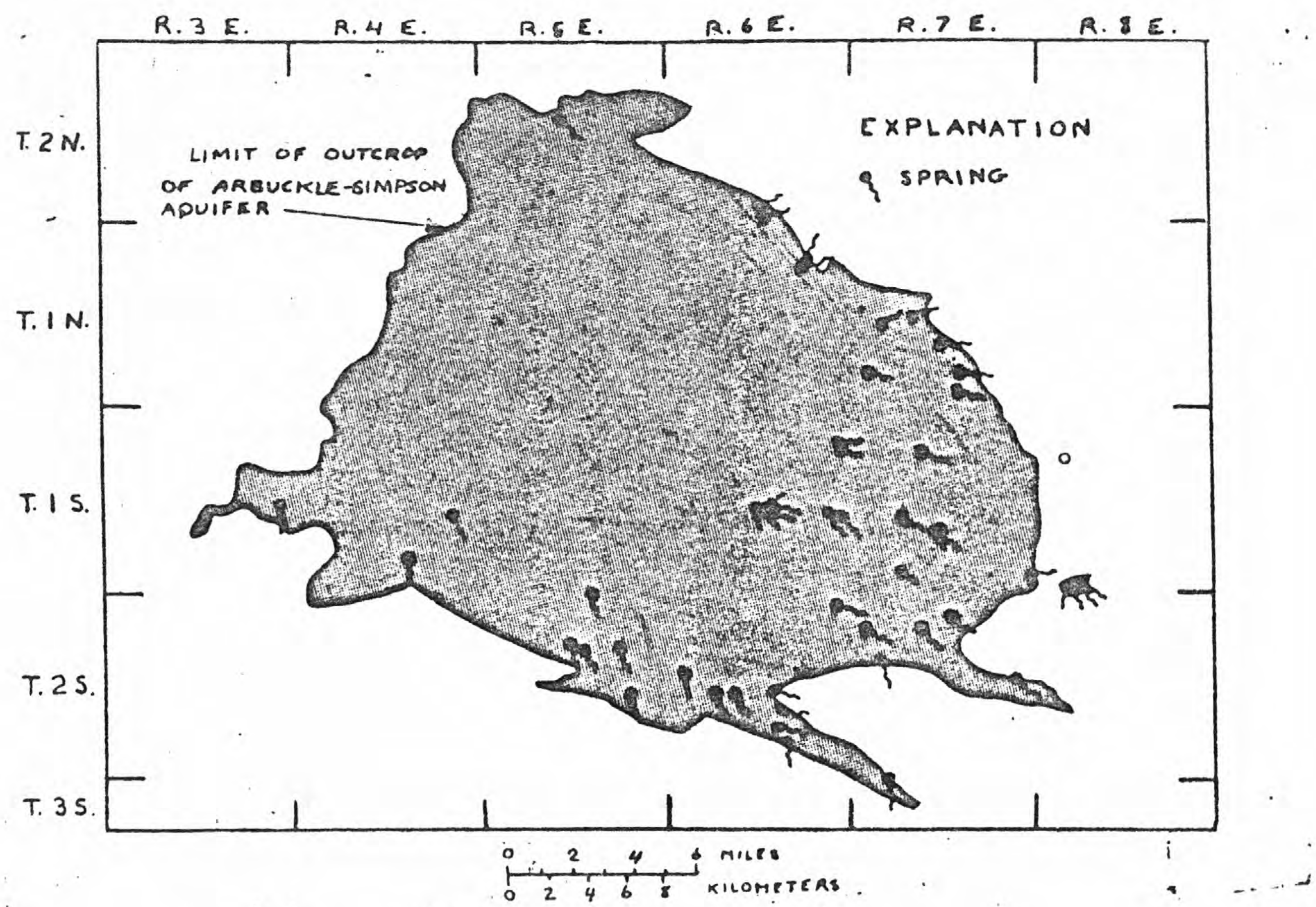

Figure 24.--Location of springs in the eastern part of the Arbuckle Mountains.

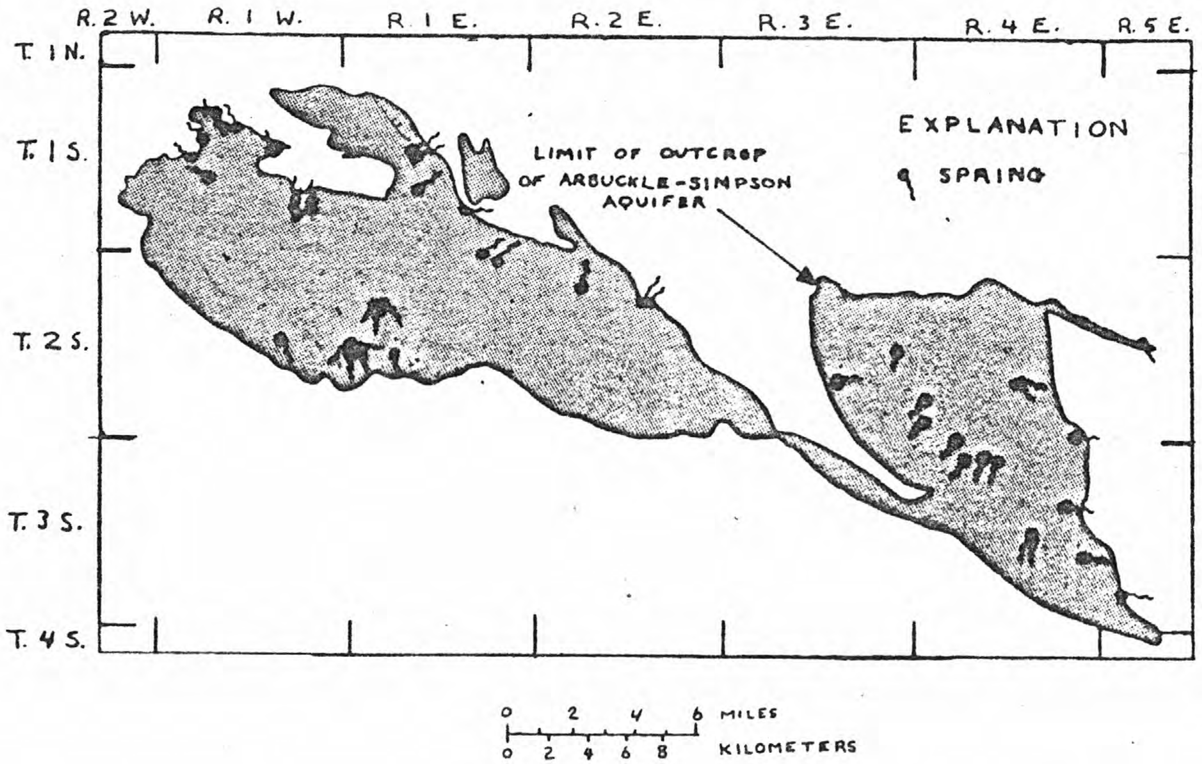

Figure 25.--Location of springs in the western part of the Arbuckle Mountains.

In several places faulting has brought less permeable rocks into contact with rocks that have a greater permeability. Because of the difference in permeability across the fault, water moves to the surface through fractures and discharges from springs and seeps along the fault. An example of this occurs in the southeast part of the area where faulting has brought the Tishomingo Granite in contact with rocks of the Arbuckle-Simpson aquifer (fig. 18). The granite, having a low permeability, acts as a subterranean barrier to ground-water flow in the aquifer and a ground-water mound exists on the north side of the barrier. Water is released from the ground-water mound by springs.

Several large springs contribute sufficient discharge to sustain perennial flow in some streams. Byrds Mill Spring near Fittstown in the northeast part of the area is such a spring. Data from a continuous recording gaging station established on this spring in 1959 indicate that the spring may discharge as much as 40 ft^3/s.

The relation of discharge from Byrds Mill Spring and the water level in two nearby wells (01N-06E-04 CAD 1 and 01N-05E-27 DCC 1) which penetrate the Arbuckle-Simpson aquifer is shown in figure 21. Well 01N-06E-04 CAD 1 is located 1 mi southwest of the spring and well 01N-05E-27 DCC 1 is 7.5 mi southwest of the spring. As indicated by the hydrographs in figure 21, spring discharge varies with the water level in the aquifer. The hydrograph of discharge from Byrds Mill Spring does not include an unmeasured continuous diversion of 6 to 10 ft^3/s.

In a study using thermal-infrared images to identify some common rock types (limestone and dolomite) in the Arbuckle Mountains, Rowan and others (1970, p. 3549) found that fault and fracture zones appear cooler (darker) than the surrounding ground. This difference was attributed to a greater water content of the fault and fracture zones and concomitant evaporation of the water. A difference in appearance of lineaments in images taken during pre-dawn and images taken at midday may relate to a combination of spring and vegetation effects -- that is, the springs are usually associated with faults and other fractures and vegetation is usually denser in those areas where springs occur. The study was made during the winter when evapotranspiration is low and vegetation probably had less effect than it would have had during the summer months.

Base flow of streams

Average annual ground-water discharge from the Arbuckle-Simpson aquifer was estimated using base flow separated from the streamflow hydrographs for Blue River near Connerville and Mill Creek near Ravia and miscellaneous low-flow measurements obtained at Pennington Creek, 10 other small streams draining the outcrop area, and spring discharge from Byrds Mill Spring near Fittstown.

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Table 12 lists the estimates of average annual base flow from each stream obtained by method of separation described by Olmsted and Hely (1962) which uses monthly low flow and base flow recession characteristics of the stream as criteria in defining average monthly base flow. An example of the separation of base flow from the streamflow hydrograph is shown in figure 7 for Blue River near Connerville for the 1979 water year.

Table 12.--Average annual ~~total~~ discharge and average annual base flow of principal streams draining the Arbuckle-Simpson outcrop area

[A: Drainage area. $\overline{Q}$: Average annual runoff. Q_b: Base flow.]

Station	A (square miles)	Period of record (water years)	$\overline{Q}$ (cubic feet per second)	Q_b (cubic feet per second)	$Q_b/\overline{Q}$ (in percent)
Blue River near Connerville	162	1969-71 1977-79	83	60	72
Mill Creek near Mill Creek	46.4	1969-71 1977-79	15	5	35
Pennington Creek near Reagan	65.7	1969-71 1977-79	56	20	36
Byrds Mill Spring	--	1969-71 1977-79	15	15	100
Buckhorn Creek	1.8	1977-79	--	3*	--
Rock Creek	9.1	Do.	--	1*	--
Delware Creek	17.1	Do.	--	4*	--
Walnut Creek	10.2	Do.	--	2*	--
Coal Creek	5.8	Do.	--	1*	--
Goose Creek	2.7	Do.	--	1*	--
Keel Creek	4.0	Do.	--	0.5*	--
Buzzard Creek	4.3	Do.	--	1*	--
Sheep Creek	1.3	Do.	--	3.5*	--
Oil Creek	28.6	Do.	--	8*	--
Totals	359.0			125	

* Approximate median value of low flow measurements obtained at site during period of record.

For Blue River near Connerville, separation of monthly base flow values from the hydrograph for the continuous period of record (water years 1977-79) shows that base flow represents 72 percent of the average annual discharge at this site or 60 ft^3/s for water years 1969-71 and 1977-79. To obtain an estimate of base flow at the Mill Creek near Mill Creek gage site, a relation of daily discharges between Mill Creek near Ravia and Mill Creek near Mill Creek was defined (fig. 10) using periodic discharge measurements obtained at Mill Creek near Mill Creek and observed or estimated daily mean discharges at Mill Creek near Ravia during the periods 1969-71 and 1977-79 water years. Monthly base flow was separated from the Mill Creek near Ravia hydrograph for the three years of continuous record (1969-71). These monthly base flow values were then entered into the Mill Creek near Ravia versus Mill Creek near Mill Creek relation of figure 10 to obtain an estimate of average annual base flow at the Mill Creek near Mill Creek site for this 3-year period. A comparison of this average annual base flow with the corresponding estimate of average annual discharge for the Mill Creek near Mill Creek site (table 12) indicates that base flow represents about 35 percent of the average annual discharge or 5 ft^3/s for the period 1969-71, 1977-79.

Base flow for Pennington Creek near Reagan was approximated from miscellaneous low flow measurements obtained during 1952-55, 1958-61, 1969-71, and 1976-79. These measurements indicate that the average annual base flow ranges from about 15 to 25 ft^3/s. Thus, an average value of 20 ft^3/s was used for this stream. This base flow represents 36 percent of the estimated average annual discharge for Pennington Creek near Reagan.

A comparison of the total average annual discharge of 154 ft^3/s from Blue River, Mill Creek, and Pennington Creek (table 4) with the total average annual base flow of 85 ft^3/s from these three streams (table 12) indicates that about 55 percent of the total discharge from these 3 basins is from ground water. Blue River discharges the largest amount of ground water per unit area, 0.37 $(ft^3/s)/mi^2$, and Mill Creek discharges the smallest amount of ground water per unit area, 0.11 $(ft^3/s)/mi^2$.

Continuous records of discharge at Byrds Mill Spring near Fittstown indicate an average annual flow of about 15 ft^3/s which is essentially all ground-water discharge. This estimate is based on the 6-year period 1969-71 and 1977-79 which includes an unmeasured diversion estimated to average 8 ft^3/s throughout the year.

Base flow from each of the 10 small streams draining the outcrop area was estimated as the median of summer and winter low-flow measurements obtained at these sites during the 1977-79 study period (table 12). Mean annual ground water discharge from the 10 streams is thus about 25 ft^3/s from 85 mi^2 of drainage area or 4.0 in. per unit area.

Average annual ground-water discharge from Blue River, Mill Creek, Pennington Creek, Byrds Mill Springs, and the 10 small streams averages about 125 ft^3/s from a drainage area of 359 mi^2 [about 90,000 acre-ft/yr or 250 (acre-ft/yr)/mi^2] which includes 90 percent of the eastern three-fourths of the outcrop area. This discharge represents an average unit amount of 4.7 in./yr or approximately 60 percent of the total annual runoff of 7.6 in./yr (see page 48) from the outcrop area. Also, this discharge probably represents the average annual recharge to the aquifer.

Evapotranspiration

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Differences between the summer and winter base flow recession rates of streams in the area show the consumptive use of water by evapotranspiration (ET). Figure 26 shows composite base flow recession curves for the summer and winter seasons for the Blue River at Milburn and Mill Creek near Ravia. These curves were derived graphically by averaging several recessions selected from the stream flow hydrographs for periods of no precipitation. The steeper slope of the summer recessions reflects the seasonally high rate of evaporation of surface water in the stream and transpiration of ground water by riparian vegetation along the flood plain.

An estimate of the average rate of summer evapotranspiration from riparian vegetation in the study area was obtained from the average seasonal (winter to summer) depletion in base flow along the 15.2 mi reach of the Blue River between the Connerville and Milburn gages. The area between these gages is underlain by granite with only a thin veneer of soil. Thus, most of the summer consumption of base flow can be attributed to evaportranspiration. This consumption was determined from the 7-day 2-year low flows for these two sites listed in table 6 which approximate the average winter and summer low flow conditions for the Blue River.

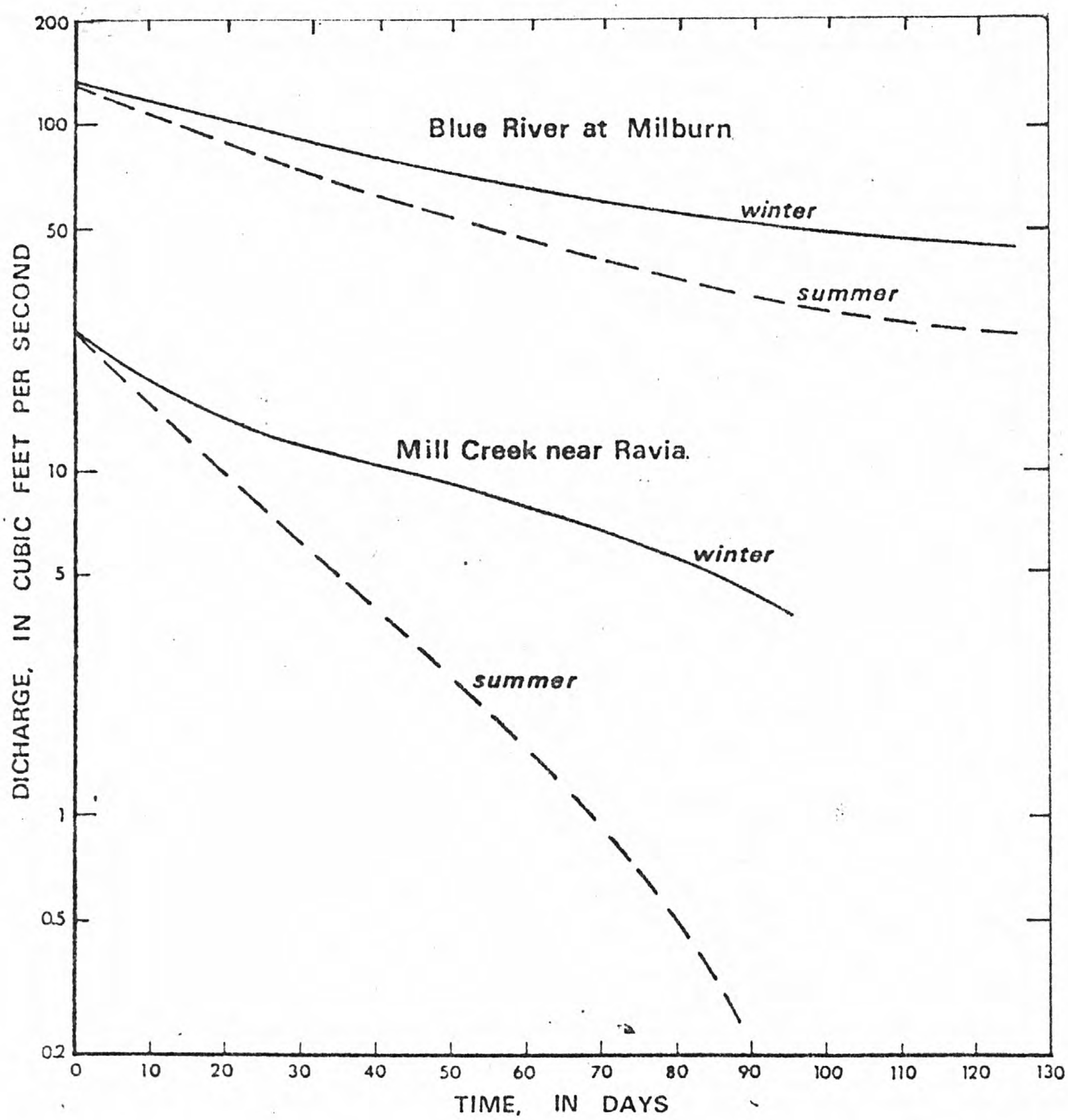


Figure 26.--Winter and summer base flow recession curves for Blue River at Milburn and Mill Creek near Ravia.

These low-flow frequency values indicate that during the winter--when ET is negligible--the river is a gaining stream with base flow incresing an average of 5 ft^3/s through the 15.2 mi reach. During the summer--when ET is maximum--the river is a losing stream with base flow decreasing an average 3 ft^3/s between the two gage sites. The total summer consumption of base flow due to ET is the winter gain of 5 ft^3/s plus the summer loss of 3 ft^3/s or 8 ft^3/s (480 acre-ft/month). This consumptive use of 8 ft^3/s is considered a low estimate of the actual rate of summer ET from the flood plain because the actual gain in base flow through the study reach may be greater than the measured gain of 5 ft^3/s--i.e. a small increment of winter ET which was assumed negligible in this analysis may occur during some periods of the winter season. In addition, the typically higher ground-water levels in the summer than in the winter most likely discharge a higher rate of ground-water into the floodplain area than the measured rate of 5 ft^3/s determined from the winter base flow. This depletion is probably a low estimate of the average rate of summer ET from the flood plain between the Connerville and Milburn gages. That is, the actual summer depletion in base flow may be greater than 8 ft^3/s due to typically higher ground-water levels in the summer than in the winter.

The surface area of the flood plain between these two gages computed from topographic maps is 1,100 acres. Thus, if the total summer consumption of base flow is 480 acre-ft/month, the average rate of summer ET from open bodies of water and riparian vegetation on the flood plain is 5.2 in. per month.

In two basins in northern Texas, south of the study area, the mean average annual water loss (evapotranspiration) was determined to be about 30 in. (Williams and others, 1940, p. 52). The area in Texas has climatic and topographic conditions similar to those in the study area.

Variations in the evaportranspiration from similar basins in the same region are caused by such factors as: (a) annual rainfall distribution and the volumes and intensities associated with individual storms; (b) sequence of wet and dry years and associated hydrologic and ecologic conditions; and (c) temperature, wind, sunshine, humidity, and other factors. Topography affects evapotranspiration because it influences land use. Throughout most of the area, the depth to the saturated zone is below the effects of evapotranspiration except where the potentiometric surface comes close to, or intercepts, the land surface in the stream valleys. Ground-water evapotranspiration outside the stream valleys was not determined during this study but is thought to be a relatively small part of the total annual evapotranspiration.

Consumptive use factors derived by Blaney-Criddle (1962) indicate that, for south-central Oklahoma, approximately 60 percent of the annual ET occurs during the 3-month period, June-August. Assuming that 5.2 in. per month is an average rate of ET for this June-August period, then the annual ET is estimated at about 3x5.2/0.6 = 26 in. per year. The consumptive use factors derived by Blaney-Criddle are from empirical data and may explain the difference in yearly evapotranspiration as determined from base flow data collected during this study. Also, the estimate of ET from base-flow depletion is considered a conservative estimate because it does not consider a small component of ET derived from ground water in the depressions and low elevation fields beyond the stream valleys.

Aquifer Characteristics

The hydraulic characteristics of an aquifer describe its ability to store and transmit water and can be described in terms of the storage coefficient (S) and transmissivity (T). The specific capacity of a well is a measure of the ability of a well to yield water and can be used to give an approximate transmissivity of the aquifer. All the above terms are defined in the glossary of this report.

Several analytical techniques have been developed to define the hydraulic characteristics of an aquifer. One of the basic assumptions of most techniques is that flow takes place through a homogeneous medium. Rocks of the Arbuckle group have little or no intergranular porosity; all void space is in the form of joints, fractures, and solution channels. Only the sandstone beds in the Simpson Group may act as a homogeneous (granular-type aquifer) unit.

Although the basic assumption of homogeneity is not precisely met for the Arbuckle-Simpson aquifer, some analytical concepts can be considered applicable when used in a regional analysis of the aquifer. The fractures and solution channels are thought to be interconnected through the aquifer and thus are assumed to approximate a homogeneous aquifer on a regional basis.

Specific capacity tests

No test drilling was conducted during this investigation. Instead, a number of specific capacity tests and short-term recovery tests were performed on existing wells (table 13). Included in table 13 is information from the files of the U.S. Geological Survey from tests on wells in the study area dating back to 1951.

The short-term tests were conducted using a submersible pump rated at 50 gal/min with a 150-ft lift and powered with a gas-powered electric generator. Discharge was regulated by a gate valve, measured in a 57-gallon oil drum, and timed with a stop watch. Water was discharged through a 75-ft flexible plastic hose connected to a leakproof valve. Because the original depth to water in the wells was 50 ft or more below land surface and the tests were of short duration (generally a few hours), return flow may be considered negligible.

Changes in the depth to water were systematically measured to the nearest one-hundredth of a foot.

Table 13.-- Summary of specific capacity of wel

[Ft (feet); gal/min (gallons per mi

Well number	Depth (ft)	Perforated interval or open hole (ft) Top	Bottom	Yield (gal/min)	Dra (f
JOHNSTON COUNTY					
02S-05E-08 ABB 1	110	45	105	---	--
02S-05E-08 ABB 2	107	75	105	153	
02S-05E-08 ABB 3	167	83	164	---	-
MURRAY COUNTY					
01N-04E-21 DDA 1	1,170	---	---	1,700	
01N-04E-22 DDA 1	780	---	---	2,500	
				1,000	
				2,000	
01N-03E-26 CCC 1	511	414	511	185	1
01N-04E-15 BDA 1	133	---	---	53	
01S-04E-16 CBA 1	122	---	---	16.2	
01S-01W-35 DCA 1	1,080	---	---	22.4	
01S-01W-36 CBC 1	145	---	---	46.2	
02S-01E-14 CBD 1	45	---	---	33.2	
02S-03E-11 DBB 1	150	---	---	48.8	[illegible]
02S-03E-12 CAA 1	55	40	55	39.6	[illegible]
02S-03E-13 CCD 1	79	---	---	9.3	[illegible]
02S-03E-25 DCD 1	360	25	360	85	4
02S-04E-18 BBD 1	88.5	0	88.5	42.2	6
PONTOTOC COUNTY					
01N-05E-27 DCC 1	2,500	325	2,500	670	1
01N-06E-03 CCC 1	700	---	---	1,900	5
01N-06E-04 CAD 1	396	122	396	50	
	396	122	396	385	
01N-06E-09 ADD 1	1,503	---	---	1,000	8
01N-06E-16 AAA 1	1,573	---	---	1,200	8
02N-05E-10 DDD 1	2,403	71	2,403	37.1	7
02N-05E-22 ADC 1	805	60	850	34.5	3
02N-05E-25 CCC 1	1,527	250	1,527	555	4
	1,527	250	1,527	570	4
02N-05E-36 AAD 1	2,048	---	---	390	11

As indicated in table 13, the specific capacity of wells ranges from 0.17 to 104 (gal/min)/ft of drawdown. Deep wells have the highest specific capacity because they penetrate more fractures and solution channels than wells that penetrate only the upper part of the aquifer. Information from drillers and land owners suggests that the upper few hundred feet of the Arbuckle Group has a much lower permeability than the lower part. This seems contrary to normal carbonate characteristics (Legrand and Stringfield, 1971) but may reflect the complex geologic and structural history of the rocks that make up the Arbuckle-Simpson aquifer. In places, wells as much as 250 ft deep yield less than 1 gal/min and have a very slow recovery. Such wells were probably drilled in relatively dense impermeable rocks and do not penetrate interconnected fractures or solution channels.

Aquifer tests

As indicated earlier, several short-term aquifer tests were performed on selected existing wells. Estimates of the transmissivity of the aquifer at each site were determined by use of the modified nonequilibrium equation (Ferris and others, 1962, p. 101) in which

$$T = \frac{264\ Q}{\Delta s'} \qquad (3)$$

where

T = transmissivity (L^2/T);

Q = rate of discharge of well in gallons per minute; and

$\Delta s'$ = change in residual drawdown, in feet, over one log cycle of time (L).

The method used assumes an ideal aquifer which is homogeneous, isotropic, and of infinite areal extent. It also assumes that the tested well penetrates the entire thickness of the aquifer. Geologic information from previous studies of the area indicate that the Arbuckle-Simpson aquifer does not satisfy these criteria. Therefore, the transmissivity values computed from the tests can be expected to give only a rough estimate of the transmissivity in that part of the aquifer tested and may be greater or less than the true value obtained from a well that penetrates the entire thickness of the aquifer.

Plots of the recovery of water levels in seven wells at various locations in the eastern and western parts of the study area are shown in figures 27 and 28 and information about the wells tested and resulting T values computed from equation 3 are listed in table 13.

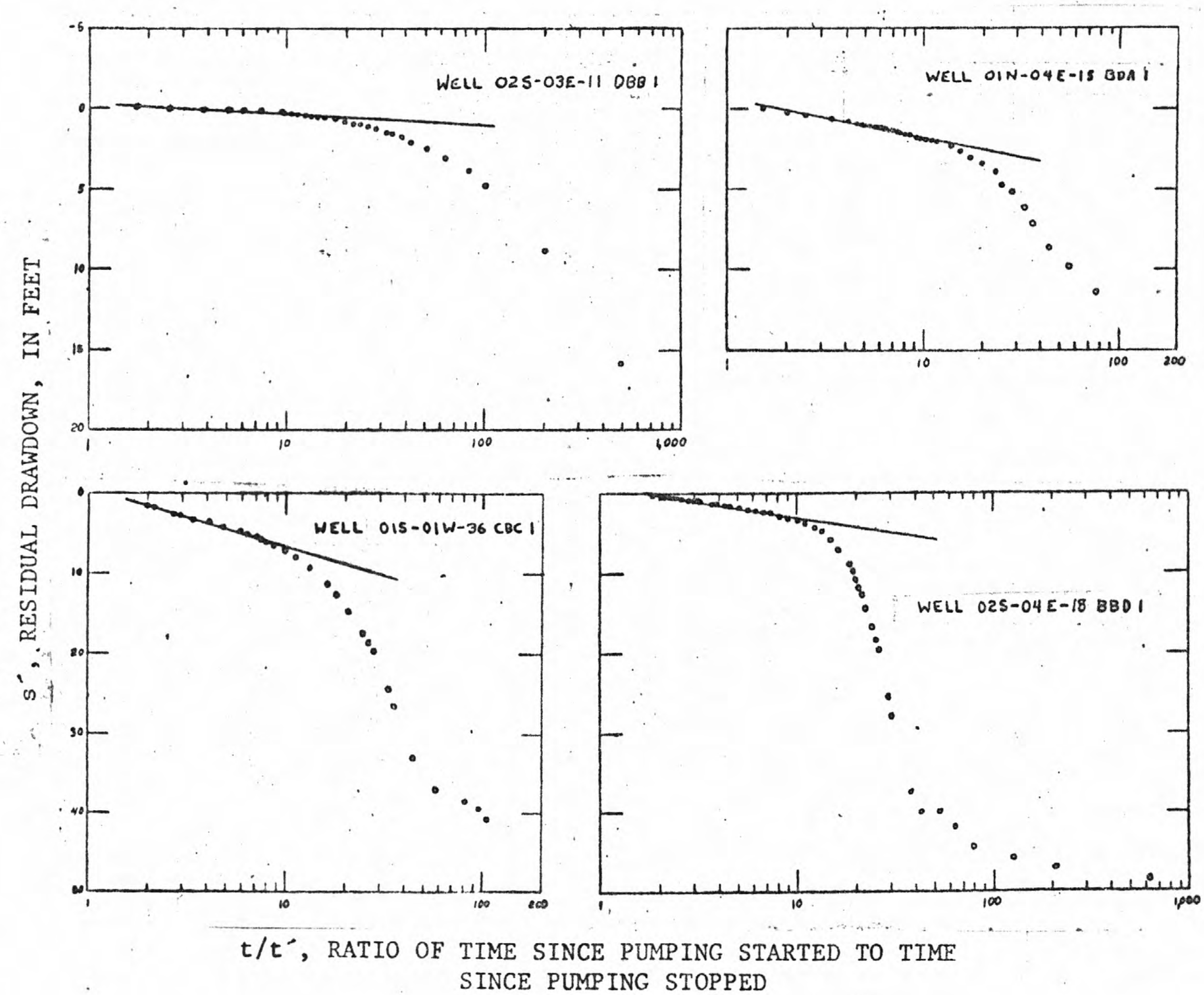
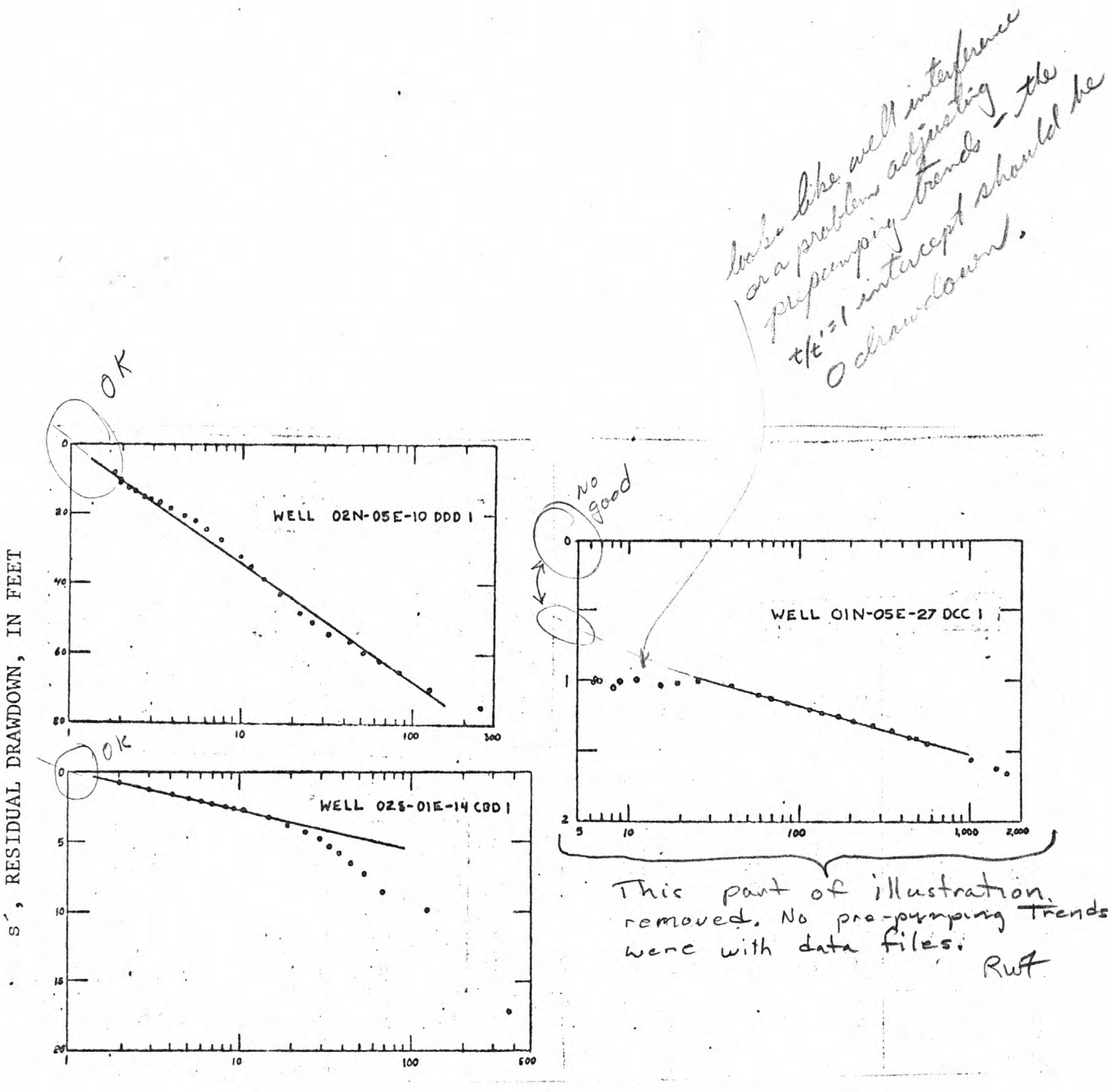


Figure 27.--Time-recovery plots of water levels in four selected wells.



t/t', RATIO OF TIME SINCE PUMPING STARTED TO TIME SINCE PUMPING STOPPED

Figure 28.--Time-recovery plots of water levels in three selected wells.

Aquifer tests were also performed at 3 well sites in the northeastern part of the area in 1959. The wells pumped, the number of observation wells monitored and the distances of the observation wells from the pumped wells are as follows:

Pump well	Depth (ft)	Number of observation wells	Distance of observation wells from pumped wells (ft)
01N-05E-27 DCC 1	2,500	4	520 to 7,000
01N-06E-04 CAD 1	396	9	480 to 8,000
02N-05E-25 CCC 1	1,527	11	830 to 12,000

No drawdown occurred in any of the observation wells. Most of the observation wells were less than 200 ft deep. One observation well used during the test of well 01N-06E-04 CAD 1 was 670 ft deep. This well was also used in the test of well 02N-05E-25 CCC 1 which had two other observation wells, 2,050 and 1,380 ft deep. Recovery of water levels in the pumped wells at two of the sites (wells in sections 04 and 25) was very rapid and no aquifer characteristics could be determined from the tests. Well 01N-05E-27 DCC 1, however, had a slower rate of recovery but the data obtained during the test suggested possible well interference or problems with pre-pumping trends. The results of the test were not accepted.

URE 29
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Estimates of transmissivity were obtained from analysis of an aquifer test of wells in the Simpson Group about 1.5 mi east of town of Mill Creek (fig. 29).

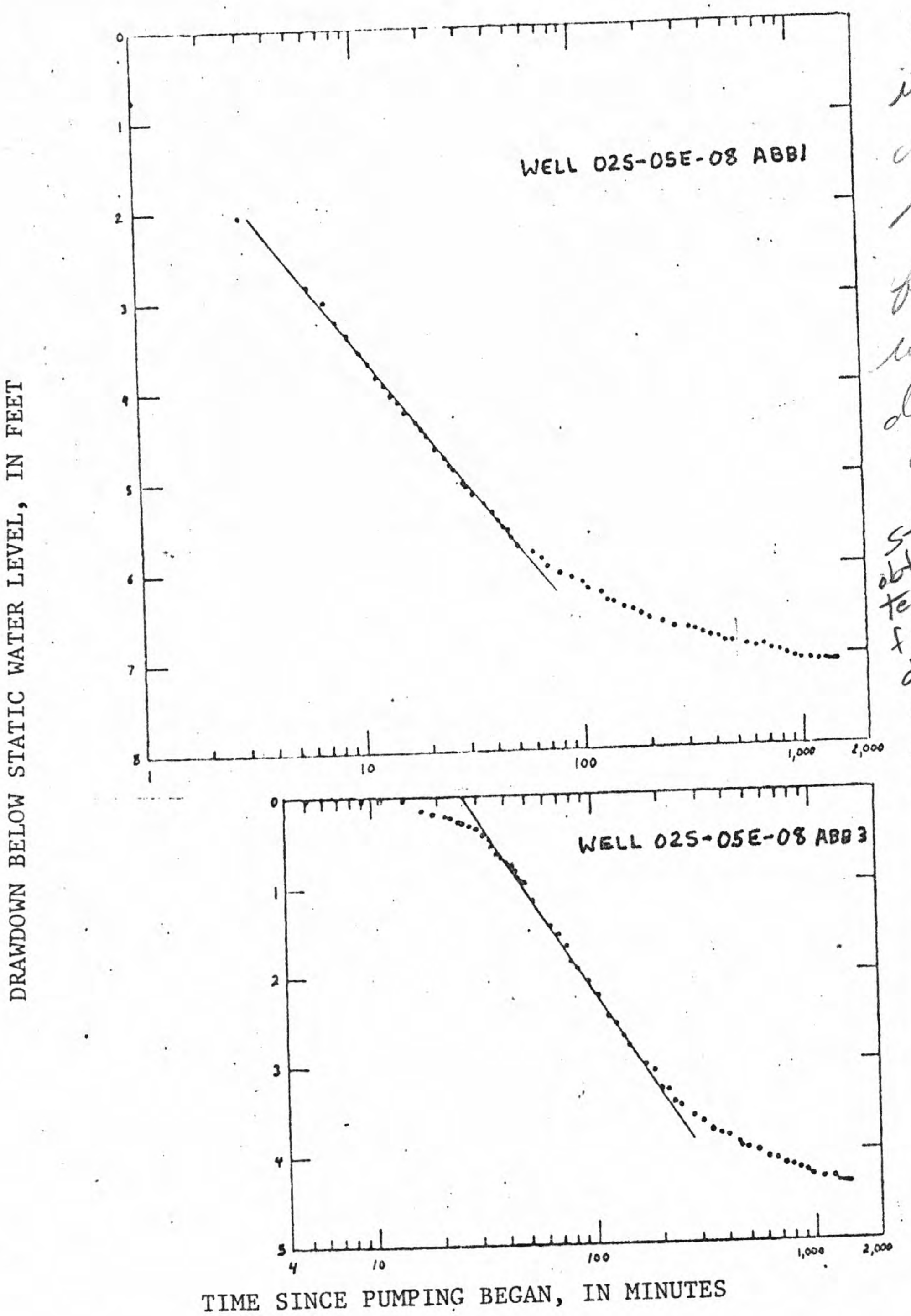

Figure 29.--Time-drawdown plots of water levels in two selected wells.

It would be interesting to compare the storage coeff. from this test with the values derived from w.l. changes. -JmE

Storage coefficients obtained from this test were different for each well. The difference was questionable and the values obtained were not used. RWF

Well 02S-05E-08 ABB 2 was pumped and water levels were measured in observation wells 02S-05E-08 ABB 1 and 02S-05E-08 ABB 3. Information about the pumped wells and the two observation wells and the results of the test are shown in table 13.

Well 02S-05E-08 ABB 2 is 107 ft deep and 8 in. in diameter. Like the observation wells, the pumped well was gravel packed and the casing was perforated with 5/32-inch drill holes. None of the wells used in the test fully penetrated the Simpson Group.

Estimates of the transmissivity of the aquifer from analysis of the drawdown in wells 02S-05E-08 ABB 1 and 02S-05E-08 ABB 3 were determined by applying the modified nonequilibrium equation to drawdown data (Ferris and others, 1962, p. 100), in which

$$T = \frac{264\ Q}{\Delta s} \qquad (4)$$

where T and Q are as defined in recovery tests and Δs is the change in the drawdown, in feet, over one log cycle of time.

The assumptions used to derive equation 4 are the same as those used to derive the equation used in the recovery tests.

Estimates of the storage coefficient of the aquifer were determined from data obtained from the same semilog plot of the drawdown data discussed above and by applying the modified nonequilibrium equation (Ferris and others, 1962, p. 100) in which

$$S = \frac{0.3Tt_o}{r^2} \qquad (5)$$

where T is as previously defined, and

S = storage coefficient (dimensionless);

t_o= the time intercept, in days, where the plotted straight line intersects the zero-drawdown axis;

r = distance, in feet, from the pumped well (L).

The storage coefficient was 5.0×10^{-5} for well 02S-05E-08 ABB 1 and 3.7×10^{-4} for well 02S-05E-08 ABB 3 and suggest an artesian condition. Variation in the S values can be expected because of lithologic variations in the aquifer at the test site and the slope and placement of the straight line through the drawdown data points.

The transmissivity values obtained from the foregoing recovery and drawdown aquifer tests range from 40 to 2,460 ft^2/d (table 13).

Determinations from regional techniques

Streamflow and ground-water-level hydrographs were also used to determine the aquifer characteristics on a regional basis. The regional methods are valuable in obtaining average values for the aquifer characteristics because the local anisotropy and heterogeneity of the carbonate aquifer probably tend toward isotropy and homogeneity when analyzed on a regional scale. The regional methods assumed a uniform transmissivity and storage coefficient, and equal distance from the ground-water drainage divide to the discharge point throughout the length of the drainage basin. Recharge to the aquifer is assumed to be uniform and instantaneous. The streamflow gaging station on Blue River near Connerville and continuous ground-water-level recorders at two wells, 01N-05E-27 DCC 1 and 01N-06E-04 CAD 1, were used in this analysis.

E 14

HERE

Storage coefficient was calculated as the ratio of recharge to the rise of the ground-water level. The recharge for the March 26-28, 1977, event has been shown to be 1.4 in. (table 10) and the corresponding average water-level rise in the two ground-water wells was 173.2 in. Therefore, the average storage coefficient for these two sites, as determined from this event, is 0.008. Similar determinations of storage coefficient computed from three other storm events during 1977 and 1978 are shown in table 14 and indicate a range from .006 to 0.011. Differences in the values are due primarily to inaccuracies in the determination of recharge. Recharge is influenced by rainfall duration and intensity.

Table 14.--Results of calculations of aquifer characteristics using regional techniques

[Δt: Time required for streamflow hydrograph to decline through one log cycle]

Date	Recharge, in inches	Ground-water-level rise, in inches: 01N-06E-04 CAD 1	Ground-water-level rise, in inches: 01N-05E-27 DCC 1	Ground-water-level rise, in inches: Average	Average storage coefficeint	Δt in days	Diffusivity, in square feet per day	Transmissivity, in square feet per day
March 26-28, 1977	1.4	113	233	173	0.008	160	1.36×10^6	1.09×10^4
May 18-21, 1977	0.48	---	42	42	0.011	150	1.46×10^6	1.16×10^4
March 23-24, 1978	0.51	43	115	79	0.006	170	1.28×10^6	1.02×10^4
June 5-8, 1978	0.28	---	---	---	---	155	1.41×10^6	---
June 4-10, 1978	0.64	70	---	70	0.009	165	1.32×10^6	1.19×10^4

An estimate of the storage coefficient was also obtained from the seasonal decline in ground-water levels and corresponding ground-water discharge to the stream. Five gound-water wells distributed over the Blue River drainage basin were used to compute the volume of the aquifer dewatered during the seasonal ground-water level decline. Base flow at the Blue River near Connerville gage site was used to compute the volume of water discharging from the aquifer during the seasonal decline in ground-water levels. Table 15 lists the five ground-water wells used to determine the ground-water level declines occurring during the 8-month season, June through January. The average decline in ground-water levels as calculated from the average water-level changes indicated in table 15 was 20.5 ft. Considering that the ground-water divide for the Blue River basin defines a drainage area of 96,000 acres (150 mi^2), the total volume of the aquifer dewatered within this area during each 8-month season averaged 1,968,000 acre-ft. The corresponding total volume of ground water discharging from the aquifer as measured by base flow in the stream averaged a total of about 21,100 acre-ft during each of these two 8-month seasons. The ratio of the volume of ground water discharging from the aquifer to the volume of the aquifer dewatered was 0.011. This value defines the specific yield of an aquifer which, under water table conditions in an unconfined water body, is virtually equal to the storage coefficient. Probably the water discharges from both confined and unconfined parts of the aquifer.

Table 15.--Maximum and minimum ground-water levels in feet above National Geodetic Vertical Datum of 1929 of five wells and the corresponding total ground-water discharge from the aquifer in the Blue River basin for two recession periods during 1977-79

Well number	Maximum elevation (feet) 5-24-77	Minimum elevation (feet) 2-1-78	Maximum elevation (feet) 6-8-78	Minimum elevation (feet) 2-2-79
02N-05E-21 DCD 1	1110	1085	1109	1083
01N-05E-27 DCC 1	1106	1071	1095 e	1070
01N-06E-29 CAB 1	1039	1022	1038	1020
01N-06E-24 CAB 1	1052	1032	1053	1035 e
02S-07E-07 AAA 1	908	900	917	903
Average elevation	1043	1022	1042	1022
Average elevation change	21 feet		20 feet	
Total base flow discharge	21,065 acre-feet		21,124 acre-feet	

e = Estimated

Methods of estimating the diffusivity of the aquifer, defined as the ratio of transmissivity to storage coefficient (T/S), were determined from streamflow recessions and natural fluctuations of water levels in observation wells. Streamflow data collected at the Blue River near Connerville site were selected because the basin headwaters lie entirely within the outcrop area of the Arbuckle-Simpson aquifer. Also, the Blue River basin characteristics (that is, geology, topography, and permeability of aquifer rocks) are similar to other stream basins in the study area. Thus, diffusivity values determined for the Blue River basin can be considered applicable to the aquifer in other parts of the study area.

Diffusivity was determined from the streamflow hydrograph using a method described by Rorabaugh (1966). In simplified form, the equation is

$$\frac{T}{S} = \frac{0.933a^2}{\Delta t} \qquad 6\ (5)$$

in which:

T = transmissivity (L^2/T);

S = storage coefficient (dimensionless);

a = average distance from the stream to the ground-water drainage divide (L); and

Δt = time required for streamflow discharge to decline through one log cycle (T).

The value for <u>a</u> was determined by dividing the area of the ground-water basin by twice the stream length giving <u>a</u> = 2.9 mi, or 15,300 ft. The value of Δt, as determined from the five streamflow recessions following the storm events listed in table 10, ranged from 150 days to 170 days, and averaged 160 days. Diffussivity (calculated from equation 5) for the March 26-28, 1977, storm is thus 1.36×10^6 ft^2/d. Using an average storage coefficient of 0.008, the corresponding transmissivity was determined to be 1.09×10^4 ft^2/d. The results of this and similar calculations for the other four events are listed in table 14.

Rorabaugh (1960) also describes a method to estimate the diffusivity (T/S) from water-level recessions in observation wells. This method is applicable only to conditions where sufficient time has elapsed after a recharge event for the potentiometric surface profile to become stabilized. The critical time (t) for a potentiometric surface profile to stabilize can be approximated by $t = 0.15 \frac{a^2S}{T}$, (Rorabaugh, 1960, p. 315). The potentiometric surface is considered to be stable when water levels decline exponentially with time. After the potentiometric surface has stabilized, an expression for diffusivity is

$$\frac{T}{S} = 0.933a^2 \log (h_1/h_2)/(t_2-t_1) \qquad (7)$$

where T, S, and a are as previously defined and

h_1 and h_2 = the potentiometric surface heads at any point in the aquifer (L); at

t_1 and t_2 = times following a recharge event (T).

The equation is based on the assumption that the potentiometric surface is horizontal prior to the recharge event and that the aquifer is finite with parallel boundaries and is fully penetrating at the discharge boundary.

Selection of a reasonable value for <u>a</u> first requires that the discharge boundary and the ground-water divide be defined. On the basis of topography and potentiometric contours, the potentiometric surface in the eastern part of the study area has many intermediate divides. However, the western edge of this area defines the "regional" ground-water divide for the aquifer. The discharge boundary was estimated along a line indicated by the location of springs which represent points where the potentiometric surface intercepts the land surface.

To determine diffusivity, water levels in feet above base level were plotted on the log scale versus time in days plotted on the arithmetic scale (figs. 30 and 31). Base level represents the altitude of the discharge boundary at a point on a line that passes through the well location and is approximately parallel to the hydraulic gradient.

The resulting diffusivities as computed from equation 6 using the water-level recession at five selected wells are listed in table 16. The average diffusivity for these five wells is 2.7×10^6 ft^2/d. If the storage coefficient of the aquifer is 0.008, then the transmissivity is 2.2×10^4 ft^2/d.

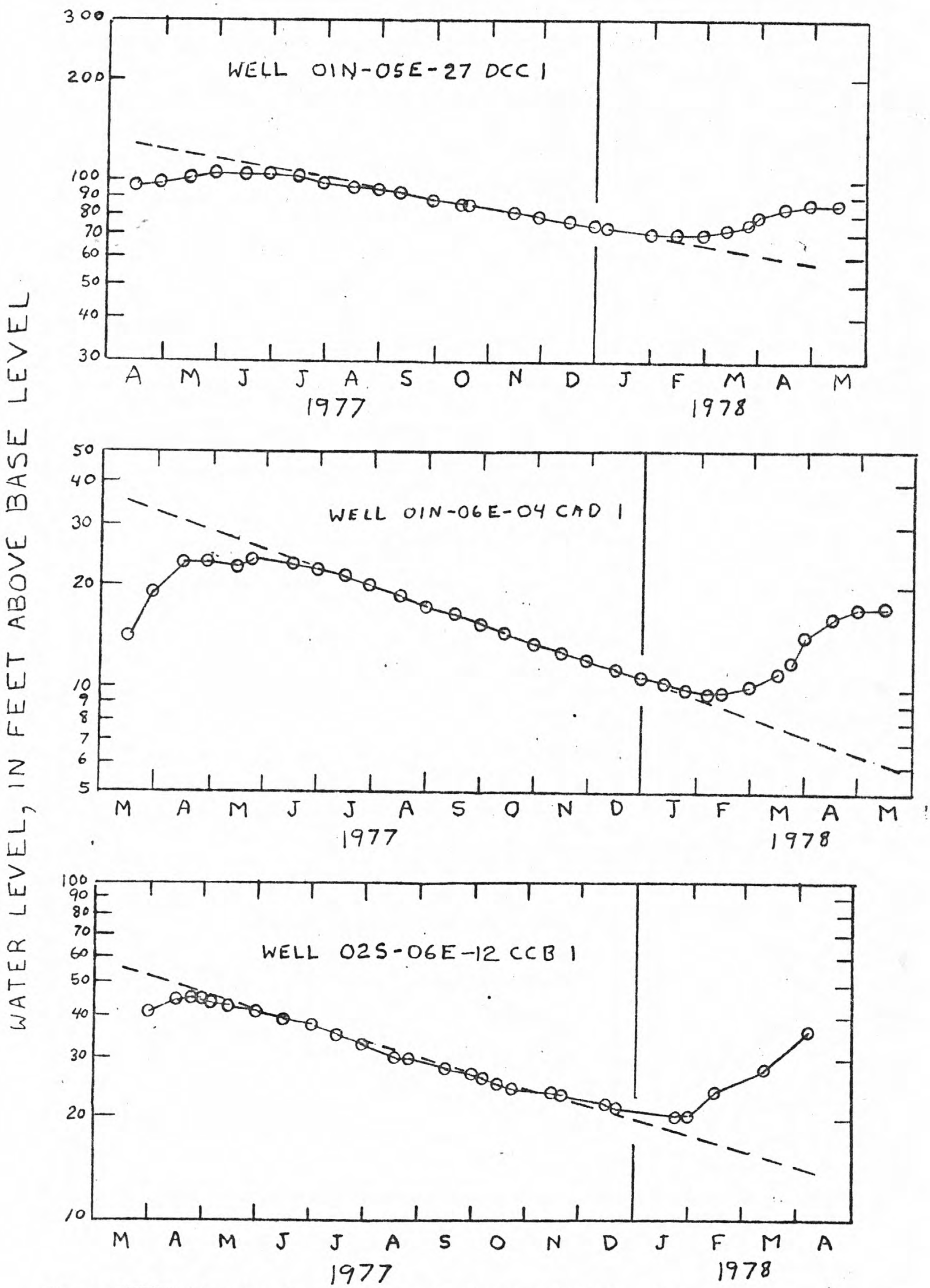

Figure 30.--Water-level recessions in three selected wells.

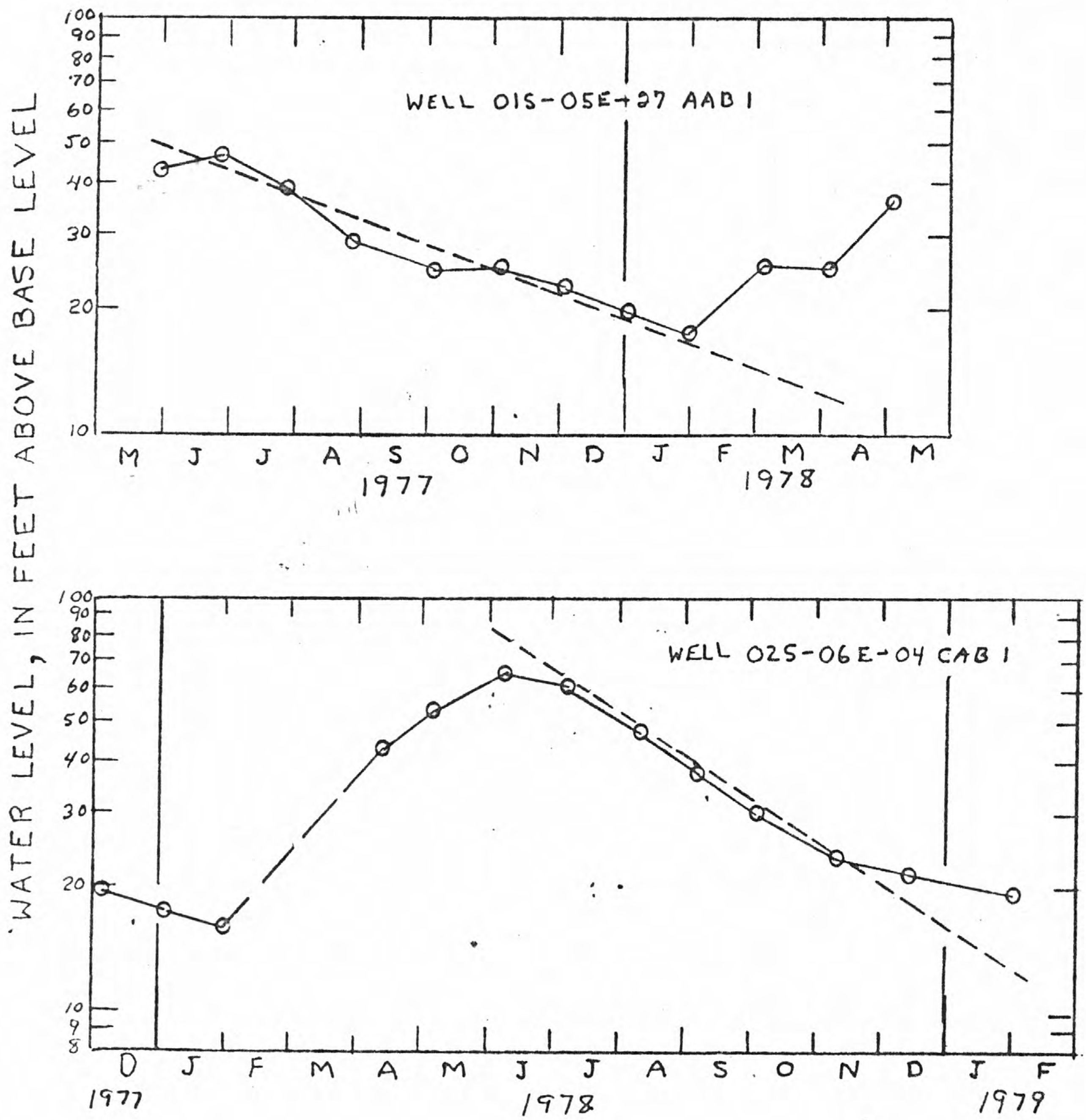

Figure 3/ .--Water-level recessions in two selected wells.

Table 16.--Diffusivities at five wells in the Arbuckle-Simpson aquifer computed from selected water-level recessions

[*a*: the distance from the ground-water divide to the discharge boundary. Δt: time interval per log cycle]

Well number	Well depth (feet)	*a* (feet)	Recession period	Δt (days)	Diffusivity (square feet per day)
01S-05E-27 AAB 1 [1]	267	14,300	May 1977 - April 1978	420	0.4×10^6
02S-06E-04 CAB 1	143	32,000	June 1978 - Feb. 1979	300	3.2×10^6
01N-05E-27 DCC 1	2,500	84,500	July 1977 - Feb. 1978	1,080	6.2×10^6
01N-06E-04 CAD 1 [2]	396	10,600	May 1977 - Feb. 1978	555	1.9×10^6
02S-06E-12 CCB 1	75	10,600	May 1977 - Jan. 1978	650	1.6×10^6
				Average	2.7×10^6

[1] Affected by periodic pumping.

[2] Well originally 1,707 feet deep; obstruction at 396 feet.

Another estimate of the transmissivity of the aquifer was obtained from an evaluation of the ground-water discharge from Byrds Mill Spring in the northeast part of the area. The rate of discharge from the spring is dependent on the hydraulic gradient of the ground water up-gradient from the spring outlet and the transmissivity of that part of the aquifer contributing water to the spring. A useful form of Darcy's law can be expressed as (Ferris and others, 1962, p. 73):

$$T = \frac{Qd}{IL} \qquad (8)$$

where

T = transmissivity (L^2/T);

Qd = discharge in gallons per day;

I = hydraulic gradient in feet per foot (L); and,

L = width, in feet, of the cross section through which the discharge occurs (L).

Ground-water level data used to construct the potentiometric map in figure 19 indicate that the hydraulic gradient was about 0.003 foot per foot in the vicinity of the spring during March and April 1977. The width of the aquifer contributing water to the spring is about 2.5 miles (13,200 ft). The rate of discharge from the spring during this period was estimated at 6.1 Mgal/d. Applying this information to equation 7 gives a transvissivity for the aquifer of T = 154,000 (gal/d)/ft or 20,600 ft^2/d. This is comparable to a determination in 1959 of T, from an unpublished manuscript in the U.S. Gelogical Survey files, that was estimated at 133,000 (gal/d)/ft or 17,800 ft^2/d.

Availability of Ground Water

The volume of water stored in the Arbuckle-Simpson aquifer can be computed from the saturated thickness and the storage coefficient. The storage coefficient, as determined from regional techniques, is estimated to be about 0.008.

The average saturated thickness of the Arbuckle-Simpson aquifer is about 3,500 ft in the the outcrop area. The volume of water in the aquifer, assuming a storage coefficient of 0.008, is about 9 million acre-ft that is availavble to wells within the 500 mi^2 of outcrop area. An undetermined amount of fresh water probably exists a short distance downdip in the aquifer and, if included, the total amount of water in storage is much greater.

The long-term trend in water levels in wells 01N-06E-04 CAD 1 and 01N-05E-27 DCC 1 (fig. 21) indicates that the amount of water in storage averages about the same over the period of record but varies seasonally and in response to prolonged wet or dry periods. Withdrawl of water from the aquifer by man averages probably less than one percent per year of the total volume in storage and is replenished by recharge.

HYDROLOGIC BUDGET

A generalized hydrologic budget for the study area can be expressed as P = Q + ET where P is the average annual precipitation, Q is the total average annual runoff in the stream including spring flow, and ET is the average annual evapotranspiration. The hydrologic budget assumes that there is no significant change in ground-water storage from year to year and no significant pumpage from the aquifer.

Solving this expression for ET using P = 38.4 in. from table 2 and Q = 7.6 in. computed as the average runoff from the Blue River, Mill Creek, and Pennington Creek in table 4, gives:

$$ET = 38.4 \text{ in.} - 7.6 \text{ in.} = 30.8 \text{ in./yr.}$$

Thus, evapotranspiration from the study area averages about 31 in./yr or 80 percent of the average annual precipitation.

The remaining 20 percent of the average annual precipitation falling on the study area discharges as runoff (Q = 7.6 in.). Runoff can be separated into two parts; direct runoff which is flow in a stream following a precipitation event, and base flow which is flow derived from ground-water sources. Table 12 indicates that base flow averages 125 ft^3/s or 4.7 in./yr leaving a residual of 3.0 in./yr as direct runoff. Thus, base flow exceeds direct runoff and averages about 12 percent of the average annual precipitation. The pie diagram of figure 32 shows the proportions of each component in the hydrologic budget and illustrates that the major loss of water from the study area is by evapotranspiration.

HYDROLOGIC BUDGET

PRECIPITATION = BASE FLOW + SURFACE RUNOFF + EVAPOTRANSPIRATION

(38.4 IN. = 4.6 IN. + 3.0 IN. + 30.7 IN.)

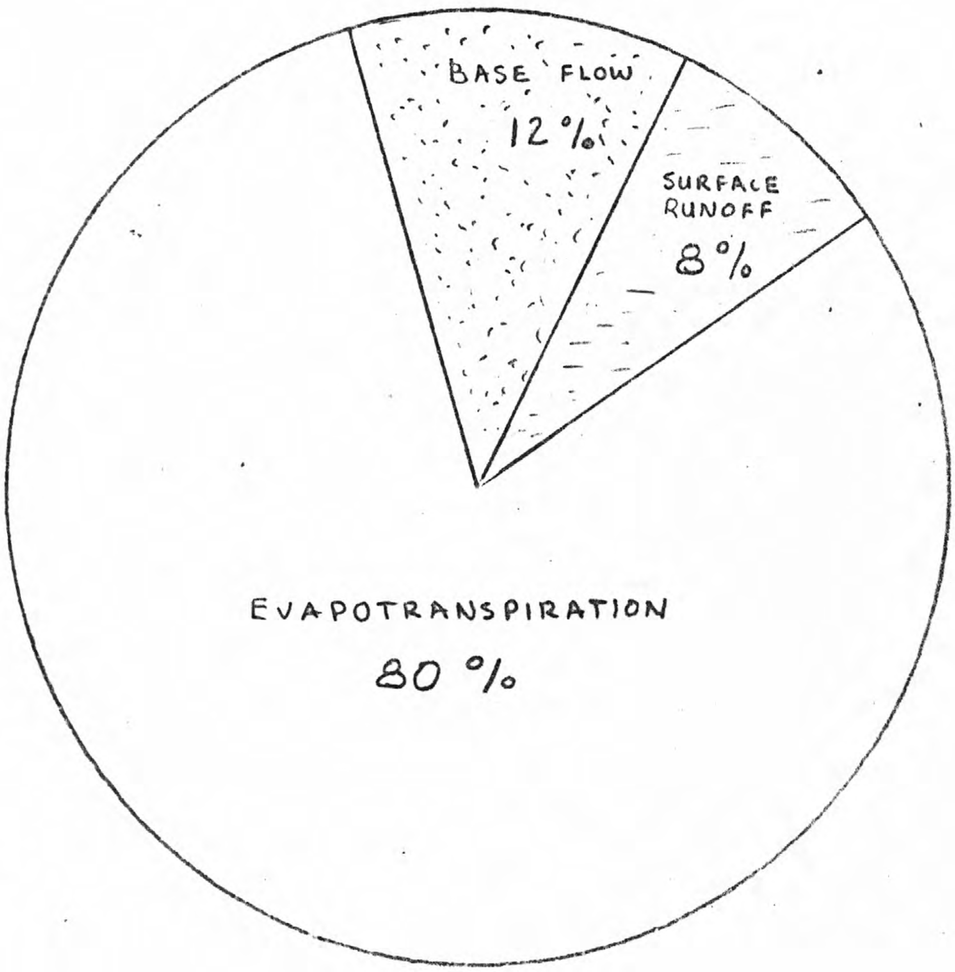

Figure 32.--Hydrologic budget of the study area.

A comparison of the above derived ET = 30.7 in./yr with the previously derived ET = 26 in./yr from a base flow depletion analysis supports the assumption that ET derived from base flow depletion does not consider that ET outside the areas of riparian vegetation. Some of the difference between the two estimates of ET also reflects errors in the determination of the components used to derive each ET estimate.

WATER QUALITY

Most of the dissolved matter in water originates from solution of the rocks through which the water has moved. The amount of dissolved matter in the water depends on the physical and chemical characteristics of the original water and the length of time it is in contact with the rocks. Rainfall contains minor amounts of dissolved gases and some solids from dust.

Temperature, pH, and specific conductance of water from wells, springs, and streams were determined during the field inventory phase of the study. These field determinations were used as guides in the collection of water samples for laboratory analysis.

Samples of water were collectd from wells, springs, and streams and analyzed for comparison of various chemical constituents. Table 17 is a listing of maximum, average, and minimum concentration of common dissolved chemical constituents from these three sources.

The relation between specific conductance and dissolved solids (residue on evaporation at 180°C) in water is shown for wells, springs, and streams in figures 33, 34, and 35, respectively. The correlation coefficient for the plot of specific conductance versus dissolved solids in water from wells (fig. 33) is 0.95, 0.73 for springs (fig. 34) and 0.91 for streams (fig. 35).

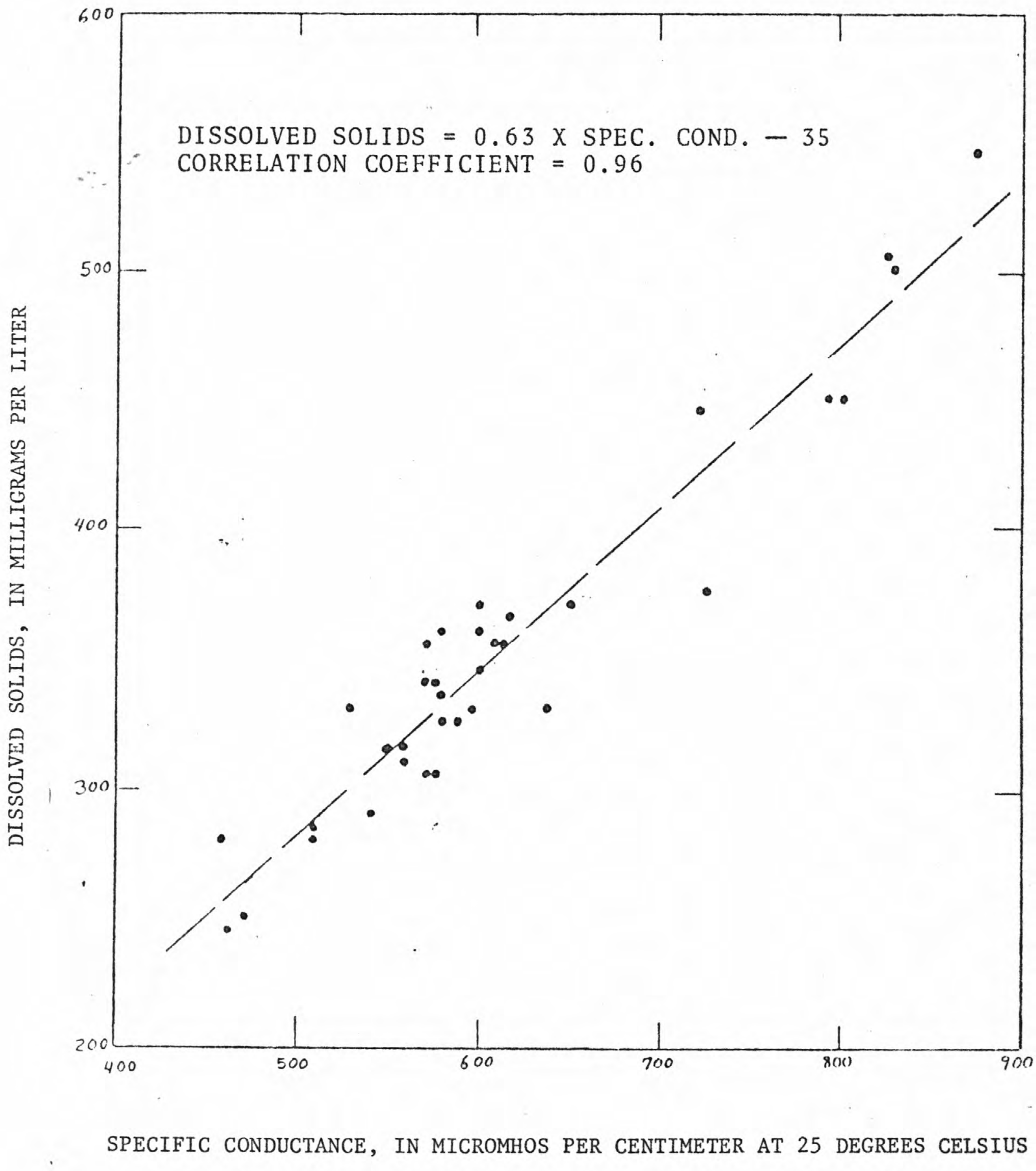

Figure 33.--Relation of specific conductance and dissolved solids (residue on evaporation) in water from wells in the study area.

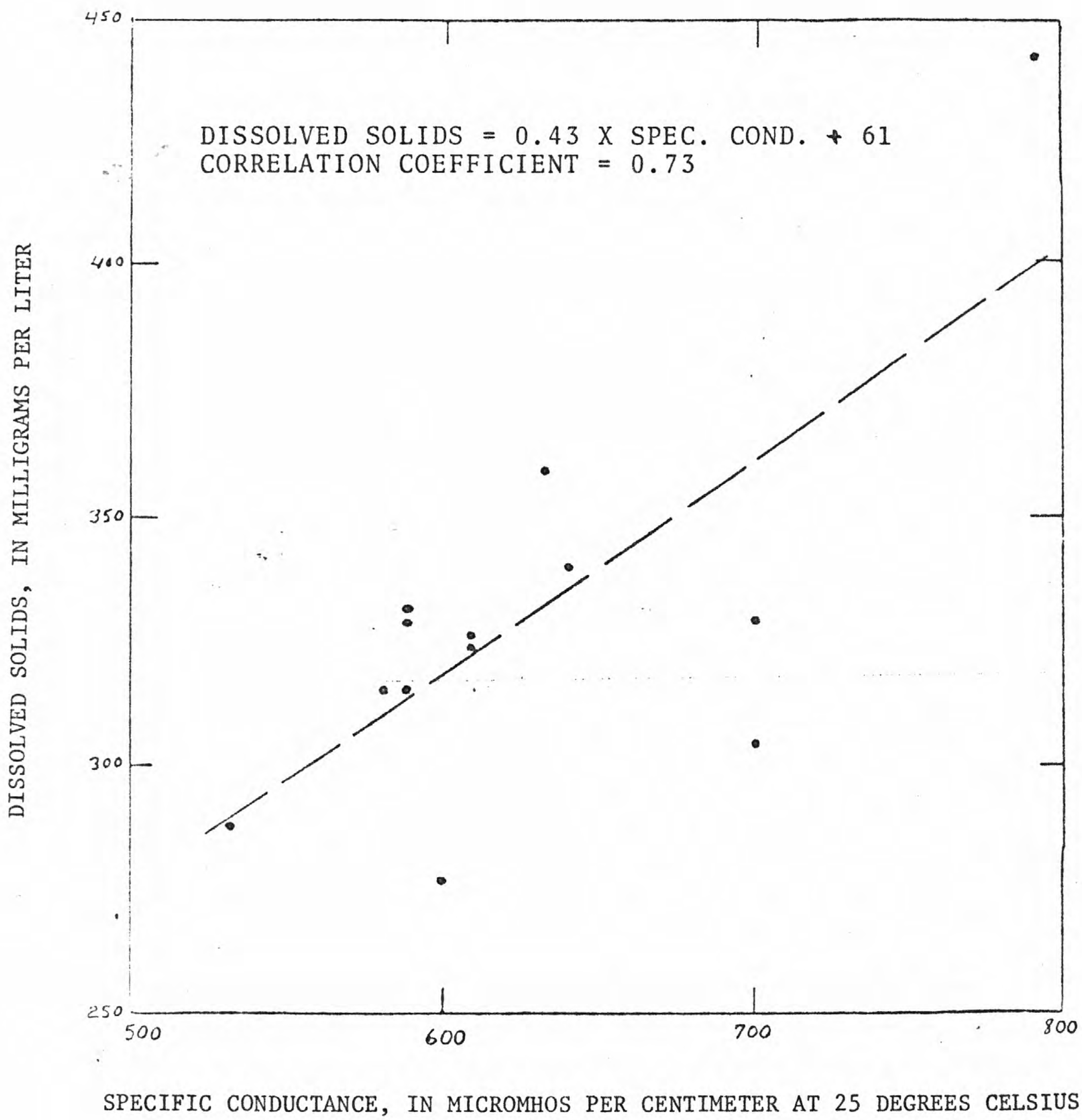

Figure 34.--Relation of specific conductance and dissolved solids (residue on evaporation) in water from springs in the study area.

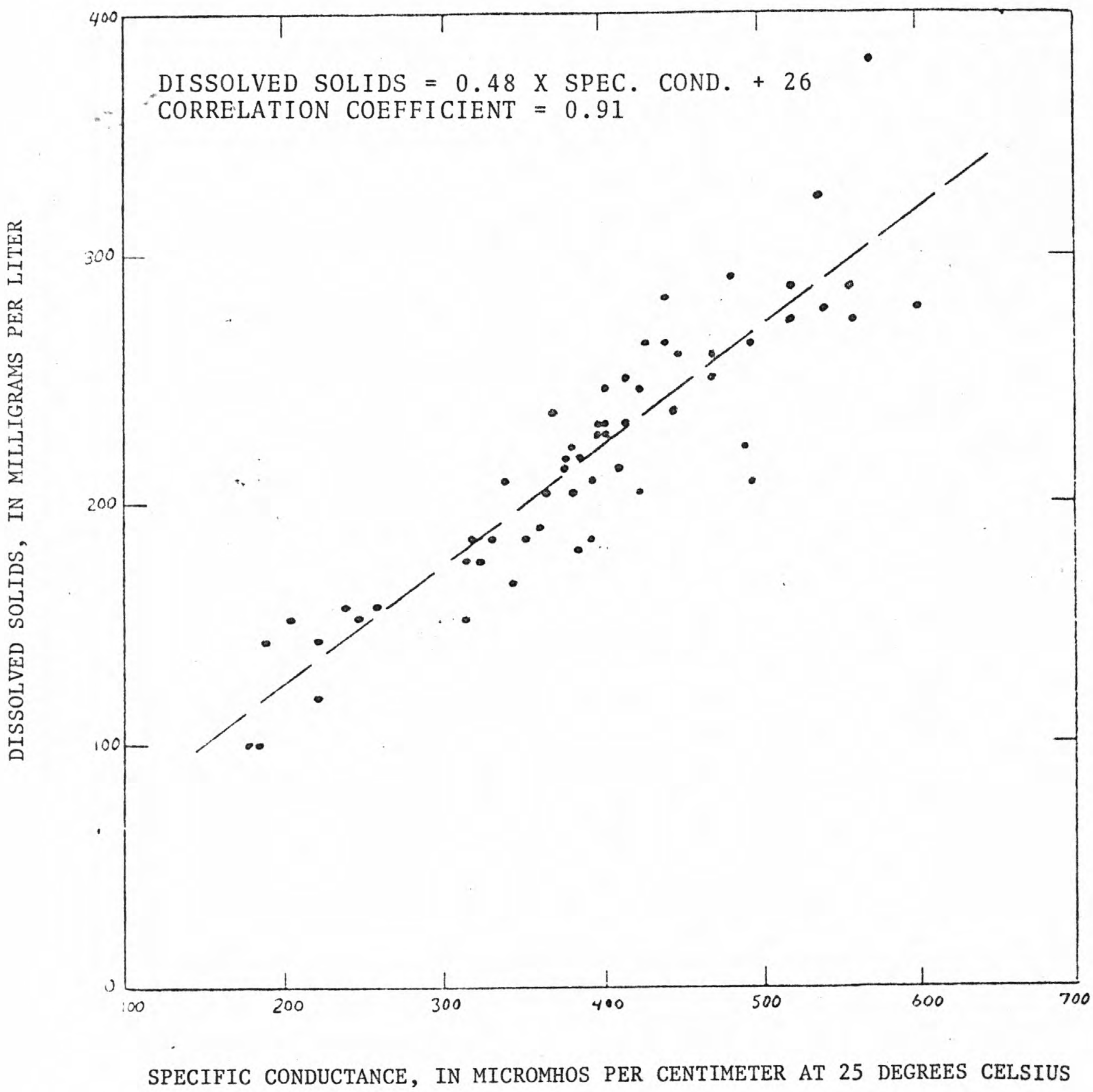

Figure 35.--Relation of specific conductance and dissolved solids (residue on evaporation) in water from streams in the study area.

Table 17.--Maximum, average, and minimum concentration of common dissolved chemical constituents in water from 23 wells, 12 springs, and 12 streams in the study area [Constituents in mg/L except where otherwise indicated]

	Wells			Springs			Streams		
	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum
Calcium	140	91	39	110	83	72	110	68	43
Magnesium	54	27	5.2	41	32	11	40	25	7.7
Hardness 1/	470	338	170	380	336	300	350	275	160
Dissolved Solids	554	358	282	441	328	276	379	269	186
Carbon Dioxide	55	34	12	77	34	16	22	4.6	1.2
Bicarbonate	460	371	290	440	379	280	370	295	180
Sodium	69	13	1.4	31	5.6	1.9	20	6.5	1.9
Chloride	93	14	1.9	62	9.0	2.3	39	9.3	2.5
Fluoride	0.6	0.2	0.1	0.2	0.1	0.1	0.2	>0.1	0.1
Specific Conductance 2/	875	598	460	790	632	580	600	498	320
Temperature 3/	25.0	15.5	10.0	22.0	16.5	7.0	33.0	18.3	2.0
pH 4/	7.6	7.3	7.0	7.5	7.3	6.9	8.5	8.2	7.4

1/ As $CaCO_3$

2/ In micromhos per centimeter at 25°C.

3/ In °C.

4/ Units

Piper diagrams showing the proportions of cations and anions in water from the wells, springs, and streams are shown in figure 36. The concentration of data points on the left side of the diagrams indicate that water from all three sources is a calcium-magnesium bicarbonate type. The samples were collected when water levels in wells were low and flow in streams was primarily base flow. Magnesium shows the greatest variation in water from all three sources. This variation in magnesium is probably related to the rock type that the water had been in contact with. Dolomite, $CaMg(CO_3)_2$, could be the source of the magnesium. According to Ham (1955, p. 1) the rocks of the Arbuckle Group are mostly limestone, $CaCO_3$, in the western part of the area but are mostly dolomite in the east and northeast parts of the area.

A few data points plot outside the normal grouping, especially the cations in water from wells. This scattering does not indicate a trend away from the water type indicated by the majority of the points. One of the wells is outside the outcrop area of the Arbuckle-Simpson aquifer and may yield water from other formations that overlie the aquifer. This well also has a slightly higher percentage of chloride concentration than water from other wells. The grouping of all other points in the anion diagrams of water from wells, streams, and springs indicates that the percentage of anion concentrations in water from all three sources is similar.

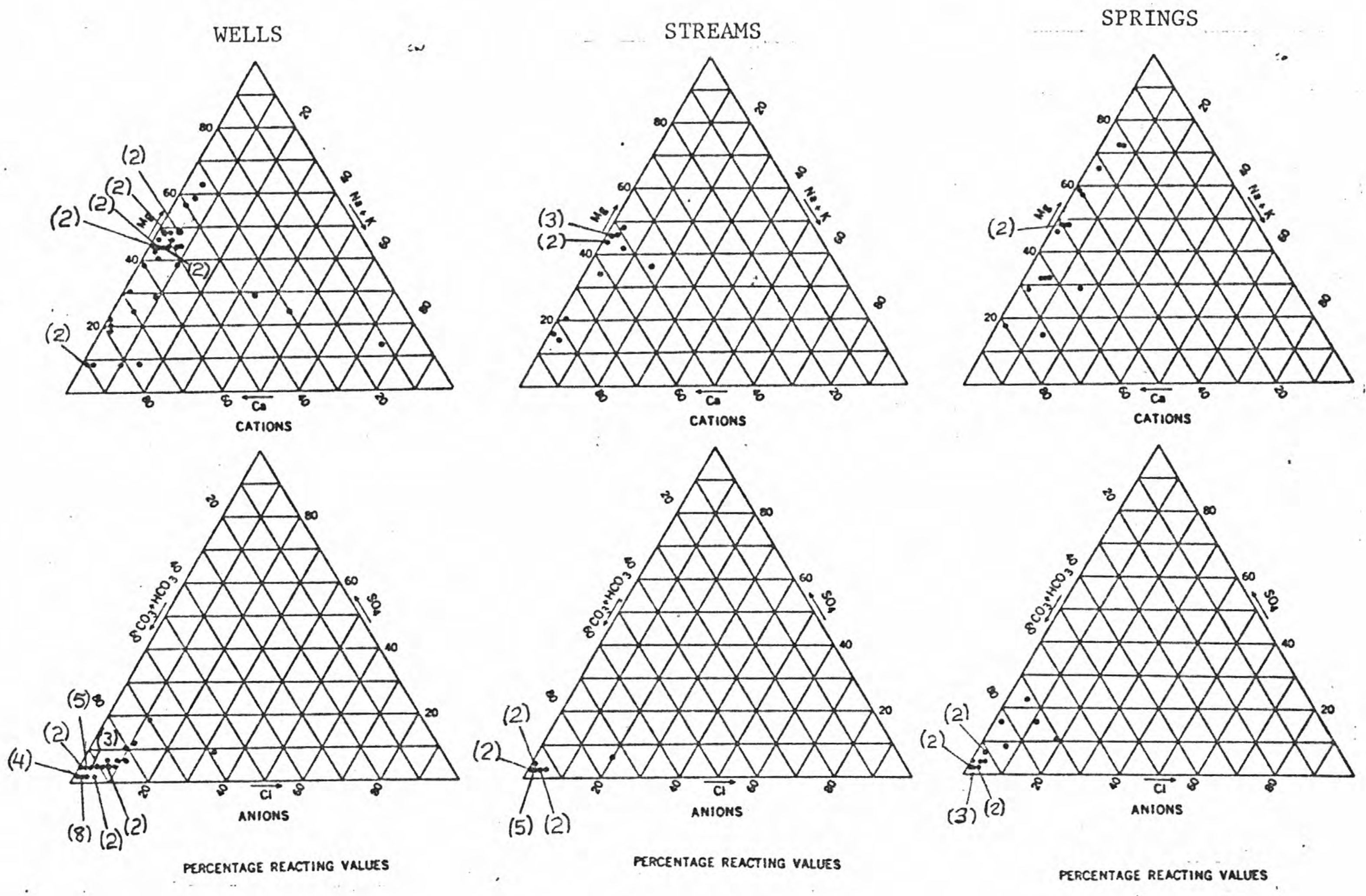

Figure 36.--Proportions of cations and anions in water from wells, streams, and springs in the study area (number in parentheses is the number of samples represented by the point indicated).

The chemical quality of water from wells that tap the Arbuckle-Simpson aquifer in the study area is suitable for most industrial and municipal uses. Concentrations of most mineral constituents and chemical properties of the water are within the limit recommended by the Environmental Protection Agency (1976). Recommended limits for some of the chemical constituents in public water supply are shown in table 18.

Water samples from 23 wells in the study area were analyzed for common ion and trace-element concentrations. All samples were collected at the well head and are possibly a composite of water from more than one producing zone.

The concentration of trace elements in water from wells, springs, and streams is listed in table 19. Iron exceeded the recommended limit of 300 micrograms per liter in a sample from well 02S-03E-09 AAB 1 (Fe = 550 micrograms per liter) but would not be a cause for rejection of the ground water in the area as a drinking water source.

Table 18.--Recommended or required quality standards for public water supplies

~~[Concentrations in mg/L except where otherwise indicated]~~

Chemical substances	Limit not to be exceeded
Physical	
color (units)	75 platinum-cobalt units
odor (units)	unobjectionable
pH (units)	5.0 to 9.0
Chemical (common ions) (milligrams per liter)	
Chloride	250
Fluoride [1]	1.4 - 2.4
Sulfate	250
Nitrate (as N)	10 [2]
(trace metals) (milligrams per liter)	
Arsenic	0.05 [2] mg/L
Cadmium	0.010 [2] mg/L
Chromium	0.05 [2] mg/L
Copper	1 mg/L
Iron	0.3 mg/L
Lead	0.05 [2] mg/L
Maganese	0.05 mg/L
Mercury	0.002 [2] mg/L
Zinc	5 mg/L

[1] The concentration of fluoride should be between the limits expressed depending on the annual average of maximum daily air temperatures at a location being considered.

[2] Maximum contaminant level as set by the Environmental Protection Agency (1976); primary drinking water regulations.

able 19.--Maximum, median, average, and minimum concentration of dissolved trace elements in water from 23 wells, 12 springs, and 12 streams in the study area

	Trace-elements concentration (in micrograms per liter)									
	Aluminum (Al)	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manganese (Mg)	Mercury (Hg)	Zinc (Zn)
					Wells					
Maximum	70	1	3	22	25	350	30	10	0.0	1,900
Median	10	1	0	0	7	50	5	0	0.0	100
Average	13	0.8	0.3	2.5	8.7	71	8.6	2.3	0.0	208
Minimum	0	0	0	0	0	0	0	0	0.0	0
					Springs					
Maximum	40	1	10	10	7	80	110	80	0.0	800
Median	20	1	1	0	3	20	8	4	0.0	60
Average	18	0.8	1.8	1.7	3.5	32	25	11	0.0	166
Minimum	0	0	0	0	0	10	3	0	0.0	20
					Streams					
Maximum	20	1	1	10	6	650	170	20	0.0	1,000
Median	10	1	0	0	3	25	10	8	0.0	25
Average	11	0.8	0.4	3.8	2.7	78	25	6.5	0.0	186
Minimum	0	0	0	0	0	10	0	0	0.0	10

Water from well 01N-05E-27 DCC 1 was sampled at various depths and tested for chemical and physical properties during a well-performance test (Oklahoma Water Resources Board, 1966). A plot of dissolved solids and hardness versus depth at which samples were taken (fig. 37) indicates that there is little or no change of chemical quality of the water to a depth of at least 2,500 ft. Hardness averages about 270 mg/L and dissolved solids averages about 330 mg/L.

FIGURE 37 APPEAR HERE

Around the periphery of the outcrop area, beds of the Arbuckle-Simpson aquifer dip steeply beneath sediments that are younger than the Arbuckle-Simpson rocks. A short distance outside the outcrop area, information from geophysical logs indicates that water in the aquifer becomes highly mineralized in a down-dip direction.

Early work by Dott and Ginter (1930) and Case 1934) dealt with the characteristics of waters in Ordovician rocks in a broad area which included the area in this report. It was found that the concentration of dissolved solids increased rapidly in a down-dip direction at a rate of 10,000 mg/L per mile (Dott and Ginter, 1930, p. 1217).

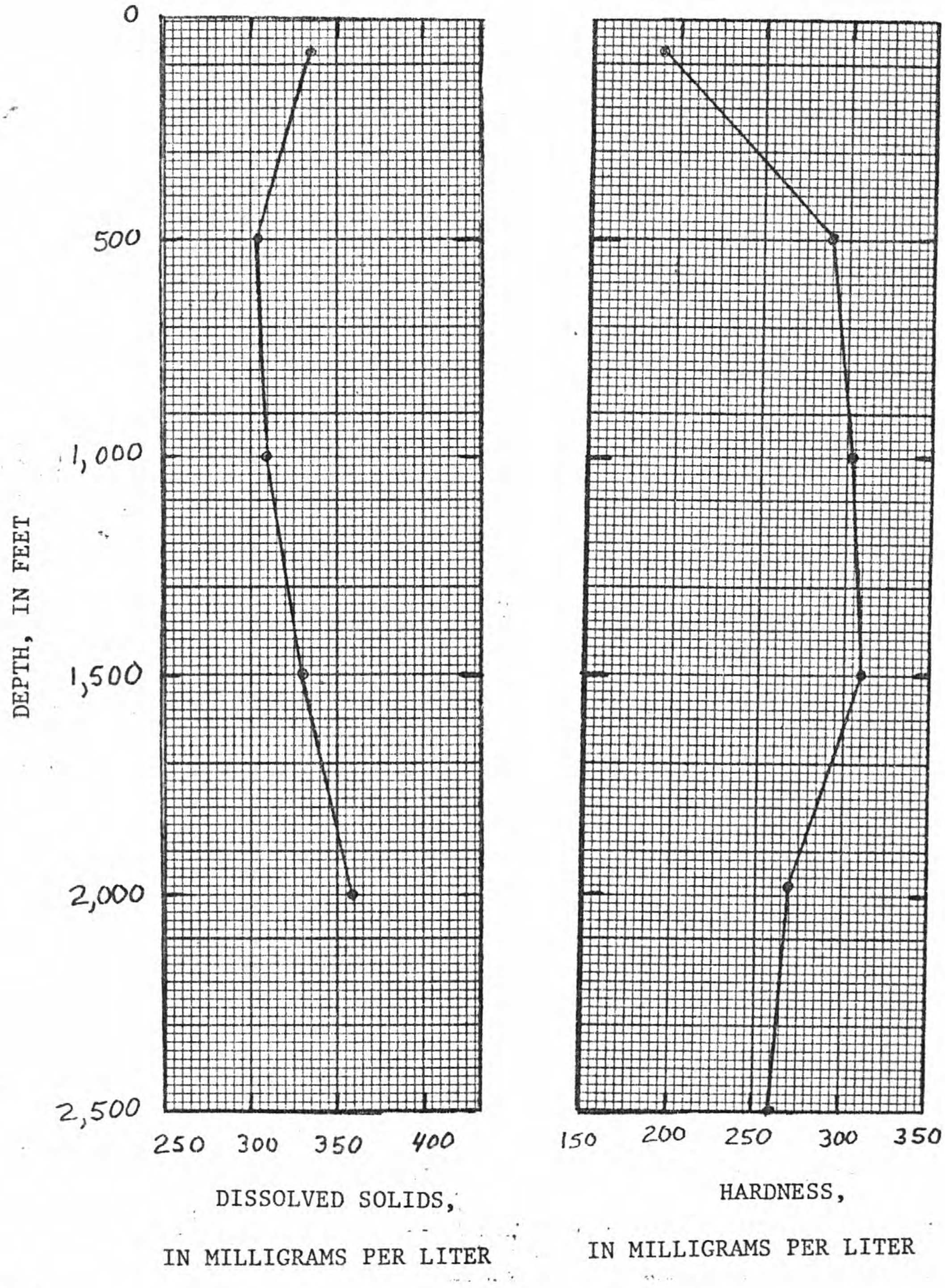

Figure 37.--Graph showing dissolved solids (residue on evaporation) concentration and hardness of water versus depth in well 01N-05E-27 DCC 1.

Water from several wells that produce from the Simpson Group contain various amounts of oily residue (asphalt) or gas. Many well owners report that the oil produces a visible film on the water surface and that the water has an oily taste or odor. Although the water is generally of adequate quality for most domestic purposes, attempts to remove the oil by filtering have had limited success. In a small area about two miles south of Sulphur in T.1 S., R.3 E., sections 14, 15, 22, and 23, most wells are no longer used for domestic supplies and city water from wells that tap the Arbuckle Group, is treated, and is piped to that area.

Water from 12 perennial springs in the area was analyzed for comparison with water from wells that tap the Arbuckle-Simpson aquifer and streams that drain the area. The spring water is chemically similar to water in the Arbuckle-Simpson aquifer. The temperature of water from springs varies slightly with the seasons but averages about 16.5°C.

The chemical characteristics of water in streams varies seasonally and has a lower mineral concentration during rainy seasons than during dry seasons. The base flow of streams in the area is derived from springs that discharge from rocks that make up the Arbuckle-Simpson aquifer. As a result, the quality characteristics of water in streams during low-flow periods is similar to water in springs that discharge from the aquifer.

The maximum, average, and minimum concentration of some common chemical constituents and physical characteristics of water from streams in the area are listed in table 17. As shown in the table, the dissolved solids concentration in stream water is generlly less than that in water from wells and springs.

The temperature of water in streams varies seasonally and ranges from 2.0 to 33.0°C. Streams fed by springs seldom freeze over completely during the winter although a thin ice sheet may form over the surface of ponded water.

Travertine (calcium carbonate, $CaCO_3$) deposits occur in most streambeds, especially downstream from springs. Precipitation of the travertine suggests that the water is saturated with calcium and that as it discharges from springs, CO_2 (carbon dioxide) is released and $CaCO_3$ is precipitated on the streambed material. Deposition of trvertine probably results in a small decrease of dissolved chemical constituents in stream water. This is consistant with the increase in pH observed for the streams.

A prime example of travertine precipitation from stream water is a large deposit in Honey Creek at Turner Falls. Johnson and McCasland (1971) described the despoit and indicate that blue-green algae assist in precipitating the calcium carbonate.

Another large deposit of travertine occurs in Honey Creek about one mile west of Turner Falls on the west side off the East Timbered Hills. The creek flows through a chasm in the upstream deposit which probably has a depositional history similar to the deposit at Turner Falls. Several springs are upstream from the Turner Falls deposit. Above the springs, the streambed material is coated with travertine ~~and~~ although no flow occurs in this reach of the stream during the summer dry season.

WATER USE

Water from the Arbuckle-Simpson aquifer, although used only in small amounts, serves as a source for domestic, industrial, commercial, and agricultural purposes. Most of the water withdrawn is used for stock supplies, primarily for dairy and beef cattle. Irrigation is limited to bottom land and is used mostly to raise hay. Each rural residence has its own water supply system and in many cases, the water is used for stock supplies.

Water is also supplied to rural areas through distribution lines operated by Rural Water Districts (Oklahoma Water Resources Board, 1980). The water is obtained from wells that tap the Arbuckle-Simpson or from the Lake of the Arbuckles which gets much of its water from springs that issue from Arbuckle and Simpson outcrops.

At the time of this study, only one Rural Water District in the study area uses water from wells in the Arbuckle-Simpson aquifer--Rural Water District No. 3 at Mill Creek. Rural Water District No. 6 at Fittstown gets water from Byrds Mill Spring that issues from the Arbuckle-Simpson aquifer.

Industrial use of the water at the time of this study is limited to cooling water in electric generation and for hydraulic mining operations for mining glass sand.

Wells that obtain water from the Arbuckle-Simpson aquifer are usually constructed by hydraulic rotary. Many of the older wells were drilled by use of cable tool or were hand dug and are still in use.

The wells are cased depending on the type of the strata that is penetrated. Where wells are drilled into limestone, only 25 to 50 ft of casing is used to prevent soil or sand from collapsing or flaking into the well bore. Below the casing the hole is open. Wells that are drilled in fine sand of the Simpson Group are often cased to the bottom of the hole. The casing is perforated and screened at one or more producing intervals to allow water into the well bore. In some cases, the annular space between the walls of the hole and the casing is gravel packed to increase the yield.

Wells used as a water supply for stock are usually equipped with a windmill. Yield is usually less than 1 gal/min but is adequate under most conditions. During prolonged drought periods, water levels may decline below the pump piston. In some cases, lowering the pump piston is enough to overcome loss of yield due to declining water levels.

Many wells, particularily those used for domestic supply, are equipped with a submersible pump, powered by a 0.5 to 1 horsepower electric motor. In some cases, a deep-well jet pump is adequate where the water level is 75 ft or less below land surface. A few deep wells used for public supply or irrigation are equipped with turbine pumps.

SUMMARY

~~Several~~ perennial streams in the Arbuckle Mountain area are fed by springs that issue from the limestone and sandstone that make up the Arbuckle-Simpson aquifer. The major streams include Pennington, Mill, Falls, Honey, Oil, and Delaware Creeks, and the Blue River and its tributaries.

The Arbuckle-Simpson aquifer crops out in a little over 500 mi^2 in the Arbuckle Mountains province in south-central Oklahoma. The Arbuckle and Simpson Groups that make up the aquifer consist of Upper Cambrian to Middle Ordovician limestone, dolomite, and sandstone. All rocks of the aquifer were structurally deformed during Late Paleozoic mountain-building periods and act as a reservoir in which water is stored in numerous interstices from small intergranular pores to open fractures and caverns.

Secondary permeability is provided by numerous fractures, joints, and solution channels. The average saturated thickness of the aquifer is about 3,500 ft in the outcrop area.

Water in the aquifer is confined in various parts of the outcrop area while in other parts, the water is unconfined. The rapid response of water levels in wells to precipitation indicates that many wells tap a confined part of the aquifer. During the study, water levels were monitored in 33 observation wells to determine long-term trends, seasonal fluctuations, and the relationship between ground water and surface water.

Water levels in wells fluctuate from about 8 to 53 ft each year, primarily in response to rainfall, and are lowest during January and February and highest during May and June. No long-term trends in the rise or decline in water levels are indicated from the 3 years of ground-water level data which was collected in the study area during the study.

Recharge to the aquifer is from precipitation that falls within the area. Long-term precipitation records from Sulphur and Pontotoc located in the study area and Ada located about 15 miles north of the area define an average annual precipitation of 38.2 in./yr. Precipitation was about 80 percent of the long-term average during the study period.

Recharge to the aquifer, based on the total average annual base flow from streams that drain the area, amounts to 4.7 in./yr.

Discharge from the Arbuckle-Simpson aquifer is by evapotranspiration, through springs and seeps, and by pumpage from wells.

Throughout much of the area, the depth to the saturated zone is below the effects of evapotranspiration except where the potentiometric surface comes close to, or intercepts, the land surface. Almost 100 springs discharge water from the Arbuckle-Simpson aquifer to streams that drain the study area. This discharge occurs as base flow in the streams and amounts to 4.6 in./yr or approximately 60 percent of the total annual runoff from the outcrop area. At the time of this study, withdrawal of water from the aquifer by pumpage, although not determined, accounted for only a minor portion of the discharge.

The chemical quality of water from the Arbuckle-Simpson aquifer is suitable for most industrial and municipal uses. The water is hard and of the bicarbonate type; hardness averages 338 mg/L and dissolved solids average 358 mg/L.

In the central part of the outcrop area, there is little or no change of chemical quality of the water to a depth of at least 2,500 ft. Around the periphery of the outcrop area, beds of the Arbuckle-Simpson aquifer dip steeply beneath younger sediments. Water in this region of the aquifer becomes highly mineralized in a down-dip direction.

SUMMARY OF INFORMATION REQUIRED TO MEET OKLAHOMA GROUND-WATER LAW

This section of the report is included as agreed upon by the U.S. Geological Survey, the Oklahoma Geological Survey, and the Oklahoma Water Resources Board. The information is provided in order for the Oklahoma Water Resources Board to meet the requirements of Oklahoma State Law (82 Oklahoma Statutes Supp. 1973, paragraph 1020.1 et seq.). This law requires that the Oklahoma Water Resources Board make a determination of the maximum annual yield of each ground-water basin for a minimum 20-year life based on the following:

1. The total land area overlying the basin or subbasin;
2. The amount of water in storage in the basin or subbasin;
3. The rate of natural recharge to the basin or subbasin and total discharge from the basin or subbasin;
4. Transmissivity of the basin or subbasin; and
5. The possibility of pollution of the basin or subbasin from natural sources.

According to determinations made by the Oklahoma Water Resources Board, the total amount of ground water established under prior rights is 5,984 acre-ft per year and the total amount of land covered by prior rights is 624 acres.

Based upon this study, the following information is provided to assist the Oklahoma Water Resources Board to meet the requirements of Oklahoma ground-water law:

1. The total land area overlying that part of the basin in this study is 326,400 acres. Ground-water basin by Oklahoma law means a distinct underground body of water overlain by contiguous land and having substantially the same geological and hydrological characterisitcs and yield capacities. As used in this report, "basin" refers to the area where rocks that make up the aquifer are exposed at the surface.
2. The amount of water in storage in the "basin" and available for use was estimated at 9 million acre-ft as of September 30, 1979.
3. The rate of natural recharge to the "basin" is estimated at 128,000 acre-ft per year. Total discharge from the basin is estimated at 128,000 acre-ft per year; discharge from wells accounts for less than 2 percent of this amount. If the hydrologic system remained completely static except for recharge and if all the water available from storage could be removed over the 20-year life of the "basin," the amount that could be withdrawn from the aquifer is estimated at 1.8 acre-ft per acre per year.

4. The transmissivity of the "basin" ranged from 40 to 49,600 ft^2/day and averaged an estimated 15,000 ft^2/day.
5. No known source of natural pollutants have been identified as of September 30, 1979. Owing to the near surface open features, such as sinkholes and solution cavities, the possibility of pollution exists either from natural sources or from man's activities.

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